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MASS BALANCE OF BASIN AND RANGE EXTENSION AS A TOOL FOR GEOTHERMAL EXPLORATION

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ABSTRACT

Despite large spatial variations in the magnitude of Cenozoic extension, crustal thickness seems surprisingly uniform throughout the Basin and Range. Within the highly extended Death Valley region, correlations of offset geologic markers constrain detailed palinspastic reconstructions that allow measurement of changes in map-area and line-length resulting from Cenozoic tectonism. The ratio of these parameters is used to calculate regional strain partitioning by normal and strike-slip faults, that is, the proportions of northwest-directed extension balanced by crustal thinning and wrench faulting. Less than 20% of the total finite strain budget is accommodated by map-view plane strain across strike-slip faults, in general agreement with previous work. Increases in map-area indicate an average crustal stretching factor of about 2.3 - 3.0, however, maximum values exceed 10 over a substantial area. Mass balance requires either addition of new crustal mass or redistribution of existing lower crustal material. Both processes advect heat toward the surface within areas of extreme extension while equalizing crustal thickness differences with less extended areas. Regional strain maps may prove useful as geothermal exploration tools within extensional orogenic belts.

INTRODUCTION

Thermal consequences of extensional tectonism involve advection of heat toward earth's surface (e.g. Buck et al., 1988). Structural processes remove and redistribute material overlying hotter, more deeply buried rocks, or stretch and thin the material lying between isotherms. Magmatic processes release the heat of crystallization following migration of melt to new crustal positions. Specific mechanisms of extension, such as the role of strike-slip faults (e.g. Mancktelow and Pavlis 1994), or the role of magmatic processes in extension (e.g. Lipman, 1992) remain controversial. Regardless, understanding the mass balance of an extensional orogen bears directly on predicting where hot rocks are likely to exist near the surface.

In this paper, methods for calculating extensional strain are reviewed. As an example, a newly revised palinspastic map of the highly extended Death Valley region of the Basin and Range is presented. This reconstruction facilitates evaluation of strain partitioning and mapping the regional distribution of true crustal stretching. Regions of extreme stretching (>1000%) may offer potential for geothermal exploration.

MEASUREMENT OF EXTENSION

The Basin and Range Province at the latitude of Death Valley, California, lies between the unextended Colorado Plateau and Sierra Nevada crustal blocks (Fig. 1). Extension is accommodated by numerous high-angle normal faults, several detachment systems, and an apparently conjugate system of large strike-slip faults (Fig. 1; e.g. Wernicke et al., 1989). Prior to Cenozoic extension, the region experienced contractile deformation resulting in an extensive fold and thrust belt (Fig. 2a; Wernicke et al., 1988; Snow, 1992a) developed dominantly within a miogeoclinal passive margin sequence (e.g. Wernicke et al., 1988, 1989).

Accurate measurements of the magnitude and uncertainty of relative displacements are obtainable from correlations among structures of the pre-extensional fold and thrust belt now exposed in widely scattered ranges throughout the extended terrane (e.g. Wernicke et al., 1988; Snow and Wernicke, 1989). Apparent offsets of miogeoclinal isopach trends and facies boundaries have also been used to estimate displacements (Stewart, 1983; Stevens et al, 1991), but such estimates remain imprecise because the current location and original configuration of such markers are poorly constrained in many cases (Fig. 2; Prave and Wright, 1986; Snow 1992b).

Net translation of the Sierra Nevada relative to the Colorado Plateau during Cenozoic extension can be determined by vector addition of a series of relative displacements (Wernicke et al., 1988). Individual displacement vectors seldom link together head to tail but must be tied through unextended strata connecting different points. Vertical-axis rotation moves a vector tail relative to an adjacent head proportional to the magnitude of rotation and distance separating the vectors. Depending on the precise geometry, rotations increase or decrease total displacement. Rotation of the Spring Mountains block (Fig. 1) was included as a source of error by Wernicke et al. (1988), but rotations in other parts of vector path were considered unlikely.

Elongation, or apparent crustal stretching, is calculated by comparing the current line-length between a pair of geologic markers and its equivalent measured in the undeformed state. If material points move only within vertical planes oriented parallel to the extension direction (cross-sectional plane strain accommodated by faults with pure normal motion) apparent crustal stretching is an accurate measure of true crustal stretching (crustal thinning), assuming conservation of mass. Conversely, if material points move only within horizontal planes (map-view plane strain accommodated by faults with pure strike-slip motion) large elongations may be measurable from offset markers with no crustal thinning. True crustal stretching is related to elongation by a strain partitioning coefficient expressing the relative proportions of extensional and plane strain accommodated by normal and strike-slip faults. In nature, we expect locally complex material paths, but if a sufficiently large region of crust is investigated, these heterogeneities become second-order effects.

