Kinematics and timing of Tertiary extension in the western Lake Mead region, Nevada

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ABSTRACT

Explanation of the origin of the complex array of structures in some extensional terranes (including folds and normal, strike-slip, and reverse faults) includes many models that implicitly assume kinematic compatibility between and contemporaneous operation of these structures. We present new stratigraphic and age data from the highly extended western Lake Mead region, Nevada, together with an analysis of fault kinematics (technique of Marrett and Allmendinger, 1990) to test the assumptions of kinematic compatibility and contemporaneity of structures in an area of excellent exposure and superb stratigraphic control. Our analysis indicates an overlapping but clearly distinct chronology of deformation. Early regional extension (>18?-13.5 Ma) is marked by development of a basin into which the middle Miocene lower Horse Spring Formation was deposited. In the western Lake Mead region, this basin was disrupted by more areally restricted, post-13 Ma normal and kinematically coupled right-slip faulting along the Las Vegas Valley shear zone. Kinematic analysis of faults indicates an average regional extension direction of nearly due west for the middle and late Miocene.

Extension and right-slip faulting was followed by development of dominantly south-vergent contractional structures including tight, east-plunging folds and east-striking reverse faults. These structures deform the post-8.5 Ma Muddy Creek Formation; the Muddy Creek Formation is not cut by the Las Vegas Valley shear zone. Older faults, including the eastern Las Vegas Valley shear zone, reactivated as south-vergent reverse faults. Northeast-striking left-slip faults cut folds and reverse faults. These observations show that north-south shortening and left-slip faulting postdate the major phase of extension and right-slip faulting in the western Lake Mead area.

Dynamic models that invoke either a single stress field or rotating stress fields to explain development of structures in the western Lake Mead area are inconsistent with the kinematic and age data. Similarly, kinematic models that view all structures in the context of a single strain field are precluded by systematic cross-cutting relationships that demonstrate at least partial diachroneity of deformational styles. Large-magnitude extension south of the Las Vegas Valley and Lake Mead fault zones appears to have been followed by north-south contraction that was highly localized near the region of greatest extension. We suggest that lateral pressure gradients arising from differential crustal thinning at the northern end of the Colorado River extensional corridor may have provided the driving mechanism for localized contractional deformation.

INTRODUCTION

Considerable controversy exists regarding the origin and kinematic significance of the wide array of structures other than normal faults in extensional tectonic regimes. These structures include strike-slip faults, reverse faults, and folds. For example, strike-slip faults in extensional settings have been considered (1) transfer faults that link areas undergoing differential extension (Anderson, 1971, 1973; Davis and Burchfiel, 1973; Weber and Smith, 1987; Burchfiel and others, 1989), (2) first-order, deep-seated crustal structures that operate independently of extension (Ekren and others, 1976; Ron and others, 1986), or (3) pre-existing barrier faults that may compartmentalize later deformation (Bartley and others, 1992). Contractional structures such as folds and reverse faults may form because of listric, normal-fault geometry (Hamblin, 1965; Dula, 1991; Xiao and Suppe, 1992), localized hanging-wall contractile strains, (Brumbaugh, 1984), irregularities in footwall geometry (McClay and Ellis, 1987; Ellis and McClay, 1988), regional constrictional strains (Fletcher and Bartley, 1991; Anderson and Barnhardt, 1993), or far-field compressive stresses unrelated to the extensional process (Cakir and Aydin, 1990). Models proposed to explain the origin of diverse structural assemblages in structurally complex extensional terranes such as the Lake Mead region, southern Nevada, have assumed implicitly that all structures are kinematically compatible and developed and operated contemporaneously. These assumptions have not been tested rigorously.

Our purpose in this paper is threefold. First, using the Marrett and Allmendinger (1990) technique of fault-slip data analysis, we evaluate the kinematic compatibility of structures in the western Lake Mead area (Fig. 1), a region that contains both extensional and contractional structures. We evaluate results of this analysis in the context of new geochronological and field data. Second, we present an assessment of the Miocene extension direction in the western Lake Mead region. Previous studies variably report the extension direction as southwest (Anderson, 1973; Bohannon, 1979; Weber and Smith, 1987), approximately west (Wernicke and others, 1988; Rowland and others, 1990; Fryxell and Duebendorfer, 1990; Duebendorfer and others, 1990), west-northwest (Longwell, 1974), or invoke changing extension directions with time (Angelier and others, 1985; Choukroune and Smith, 1985). Third, we evaluate existing models for Miocene extensional tectonism in the western Lake Mead region. Existing models for Tertiary deformation in this area focus on one or two structures (Anderson, 1973; Bohannon, 1979) or provide an incomplete kinematic explanation for the varied structural elements present (Ron and others, 1986; Cakir and Aydin, 1990; Campagna and Aydin, 1991). These studies also were hampered by lack of sufficient age data to resolve adequately the timing of various structures. We conclude by

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proposing an alternative tectonic model that honors all available kinematic and timing data.

Our results show that the Marrett and Allmendinger (1990) technique, combined with development of a field-based structural chronology, is a powerful tool to establish kinematic compatibility or incompatibility between faults sets in complex areas and may be more meaningful in characterizing the overall strain pattern in complexly deformed regions than the commonly applied paleostress inversion techniques (for example, Angelier and others, 1985; see also Pollard and others, 1993).