The importance of strike-slip faulting within the Death Valley region is widely recognized (Stewart, 1988; Wernicke et al., 1988; Mancktelow and Pavlis, 1994). Many strike-slip faults form conjugate sets (Fig. 1) and accommodate map-view pure shear (constrictional strain) characterized by north-south shortening during east-west extension (Wernicke et al., 1988; Anderson, 1994). Constrictional shortening, estimated as 43 km, suggests that 20% of Cenozoic strain is accommodated by map-view pure shear along strike-slip faults (Wernicke et al., 1988).

The eastern California shear zone has been proposed as a major dextral shear system accommodating part of Pacific-North American plate motion (Dokka and Travis, 1990). If this fault system projects north from the Mojave Desert through the Death Valley region (ECSZ, Fig. 1), many strike-slip faults may cause map-view simple shear, rather than pure shear (Mancktelow and Pavlis, 1994. Apparent constrictional strain does not distinguish between these models because both can cause relative north-south convergence between points on opposite sides of major strike-slip faults, although it is difficult to explain northeast-trending, sinistral faults solely within a dextral simple shear model.

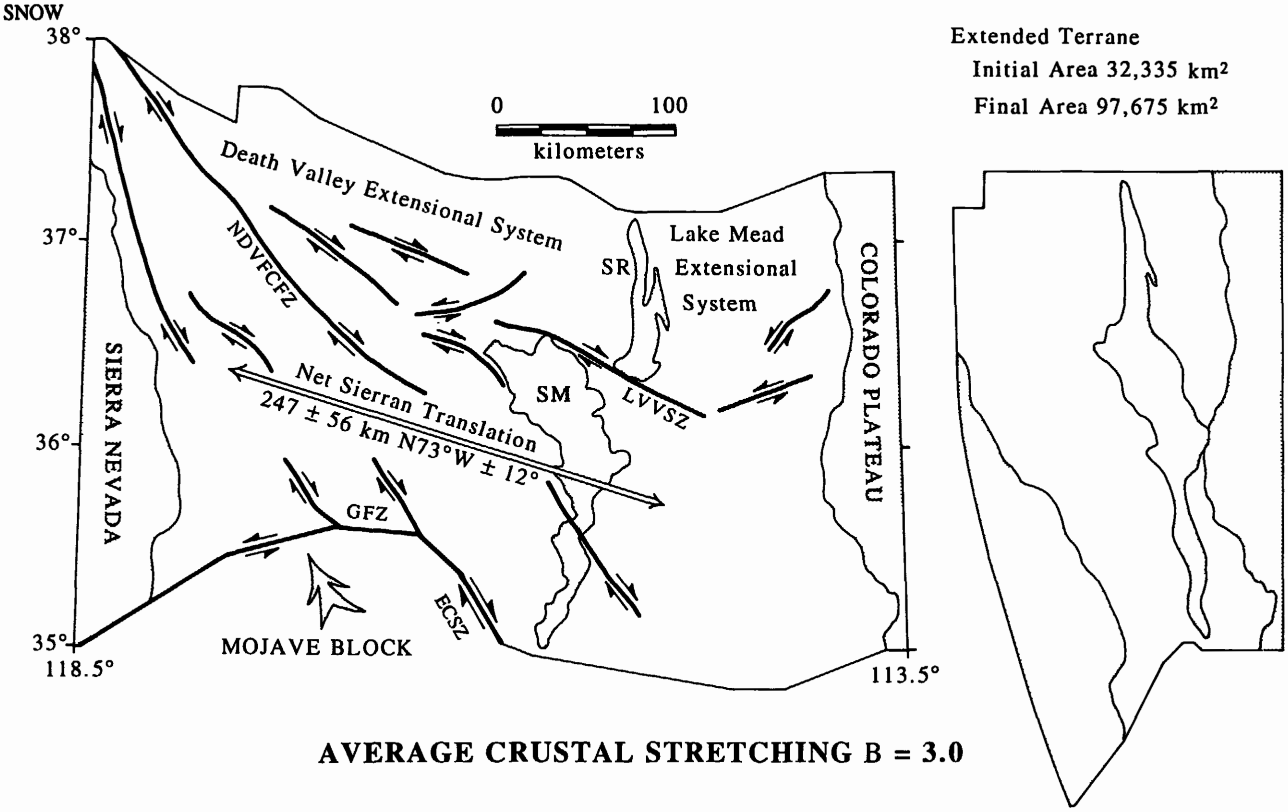


Figure 1. Map of Basin and Range Province (left) showing regions of large-magnitude crustal stretching, Death Valley and Lake Mead extensional systems, lying between the unextended Sierra Nevada and Colorado Plateau and mildly extended Spring Mountains (SM) and Sheep Range (SR) medial stable terrane (after Wernicke et al., 1988). Note Garlock fault (GFZ), northern Death Valley- Furnace Creek fault (NDVFCFZ), Las Vegas Valley shear (LVVSZ), and eastern California shear (ECSZ) zones. Reconstruction (right) of Death Valley (based on Fig. 2b) and Lake Mead (from Wernicke et al., 1988) extensional systems indicates a net Sierran translation of 294 km N73°W, within error of estimate by Wernicke et al. (1988, indicated on left map). A net area change, or true crustal stretching factor, of 3.0 and a maximum elongation, or apparent crustal stretching factor, of 3.6 indicate strain partitioning of 83% extensional strain on normal fault systems and 17% map-view plane strain on strike-slip fault systems. See text for further discussion.

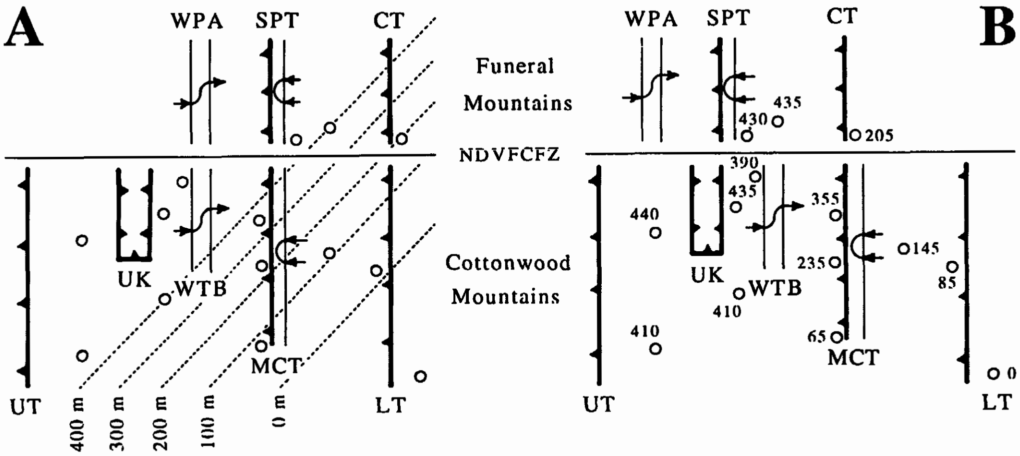


Figure 2. Correlation of major contractile structures across the Northern Death Valley- Furnace Creek Fault Zone between the Cottonwood and Funeral Mountains (NDVFCFZ, CW, and FM on Fig. 2; modified from Wernicke et al., 1993). Relative spacing and characteristic structural style shown for Ubehebe thrust (UT, part of Last Chance allochthon on Fig. 1), normal-fault bounded klippe of Ubehebe thrust plate exposed in Cenozoic graben (UK), west-vergent White Top Backfold (WTB), Marble Canyon thrust and footwall syncline (MCT), Lemoigne thrust (LT), west-vergent Winters Peak Anticline (WPA), Schwaub Peak thrust and footwall syncline (SPT), and Clery thrust (CT). See Snow and Wernicke (1989), Snow and White (1990), Snow (1992a), and Wernicke et al. (1993) for structural descriptions. Relative positions shown for measured sections of Silurian-Devonian Hidden Valley Dolomite with thicknesses in meters (Snow, 1992a, unpub. data). (A) Isopachs are constrained to be discordant to structures within the Cottonwoods (Snow, 1990, 1992a). Correlations proposed by Snow and Wernicke (1989) based on similarities of size, vergence, order, spacing, and style of structures results in simple projections of structures and isopachs across NDVFCFZ. (B) Alternative correlations proposed by Stevens et al. (1991, 1992), based on the assumption that facies boundaries are linear markers trending parallel to structures. An irregular yet geologically reasonable set of isopach contours can be drawn, but the reconstruction introduces extreme complications in the geometry of thrusts (Snow and Wernicke, 1993; Wernicke et al., 1993). Used alone, the stratigraphic data are less precise than structural correlations in resolving displacements.