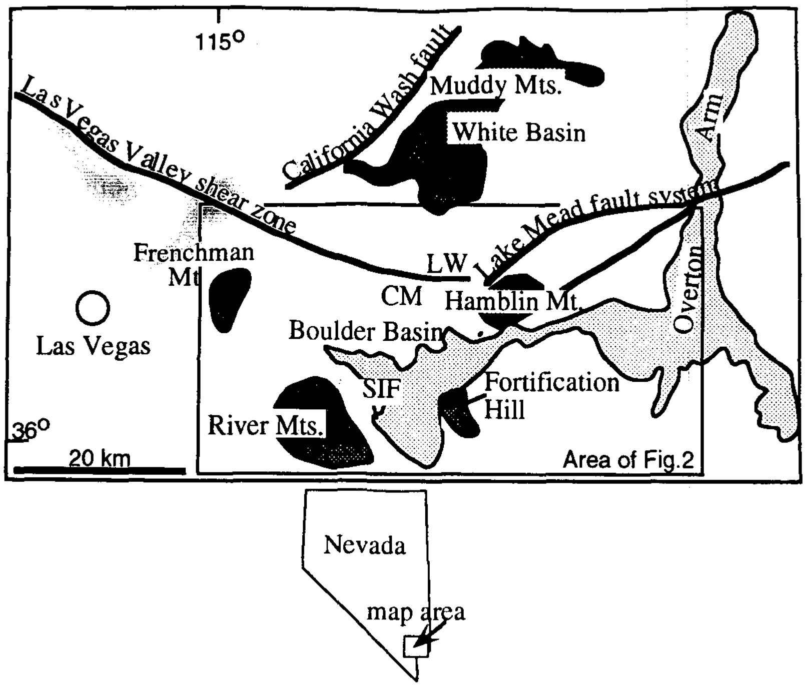


Figure 1. Map of the Lake Mead area showing principal geographic features and geologic structures. CM = Callville Mesa, LW = Lovell Wash, SIF = Saddle Island fault. Light stipple represents Lake Mead.

TECTONIC SETTING

A marked change in the style of Basin and Range extension occurs in the Lake Mead region. South of the Lake Mead area, the "core complexes" of the Colorado River extensional corridor expose ductilely deformed rocks in the lower plates of regional detachment faults (Davis and others, 1980, 1982, 1986; Howard and John, 1987; many others) and major transverse structures appear to be rare. For 250 km to the north, exposures of ductilely deformed lower-plate rocks are rare and transverse structures are common (Duebendorfer and Black, 1992). The Lake Mead area contains both core complex-type detachment systems as well as two of the largest strike-slip (transverse) faults in the Basin and Range province. These faults mark the northern terminus of the northern Colorado River extensional corridor (Faulds and others, 1990, 1992).

The three principal Tertiary structures in the Lake Mead region are the Lake Mead fault system, the Las Vegas Valley shear zone, and the Saddle Island fault (Figs. 1 and 2). The Lake Mead fault system is a zone of northeast-striking, left-slip faults that collectively accounted for between 20 and 65 km of slip between 17 and 10 Ma (Anderson, 1973; Bohannon, 1979, 1984). The northwest-striking Las Vegas Valley shear zone has well-documented right-slip displacement of 48 ± 7 km (Longwell, 1960, 1974; Burchfiel, 1965; Fleck, 1970; Wernicke and others, 1988). The Las Vegas Valley shear zone appears to be younger than 15 Ma (Fleck, 1970), and Deibert (1989) and Duebendorfer et al. (1991) suggested that significant movement postdated 13 Ma. These interpretations are supported by paleomagnetic data from sedimentary units as young as 13.5 Ma, which indicate clockwise rotations to 70° (Sonder and others, 1989; Jones and others, 1991). The Saddle Island fault is a low-angle fault that contains the characteristic elements of classic metamorphic core complexes (Smith, 1982; Choukroune and Smith, 1985; Sewall, 1988; Duebendorfer and others, 1990). Reconstruction of structurally disrupted mid-Miocene volcanic-plutonic complexes suggests 20 km of post-13.4 Ma westward translation of upper-plate rocks along the detachment (Weber and Smith, 1987).

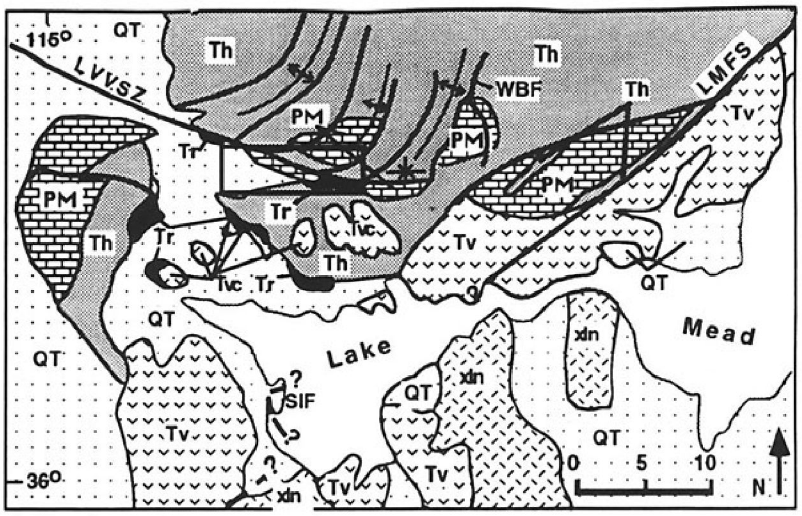
STRATIGRAPHIC FRAMEWORK

Tertiary Stratigraphy

The western Lake Mead region contains Tertiary sedimentary and volcanic rocks that lie with minor angular discordance on Triassic to Cretaceous rocks (Figs. 2 and 3). Miocene rocks of the Lake Mead region have been divided into three unconformity-bounded sequences (Bohannon, 1984). These are the Horse Spring Formation, the informally named red sandstone unit and associated volcanic rocks of Callville Mesa, and the Muddy Creek Formation.