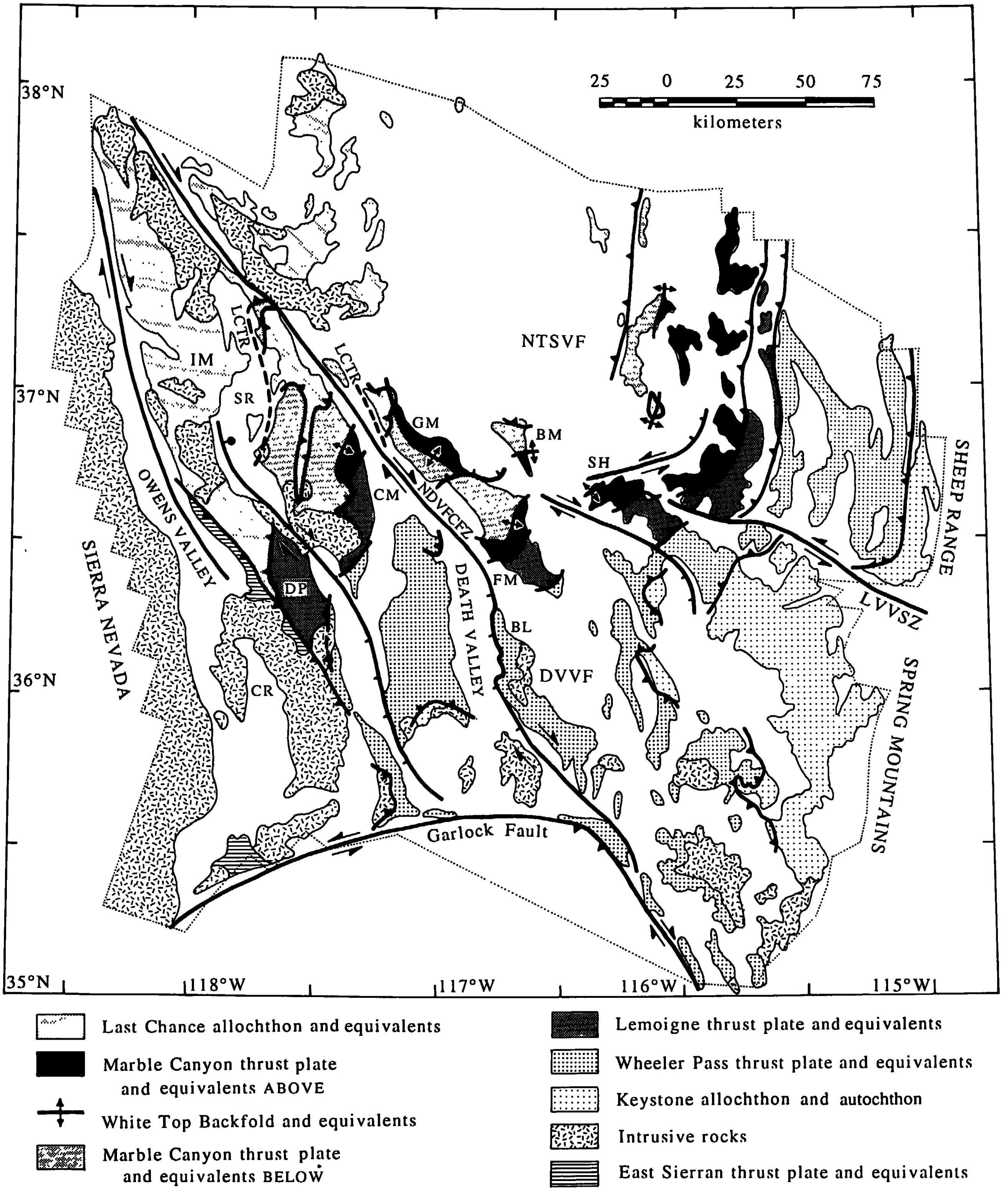


Figure 3. (A, this page) Tectonic map showing correlations and distributions of major pre-tertiary contractile structures used to reconstruct the Death Valley extensional system and selected features discussed in text (after Snow, 1992a; Wernicke et al., 1988). (B, opposite page) Palinspastic reconstruction of Death Valley extended terrane.

PALINSPASTIC RECONSTRUCTION

The present configuration of pre-Tertiary contractile structures in the Death Valley region is substantially more complex than thrust systems in areas unaffected by extensional tectonism (e.g. Price, 1981). Large, mildly extended blocks, such as the Cottonwood Mountains (CW, Fig. 3a), show a simple pre-extensional geometry where trends of contractile structures and stratigraphic markers form two subparallel, but distinctly discordant, linear arrays (Fig. 2; Snow, 1992a).

The palinspastic reconstruction presented in Figure 3b follows that of Snow (1992a; see also Wernicke et al., 1988), but differs in several important respects: (1) Vertical-axis rotations (included herein) increase total estimated elongation. (2) Net displacement vectors were used by Snow (1992a). Sequential retrodeformation at 2 m.y. increments was used herein to assure continuous geometric and kinematic viability during non-coaxial strain. (3) New constraints are herein placed on the relative position of the Grapevine Mountains.

Clockwise deflections of stratigraphic and structural markers adjacent strike-slip faults (Fig. 3a, note drag adjacent strike-slip faults) are regarded as evidence for tectonic rotations (Burchfiel, 1965; Snow and Prave, 1994) because these markers typically trend north-east in areas away from the faults. In particular, covariance between the orientations of structural and stratigraphic markers throughout the Death Valley region, despite their currently diverse orientations within separate ranges, indicates that deviations in trend between markers in individual ranges and the regional average can be used to quantitatively assess both the magnitude and uncertainty of relative rotation (Snow and Prave, 1994).

Surprisingly, paleomagnetic evidence indicates about 40° absolute clockwise rotation of the Cottonwood and Funeral Mountains, probably in Miocene or later time, even though trends of structural and stratigraphic markers there show no deviation from the regional average (CW and FM, Fig. 3a; Snow et al., 1993, unpub. data; Snow and Prave, 1994). To the east, structures trend northwest in the southern Spring Mountains but northeast in the Sheep Range (see Wheeler Pass thrust trace on Fig. 3a). Paleomagnetic evidence from the Sheep Range area suggests little absolute rotation of structures (Gillett and Van Alstine, 1982). Thus, the original trends of structures not only cut discordantly across stratigraphic trends (Fig. 2; Snow, 1992a) but gradually deflect clockwise when traced from north to the south. A similar geometry is recognized in the Sevier thrust belt to the east (Burchfiel and Davis, 1975).

Absolute vertical-axis rotation estimates are unavailable for most ranges. Combining techniques for determining relative rotations from trends of geologic markers (Snow and Prave, 1994), paleomagnetic evidence for absolute rotations (Gillett and Van Alstine, 1982; Kanter and McWilliams, 1982; Nelson and Jones, 1987; Snow et al., 1993, unpub.data), and the simple geometry of thrusts observed within large stable blocks (Snow, 1992a) suggests a pre-extensional configuration as shown in Figure 3b. However, significant rotation is also predicted for the Darwin Plateau (DP on Fig. 3a) and has yet to be independently verified.

The northwest trends of structures in the Grapevine Mountains suggest large anticlockwise rotation relative to correlative structures in the Cottonwoods and Funerals (GM, CM, and FM, Fig 3a; Snow and Wernicke, 1989; Snow and Prave, 1994). Paleomagnetic data suggests a multistage rotation history for the Grapevines, involving Miocene or younger rotation, consistent with predicted relative rotations (Snow et al., 1993, unpub.data). Correlations between Tertiary stratigraphic sequences in these ranges suggest extensional separation after 15.7 Ma (Snow and Lux, 1994, unpub.data). Paleomagnetic data from largely post-tectonic volcanic rocks in the Nevada Test Site region (NTSVF, Fig. 3a) typically indicate little rotation after 14 Ma (Hudson et al., 1994). Thus, a crudely linear array of subparallel structures seems an appropriate early Tertiary geometry for the Death Valley region prior to middle Miocene disruption.

The initial relative positions of the Grapevine and Cottonwood Mountains can be constrained with the footwall ramp of the Last Chance allochthon and the west-vergent White Top backfold (LCTR and anticline, Fig. 3a; Snow, 1992a; Strietz and Stinson, 1974). Simultaneously aligning both structures across the northern Death Valley- Furnace Creek fault zone requires at least 63 km offset. Less offset results in a strain compatibility problem, that is, the thrust ramp must overlap itself in the reconstruction. Regional discordance between structural and stratigraphic trends is maintained while reassembling the rest of the west-vergent fold system if strata at Bare Mountain and in the Grapevines restore north of more cratonal strata in the Striped Hills (BM, GM, and SH, Fig. 3b; Snow, 1992a; Snow and Prave, 1994). Sinistral displacement of the Grapevines relative to the Striped Hills may provide a simple explanation for anticlockwise rotation of the Grapevines (Snow and Prave, 1994).

EXTENSIONAL STRAIN FIELD

Wernicke et al. (1988) concluded, based on regional correlations of offset contractile structures, that the Basin and Range Province near Las Vegas has a best-fit apparent crustal stretching factor of 3.5, and a true crustal stretching (thinning) factor of about 2.8 because ~20% of Cenozoic finite strain is absorbed by conjugate strike-slip faults. Recently, Mancktelow and Pavlis (1994, p. 679) concluded that critical reevaluation of this proposed magnitude of crustal thinning is necessary because "the dominance of transcurrent motion seems well established" in the Death Valley region. They do not, however, offer alternative structural correlations or dispute those of Wernicke et al. (1988).

Figure 4 was constructed by placing a 10 x 10 km grid on the palinspastic reconstruction and then transferring each intersection point to the deformed (current) position. The result graphically illustrates variations in finite strain throughout the Death Valley extensional system. Changes in area correspond to true crustal stretching, which is quite heterogeneous. The most dramatic feature is the medial zone of extreme strain, with more than 1000% true crustal stretching apparent over a wide area. Dextral simple shear is well displayed along the northern Death Valley- Furnace Creek fault zone where the grid is strongly deformed without major changes in area, but evidence for a continuous dextral simple shear zone is absent. Although the strain field appears to have a distributed dextral shear component, extension oriented oblique to the grid would produce a similar effect.