Bohannon (1984) divided the Horse Spring Formation into four members (Fig. 3). The Rainbow Gardens and Thumb Members (24–13.5 Ma; Bohannon, 1984; Beard and Ward, 1993) occur both north and south of the major strike-slip faults in the area. The Rainbow Gardens Member consists of a basal conglomerate that fines upward into evaporite and lacustrine limestone. The unit predates or records the earliest phase of extension in the region (Anderson, 1973; Bohannon, 1979). The overlying Thumb Member contains terrigenous clastic deposits, evaporites, air-fall tuff, and distinctive megabreccia deposits. The upper two units of the Horse Spring Formation, the Bitter Ridge Limestone and Lovell Wash Members (13.5–12.0 Ma; Bohannon, 1984; Duebendorfer and others, 1991) consist of lacustrine limestone and interbedded tuffaceous siltstone and sandstone. These units show marked differences in lithology and thickness across the Las Vegas Valley shear zone, which probably record the onset of major extensional deformation in the western Lake Mead area.

The informally named red sandstone unit (11.9 ± 1.2 to 8.5 ± 0.2 Ma; Bohannon, 1984; Feuerbach and others, 1991), is composed of conglomerate, sandstone, siltstone, air fall tuff, and basaltic andesite flows and flow breccias of the Callville Mesa volcanic field (Feuerbach and others, 1991, 1993). Bohannon (1984) recognized the unit in White basin and east of Frenchman Mountain (Figs. 1 and 2); Duebendorfer and Wallin (1991) docu-



Explanation

QT	Quaternary and Tertiary (Muddy Creek Fm.) deposits (<8.5 Ma)
Tr	Red sandstone unit of Bohannon (1984)(11.9-8.5 Ma)
Tvc	Volcanic rocks of Callville Mesa (10.5-8.5 Ma)
Tv	Older Tertiary volcanic rocks (middle Miocene)
Th	Horse Spring Formation (>24-12.0 Ma)
xln	Tertiary and Precambrian crystalline rocks
PM	Paleozoic and Mesozoic rocks

Figure 2. Highly generalized geologic map of the study area. LVVSZ = Las Vegas Valley shear zone, LMFS = Lake Mead fault system, SIF = Saddle Island fault, WBF = West Bowl of Fire fault. Heavy rectangle shows location of map, Figure 14.

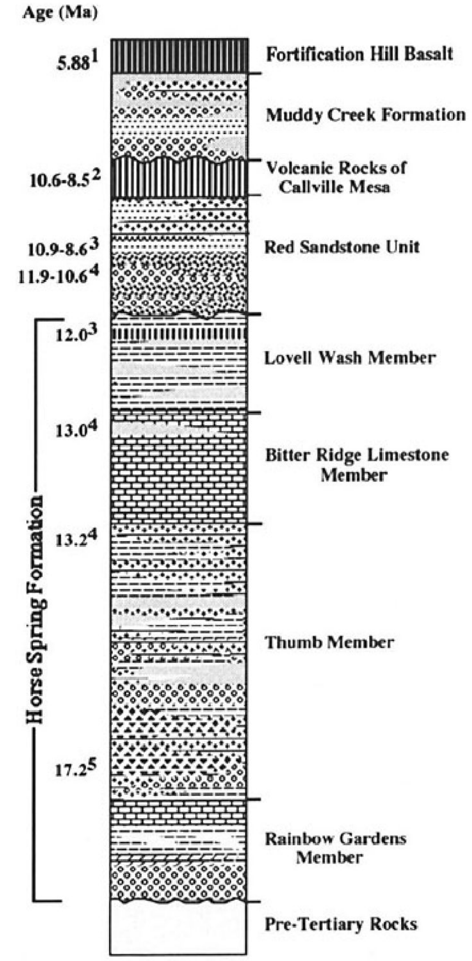


Figure 3. Generalized stratigraphic column for the western Lake Mead area (modified after Bohannon, 1984). Dates in Ma. 1 = K/Ar plagioclase (Damon and others, 1978); 2 = K/Ar plagioclase (Feuerbach and others, 1991); 3 = K/Ar plagioclase (Duebendorfer and others, 1991); 4 = fission track on air fall tuffs (Bohannon, 1984); 5 = K/Ar whole rock (Anderson and others, 1972).

mented widespread exposures of the unit in Boulder basin.

The late Miocene Muddy Creek Formation (8.5–5.8 Ma; Damon and others, 1978; Feuerbach and others, 1991) lies unconformably upon the red sandstone unit and consists of boulder-cobble conglomerate, sandstone, siltstone, and gypsum. The unit probably represents continued infilling of extensional basins formed in the middle Miocene.

Regional Stratigraphic Variations

The study area may be divided into three blocks, each of which exhibits a depositional and structural history distinct from its neighbors. These are (1) the Frenchman Mountain block, (2) the Muddy Mountains block, and (3) the Boulder Basin block (Fig. 4, inset). The pre-13.5 Ma stratigraphy is similar on all blocks; their stratigraphic records and stratal tilt relations diverge markedly at about 13.0 Ma (Fig. 4). The appearance of these differences in stratigraphy and stratal tilting signals the onset of active extension in the western Lake Mead region.