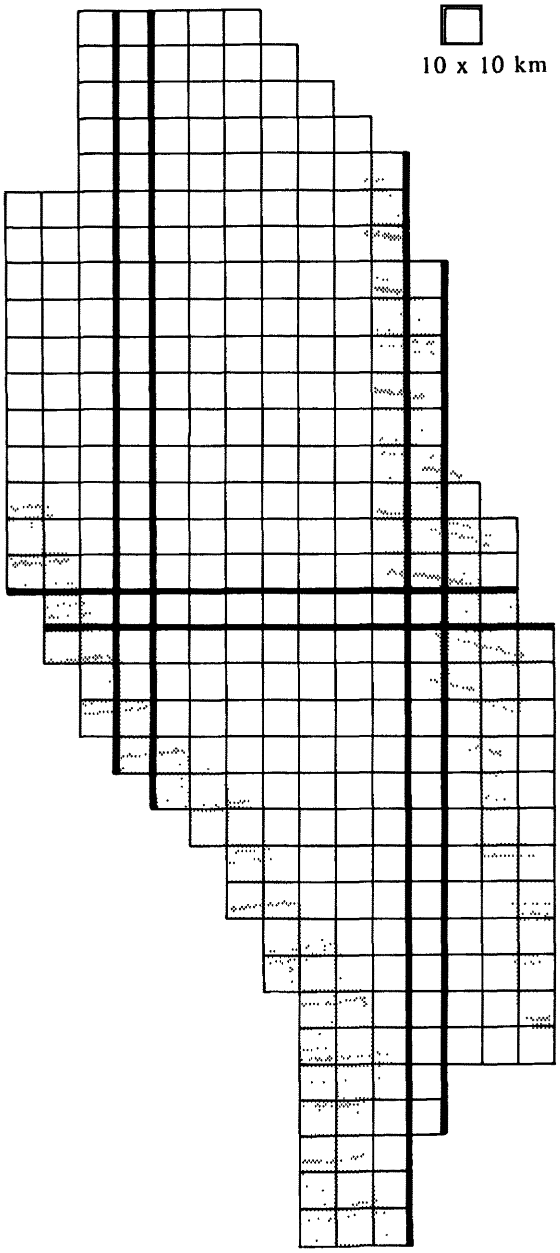
An estimate of the magnitude of regional strain partitioning can be obtained from Figure 4 by comparing the normalized change in area of 2.3 (true crustal stretching) to the maximum elongation of 2.8 (apparent crustal stretching). Within the Death Valley extensional system, which has an abundance of transcurrent faults, 82% of the finite strain is extensional, only 18% is plane stain accommodated by strike-slip (Fig. 4a). The Province as a whole has an average true crustal stretching factor of 3.0 that accounts for 83% of the finite strain (Fig. 1). This is identical, within uncertainty, to previously reported values of 2.8 and 80%, respectively, (Wernicke et al., 1988). An estimated uncertainty of about 20% in maximum elongation was determined by Monte Carlo simulation (Wernicke et al., 1988), but it is difficult to quantify uncertainties on net area changes without multiple reconstructions. Nevertheless, if the structural correlations are correct (Fig. 3), the dominance of extensional strain seems well established in the Death Valley region. Plane strain accommodated by strike-slip faulting, while significant, is a second-order feature in the total finite strain budget.

Partitioning of the map-view plane strain component into simple shear (dextral shear model of Mancktelow and Pavlis, 1994) and pure shear (constrictional strain model of Wernicke et al., 1988) is not established by the reconstruction. Large clockwise rotations and north-south shortening are compatible with either model (Holm et al., 1993). Anticlockwise rotation adjacent to sinistral faults favors the pure shear model (Snow and Prave, 1994). Displacements on left- and right-lateral strike-slip faults are approximately equal, suggesting that the plane strain is mainly pure shear (Wernicke et al., 1988). However, fault displacements are not well enough known to rule out the possibility that an small excess of dextral over sinistral offset is present. Without *a priori* knowledge of extension direction, pure shear constriction with northwestward extension or westward extension followed by dextral simple shear produce equivalent finite strains. Unfortunately, local determinations of true extension direction are complicated by vertical-axis rotations within the extended terrane (e.g. Holm et al., 1993; Snow et al., 1993; Snow and Prave, 1994).

MASS BALANCE

Crustal thickness is about 30-35 km in the Basin and Range (Serpa et al., 1988; Hauser et al., 1987) . With a 30 km present thickness and true crustal stretching factor of 3.0 (Fig. 1), a pre-extensional crustal thickness of 90 km would be required to maintain mass balance if surface extension were representative of the immediately underlying crust. A less extreme crustal stretching factor of 2.3 (Fig. 4a), still requires a remarkable thickness of 69 km. Clearly, if the reconstruction is correct, a significant amount of crustal mass must be moved into the extended terrane from the mantle or surrounding deep crust during Cenozoic extension.

Addition to the crustal mass by magmatic underplating (e.g. Hauser et al., 1987) of juvenile material from the mantle (e.g. Asmerom et al., 1990) is an end-member solution to the mass-balance problem. Eruption of the Nevada Test Site and Death Valley volcanic fields (NTSVF and DVVF, Fig. 3a) within the region of extreme crustal extension (Fig. 4a) may thus contribute at least some of the needed mass. Major volcanic centers, however, which could be attributed to heat supplied by large volumes of underplated magma, are absent from most of the extended terrane.



Redistribution of existing crustal material is the other end-member solution to the mass balance problem. Large-scale flow of lower crustal material provides a mechanism to maintain a fairly constant crustal thickness despite large variations in upper crustal strain (Fig. 5; e.g. Block and Royden, 1990; Wernicke, 1992). Flow of fluid crust from beneath the unextended Colorado Plateau or Sierra Nevada would spread the burden regional crustal mass balance over a larger area and reduce the need for large-volumes of underplated magma. Following sufficient extension, the volume of available fluid crust would be exhausted. Large upper-crustal blocks, such as the Spring or Inyo Mountains (Fig. 3a), might become "beached" on lower crust and never develop into a severely denuded terrane such as Death Valley because the facilitating fluid is not present (Fig. 5; Wernicke, 1992).

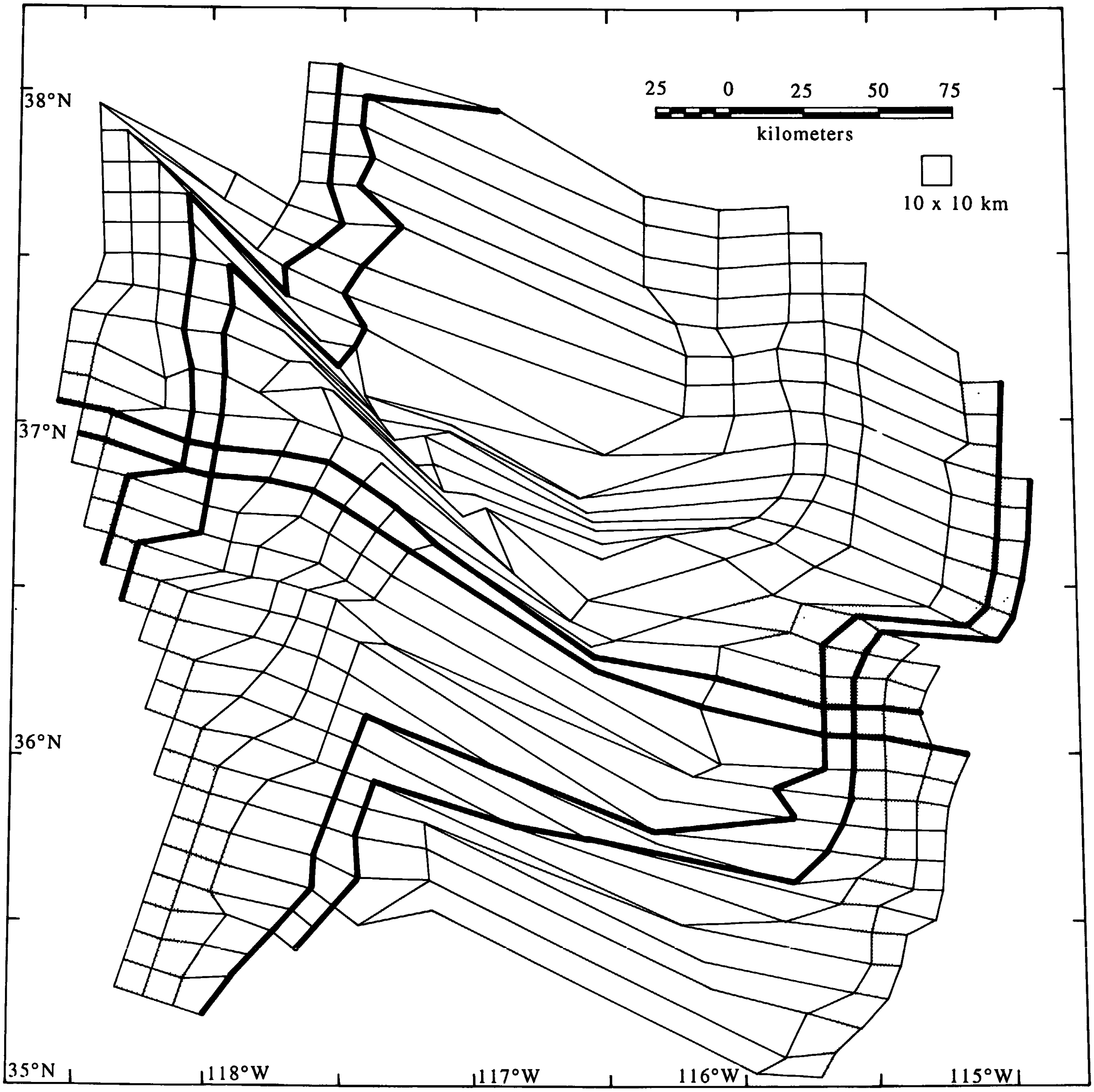


Figure 4. Strain map of the Death Valley extended terrane showing the (A) deformed current state (this page) and (B) undeformed initial state (opposite page). Grid intersection points are held fixed to material points. Shaded areas show Sierra Nevada, Spring Mountains, and Sheep Range (compare with Fig. 2). Net area change from 31,800 km^2 to 72, 822 km^2 indicates an average true crustal stretching factor of 2.3. Maximum elongation is 2.8. Finite strain is 82% extensional, with 18% map-view plane strain accommodated by strike-slip.