Frenchman Mountain Block. The Frenchman Mountain block is a structurally intact homocline that dips 45°–55°E. The block contains the most complete Tertiary section in the study area (Fig. 4); however, the Bitter Ridge Limestone pinches out to the north and contains more clastic detritus than its stratigraphic counterpart on the Muddy Mountain block. The northern end of the block, therefore, may have been topographically higher than the southern end from 13 to 13.5 Ma. The Bitter Ridge Limestone may actually represent two separate basins, one in the present Muddy Mountains and one at the south end of Frenchman Mountain. Major stratal tilting occurred between 11.9 and 8.5 Ma (Figs. 4 and 5).

Muddy Mountains Block. The Muddy Mountains block contains a complete section of the Horse Spring Formation, including thick sections of Bitter Ridge Limestone (375 m) and Lovell Wash Members (250 m), but few exposures of younger rocks. A boulder conglomerate interfingers with lacustrine deposits of the Bitter Ridge Limestone and Lovell Wash Members directly north of the Las Vegas Valley shear zone (Bohannon, 1984). These relations suggest that the Las Vegas Valley shear zone was active during deposition of the younger members of the Horse Spring Formation and may have marked the southern margin of the basin, *at that locality*, into which the units were deposited.

Boulder Basin Block. Within the Boulder basin block, the Lovell Wash Member (200–250 m) conformably overlies the Thumb Member and contains an 80- to 100-m-thick basaltic-andesite sequence dated at 12.0 ±

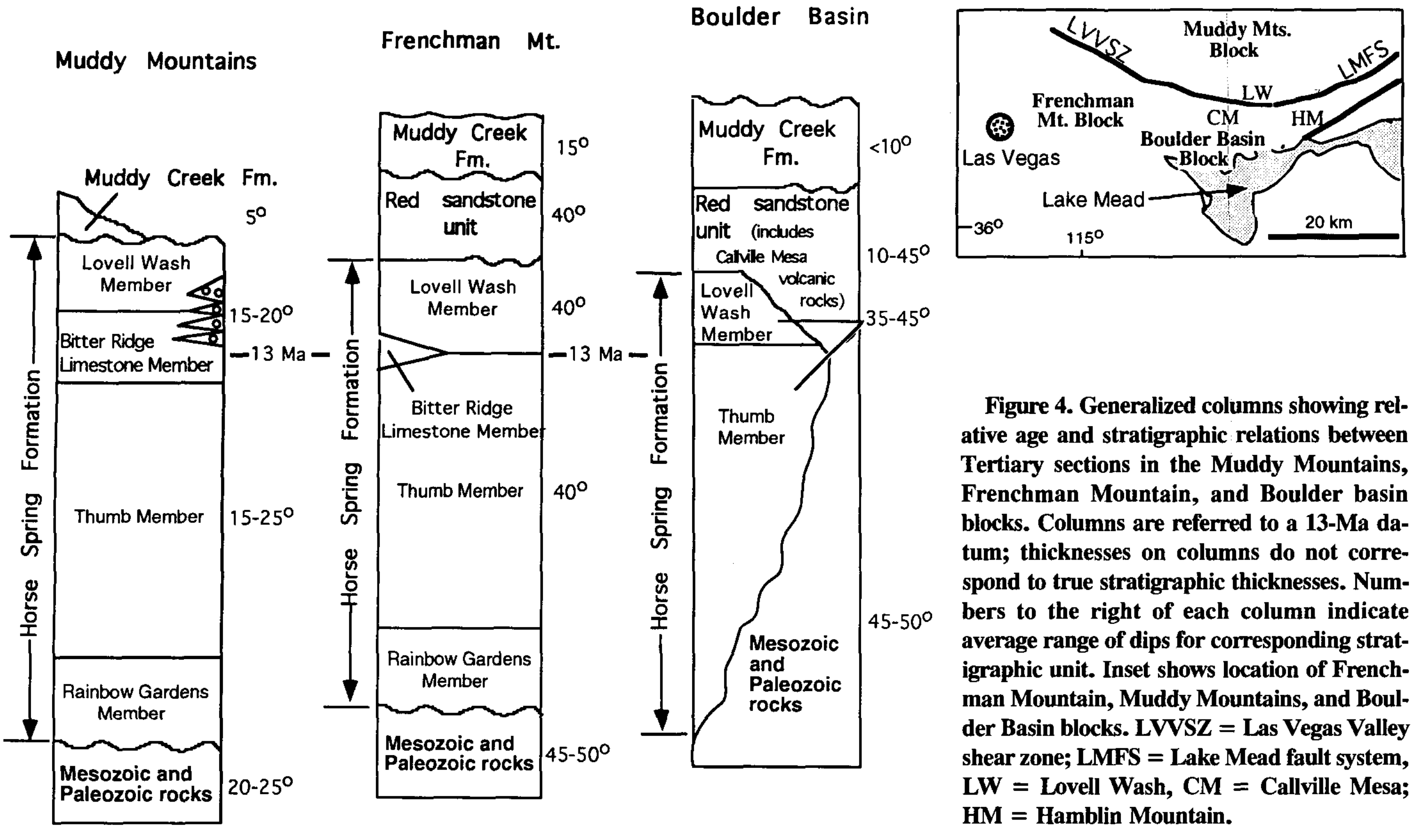


Figure 4. Generalized columns showing relative age and stratigraphic relations between Tertiary sections in the Muddy Mountains, Frenchman Mountain, and Boulder basin blocks. Columns are referred to a 13-Ma datum; thicknesses on columns do not correspond to true stratigraphic thicknesses. Numbers to the right of each column indicate average range of dips for corresponding stratigraphic unit. Inset shows location of Frenchman Mountain, Muddy Mountains, and Boulder Basin blocks. LVVSZ = Las Vegas Valley shear zone; LMFS = Lake Mead fault system, LW = Lovell Wash, CM = Callville Mesa; HM = Hamblin Mountain.