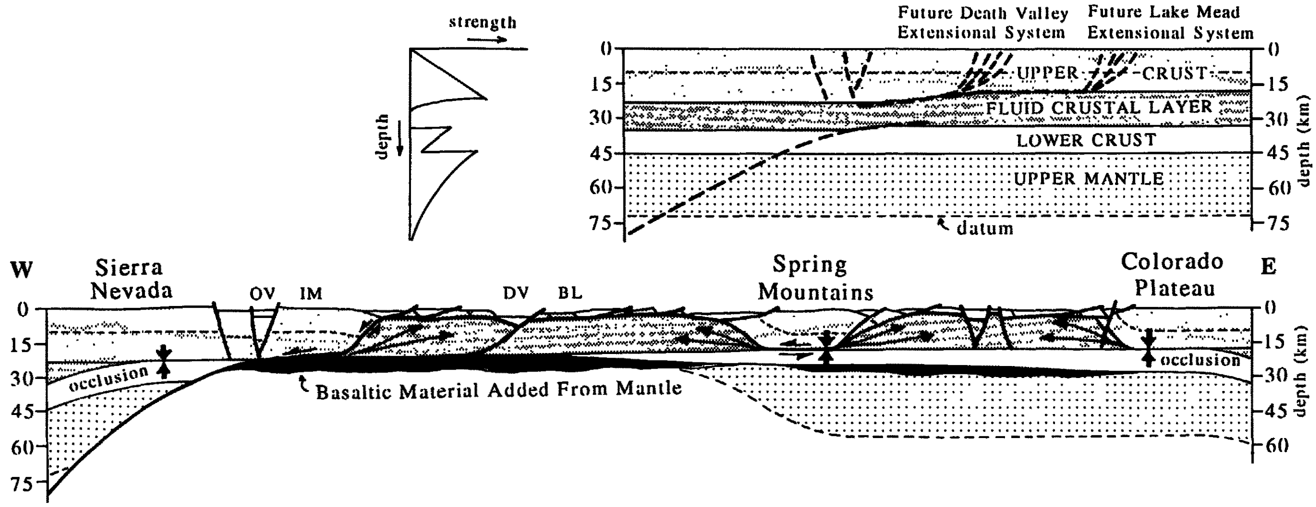


Figure 5. Model for crustal extension with mass balance maintained by large-scale flow of fluid crust (from Wernicke, 1992). See Figure 2a for locations shown on cross section.

CONCLUSION

Palinspastic reconstructions of the Death Valley extended terrane (Fig. 3), which reassemble fragments of the Cordilleran thrust belt and miogeoclinal succession scattered by Cenozoic tectonism (Fig. 2), can be used to measure the partitioning of northwesterly-directed extension into components of true crustal stretching and map-view plane strain (Fig. 4). The magnitude of strain partitioning can be estimated by comparing the increase in map-area and the maximum elongation. For the entire Basin and Range Province at this latitude, a true crustal stretching factor of 2.3 to 3.0 seems likely. Despite the abundance of transcurrent faults, plane strain by strike-slip accounts for less than 20% of the total finite strain budget, in close agreement with previous work (Wernicke et al., 1988).

Crustal mass balance considerations indicate movement of enormous volumes of hot, deep-crustal rocks to shallower crustal levels in extended areas (Fig. 5). Regions of extreme crustal stretching thus should have higher than average geothermal gradients and heat flow. Crustal strain maps (Fig. 4) coupled with accurate geologic cross-sections showing where the veneer of tilted upper crustal blocks is thin (e.g. BL on Fig. 5), may be useful guides for geothermal exploration in areas showing little direct evidence of geothermal potential.

The Saline Range, Coso Range, and Darwin Plateau volcanic fields (SR, CR, DP, Fig. 3a) appear not to be located in regions of extreme crustal stretching (Fig. 4a). Ascent of basaltic magma to the surface through deeply penetrating fractures in the crust would be facilitated by the steep normal faults characteristic of these areas and thus may be related to exhaustion of the fluid crustal layer during evolution of the extended terrane (Wernicke, 1992). Elevated geothermal gradients near the base of the upper crust (Fig. 5) may be exploration targets if the plumbing system of deeply penetrating fractures can be characterized and exploited.

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