0.3 Ma (K/Ar plagioclase; Duebendorfer and others, 1991). The block contains the most widespread and complete exposures of post-Horse Spring rocks in the Lake Mead area (Fig. 4), suggesting that Boulder basin has been a structural and topographic low since deposition of the red sandstone unit (Duebendorfer and Wallin, 1991). In the western and central parts of the Boulder basin block, the steeply dipping red sandstone unit lies above the Lovell Wash Member without angular discordance. In the eastern part of the basin, the stratigraphically high parts of the red sandstone unit are only slightly tilted and rest with significant (40°) angular discordance on the Thumb Member. The red sandstone unit is cut by many faults that do not cut the overlying Muddy Creek Formation. These observations indicate that the Boulder basin was characterized by basin development and disruption, volcanism, normal faulting, and stratal tilting between 12.0 and 8.5 Ma.

Discussion

The pre-Tertiary "basement" on all blocks was tilted <10° at the time of deposition of the basal Tertiary units (Fig. 4). Facies distributions within the lower units of the Horse Spring Formation do not appear to be governed by major strike-slip faults, suggesting that the principal period of movement on these structures occurred after Thumb time (Bohannon, 1984). The appearance of megabreccia deposits within the 17- to 13.5-Ma Thumb Member affords the earliest record of topographic relief associated with the onset of shallow-crustal extension in the *eastern* Lake Mead region (Longwell, 1974; Bohannon, 1983, 1984; Parolini, 1986; Rowland and others, 1990).

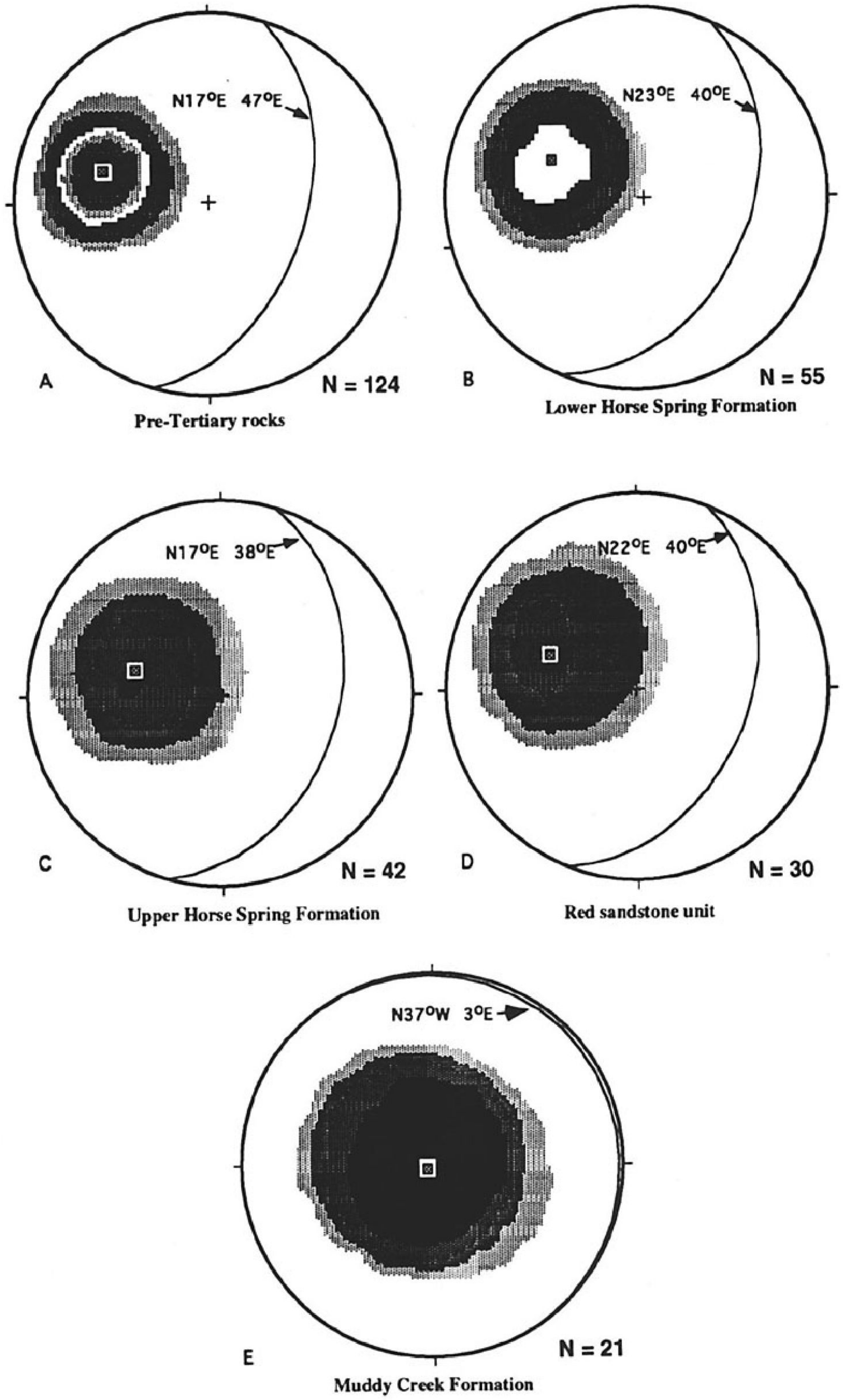
Marked differences in the stratigraphic record at 13.5–13.0 Ma signal the onset of active extension in the *western* Lake Mead region. Specifically, the abrupt southward facies transition within the Bitter Ridge Limestone and Lovell Wash Members from lacustrine deposits to coarse clastic detritus directly north of the Las Vegas Valley shear zone indicates that the Muddy Mountains block was topographically and structurally low relative to a southern block between 13.5 and 13.0 Ma. There is currently no obvious source for the lower Paleozoic clasts within the conglomerate facies of the Bitter Ridge Limestone; however, restoring 20 km of movement along the Saddle Island fault places Frenchman Mountain in a position to shed these clasts into the Bitter Ridge basin.

Presence of the red sandstone unit south of the Las Vegas Valley shear zone records development of the extensional Boulder basin produced by movement along the Saddle Island low-angle fault (Duebendorfer and Wallin, 1991). The Las Vegas Valley shear zone forms the northern margin of the Boulder basin and may have functioned as an extensional transfer fault. The red sandstone unit contains Bitter Ridge Limestone clasts derived from the north, indicating that a structural and topographic inversion had occurred across the shear zone by ~11.9 Ma.

STRUCTURE

Kinematic Analysis of Fault-Slip Data

Introduction. We employ the graphical method for kinematic analysis of fault-slip data developed by Marrett and Allmendinger (1990) to analyze faults exposed in a 250-km^2 area north of Lake Mead, east of Frenchman Mountain, and west of Hamblin Mountain (Fig. 1). The goal of this analysis is to (1) determine the kinematics of individual fault sets to infer principal shortening and extension axes for each set, (2) assess the degree of kinematic compatibility or incompatibility of different sets of faults to determine which sets may have functioned in concert to accommo-



Pre-Tertiary rocks

Lower Horse Spring Formation

Upper Horse Spring Formation

Red sandstone unit

Muddy Creek Formation

Figure 5. Lower-hemisphere, equal-area projection of poles to bedding of rocks of the Frenchman Mountain block. (A) Mesozoic and Paleozoic rocks. (B) Lower Horse Spring Formation. (C) Upper Horse Spring Formation. (D) Red sandstone unit. (E) Muddy Creek Formation. Data from Longwell (unpublished mapping) and Duebendorfer (unpublished mapping). The maximum pre-Tertiary tilt of the Paleozoic and Mesozoic section on Frenchman Mountain is 9°E. There is no significant discordance between the red sandstone unit and the Horse Spring Formation.

date regional strains, and (3) infer the collective kinematics of faults both north and south of the Las Vegas Valley shear zone to determine whether this regional geologic boundary also separates kinematically distinct domains of deformation. Sense of slip on individual faults was determined by a combination of fault striae and stratigraphic separation, brittle kinematic indicators (Petit, 1987) where available, and drag features.

The Marrett and Allmendinger (1990) method utilizes a seismological approach to three-dimensional incremental strain analysis. For each fault datum (fault surface and striae orientation combined with sense of slip), a principal incremental shortening and extension axis is determined graphically. One reading is taken from each fault. Shortening and extension axes are then contoured for a set of fault data to determine the regional kinematic axes represented by that fault set. We emphasize that this technique is fundamentally different than widely used stress-inversion techniques (for example, Angelier and others, 1985) in that it does not seek to determine the orientation of principal paleostress directions, but rather reflects the kinematics of motion on a fault. This approach partially circumvents the problem of reactivation or reorientation of faults in that a pre-existing fault may be reactivated under a different stress regime even though its orientation is not optimal for development of fractures predicted by the Coulomb fracture criterion. In the dynamic approach, such a fault could yield a spurious paleostress direction; whereas in the kinematic approach, the sense of slip would reflect a component of the overall kinematic framework independent of the regional stress field at the time of faulting.

Assumptions. Kinematic analysis of faults involves several assumptions (Marrett and Allmendinger, 1990). The most important assumptions that must be evaluated are that (1) fault kinematics are scale-independent or invariant, (2) early-formed faults are not reoriented during later deformation, and (3) reactivation of early faults has not occurred under a later stress regime.

The validity of the first assumption is impossible to evaluate in the Lake Mead region. Absolute magnitude of displacement on most faults is an elusive quantity, and estimates of finite displacement based on fault width and gouge thickness (for example, Cox and Scholz, 1988; Hull, 1988) or fault length (Elliott, 1976; Walsh and Watterson, 1988) are problematic in the study area because of large differences in mechanical properties of units juxtaposed along faults (for example, Evans,

1990) and because many faults are localized within highly incompetent evaporite units. We justify this assumption by noting the many studies that demonstrate the scale-invariant kinematics of fault systems (for example, King, 1983; Turcotte, 1986; Barton and others, 1988). The second assumption is clearly invalid for part of the study area. Adjacent to the Las Vegas Valley shear zone, structures are rotated conspicuously clockwise. The paleomagnetic results of Jones and others (1991) show, however, that post-14-Ma vertical axis rotations decrease sharply away from the fault. In view of these data, we argue that the assumption is valid for the large populations of faults away from the shear zone and note that our analysis shows that the kinematics of rotated faults near the Las Vegas Valley shear zone are compatible with those away from the fault. The third assumption (anisotropy reactivation) cannot be tested directly by examination of fault kinematics; however, we document crosscutting relations that clearly differentiate between fault sets formed at different times. Hence, although some reactivated faults may record only the final phase of motion, the large sample size ensures that a sufficient number of non-reactivated faults are represented in the data set.

These assumptions are justified in a first-order analysis of faults in the western Lake Mead region, because kinematic data are evaluated in the context of independent geologic information such as fault timing, structural analysis of folds, and the Tertiary stratigraphic record. We present the fault data and kinematic analyses in terms of 45° orientation domains both north and south of the Las Vegas Valley shear zone. We do not imply that all faults of the same orientation represent the same kinematic picture; nor do we exclude the possibility of kinematic coupling of variably oriented faults. The technique of Marrett and Allmendinger (1990), coupled with age data on faults of known movement sense (discussed below), permits an objective analysis of the kinematic compatibility of faults.

North of Las Vegas Valley Shear Zone. *North-Northeast Striking Faults.* Faults that strike north-northeast (0–45°) are the most abundant within the study area. North-northeast-striking faults are subvertical to moderately east- and west-dipping. Steeply dipping faults have subhorizontal striae and left-slip kinematics, and moderately dipping faults have a normal-slip displacement sense (Fig. 6). West-dipping normal faults dip more gently and are slightly more abundant than east-dipping faults. This observation is consistent with the general eastward tilt of strata in the area. A notable example of this fault set is the West Bowl of Fire fault (Fig. 2), a 45° west-dipping normal fault that places Bitter Ridge Limestone over Jurassic Aztec sandstone, resulting in deletion of at least 1200 m of section.

Both the left-slip and normal faults yield a statistical extension axis (Fig. 6) of 265°, thus raising the possibility of kinematic compatibility of the two fault subsets. Kinematic compatibility of faults with different orientations requires that faults either slip parallel to their line of intersection or have a conjugate relation. This is clearly not the case with the north-northeast-striking faults (Fig. 6). The bimodal distribution of fault striae suggests that the north-northeast-striking faults constitute two kinematically independent sets. Furthermore, calculated shortening (Fig. 6) axes also have a bimodal distribution that indicates both north-northwest–south-southeast contraction (left-slip faults) and shortening along a subvertical axis (normal faults).

These data may be interpreted as reflecting either two completely independent phases of faulting or a constrictional strain field in which nearly east-west extension is accompanied by shortening in both vertically and horizontally orthogonal directions. Crosscutting relations show that the more east-striking left-slip faults are among the youngest structures in the region. We therefore favor a sequence of deformation in which early normal faults are followed by later left-slip faults. This interpretation does not rule out the possibility of a component of true constrictional strain during normal faulting.

East-Northeast-Striking Faults. East-northeast-striking faults (45°–90°) are dominantly subvertical left-slip faults (Fig. 6). Shortening axes are oriented slightly east of north; the overall extension direction is 290°, which is broadly compatible with the north-northeast-striking left-slip faults described above (Fig. 6). The kinematics of the east-northeast-striking faults are so similar to the north-northeast-striking left-slip faults that they probably represent a single set. The range in orientations of faults of this set, from north-northeast to east-northeast, might be explained by clockwise rotation of early, north-northeast-striking faults to more easterly attitudes because of vertical axis rotations associated with right slip along the Las Vegas Valley shear zone. This inference is supported by the observations that east-northeast-striking faults are more abundant directly adjacent to the Las Vegas Valley shear zone, whereas north-northeast-striking faults are more abundant at greater distances from the shear zone (Bohannon, 1983; Duebendorfer, unpublished mapping).

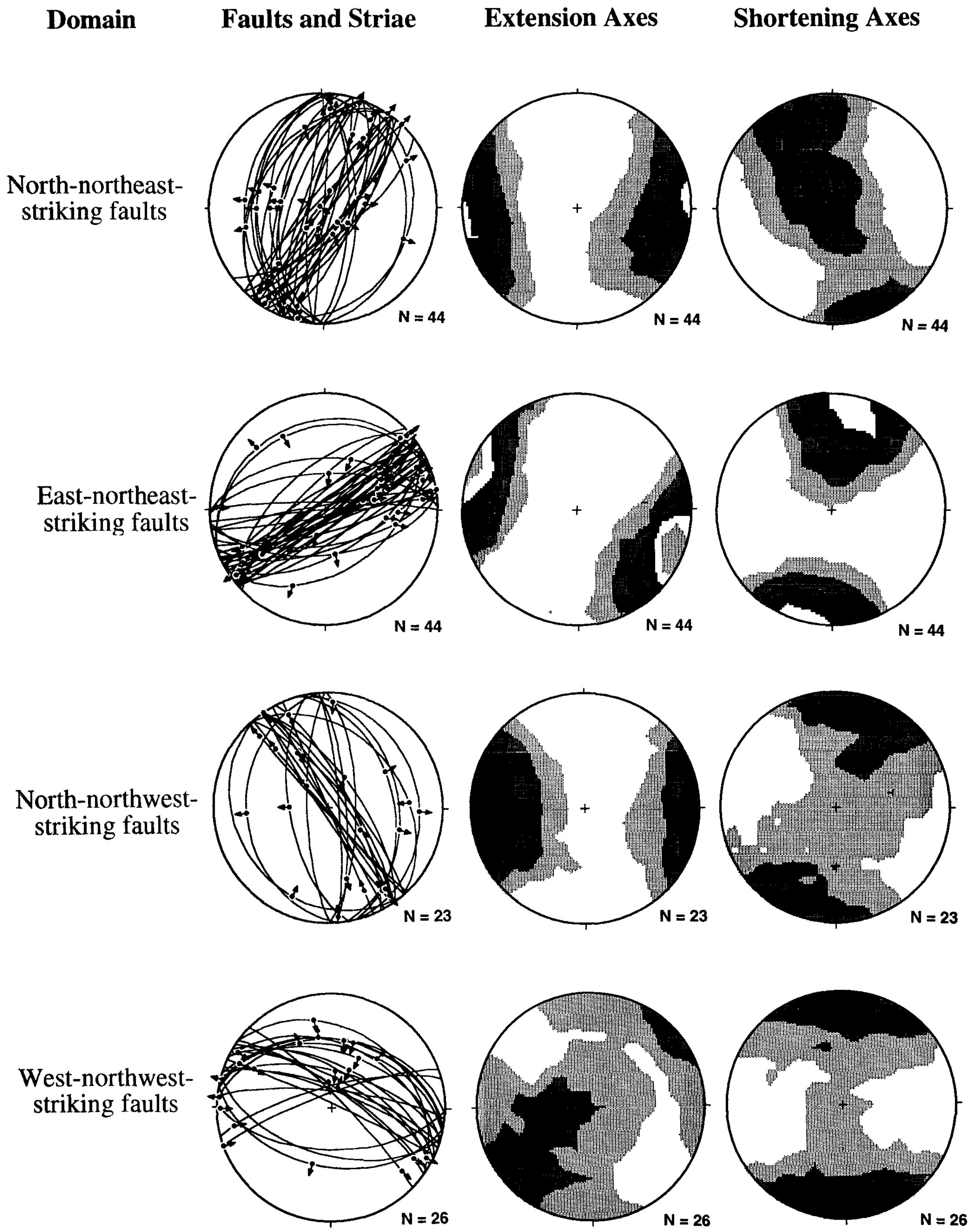
Figure 6. Lower-hemisphere, equal-area projections showing orientation and kinematic data for faults north of the Las Vegas Valley shear zone. Fault data (column 1) and kinematic analyses (columns 2 and 3) are presented in terms of 45°-orientation domains. Column 1: plots of faults (great circles), striae (dots), and slip direction (arrow shows movement of hanging wall block). N = number of measurements. Column 2: contoured diagram of extension axes. Column 3: contoured diagram of shortening axes. Contour interval = 2σ (after Kamb, 1959).

North-Northwest-Striking Faults. North-northwest-striking faults (315°–359°) north of the Las Vegas Valley shear zone can be divided into two subsets with different kinematics (Fig. 6). Most subvertical faults are right-slip faults. Moderately to gently northeast- and southwest-dipping faults have both normal and reverse slip. Although data are few, the bimodality in fault kinematics is real and may reflect a situation similar to that of the north-northeast-striking faults; that is, either two independent fault sets or a component of constrictional strain with right-slip faults accommodating subhorizontal, north-south shortening.

West-Northwest-Striking Faults. Steeply dipping west-northwest-striking faults (270°–314°) are dominantly right-slip, whereas the gently dipping faults are principally reverse faults (Fig. 6). Right-slip faults are restricted to a narrow zone directly adjacent to the Las Vegas Valley shear zone, a 30- 100-m-thick zone of east-west- to west-northwest-striking faults that range in dip from subvertical to 50°N. The fault surface is well exposed at only a few localities, and fault striae are rare. Kinematic analysis yields a weak component of subvertical extension, an anomalous subhorizontal northeast-southwest extension direction, and a strong component of subhorizontal, north-south shortening (Fig. 6). The latter is consistent with reverse faulting. We concur with Cakir and Aydin (1990), who present convincing evidence for a period of reverse displacement along the Las Vegas Valley shear zone.

Combined North-Northeast- and North-Northwest-Striking Faults. We combined

Faults north of the Las Vegas Valley shear zone



data from these fault sets to evaluate the possibility that north-northeast- and north-northwest-striking faults could represent a single set of kinematically coordinated, conjugate faults (Fig. 7). The extension direction defined by the combined data set is horizontal and east-west. Two distinct shortening-axes maxima, one north-south and subhorizontal and one nearly vertical, are present. The two maxima are separated by 15°–45° "low-density" zones. This observation argues against true constrictional strain in which shortening should be expressed equally in all directions normal to the finite extension direction. Therefore, although the right- and left-slip faults could represent a kinematically linked conjugate fault set (but see discussion of timing), the normal faults may reflect a separate phase of deformation with kinematics distinct from one or both sets of strike-slip faults. This interpretation is most consistent with timing relations between fault sets as discussed below.

Combined East-Northeast- and West-Northwest-Striking Faults. We combined data from these fault sets to evaluate the possibility that east-northeast- and west-northwest-striking faults could be kinematically related (Fig. 7). A strong maximum of subhorizontal extension axes is oriented at 293° (Fig. 7). Minor submaxima at vertical and north-south horizontal, however, suggest a non-uniform kinematic picture that is inconsistent with a single strain field. This interpretation is supported by the plot of shortening axes (Fig. 7) in which the primary and secondary shortening directions, north-south horizontal and vertical, respectively, coincide with secondary extension-axis maxima. The data suggest that the east-northeast- and west-northwest-striking faults are not kinematically compatible and probably represent different fault sets that reflect different strain regimes. This interpretation is supported by age data presented below.

South of Las Vegas Valley Shear Zone. Fault data are more limited south of the Las Vegas Valley shear zone than north, primarily because of the presence of the largely post-extensional Muddy Creek Formation and younger deposits. We acknowledge the problems inherent in analysis of a limited data set and recognize that our sampling is biased toward structures that post-date the youngest sedimentary units.

North-Northeast-Striking Faults. North-northeast-striking faults south of the Las Vegas Valley shear zone are mostly west-dipping normal faults with minor components of right or left slip (Fig. 8). The kinematic axes define an extension direction of 293° and a diffuse, but generally steep, shortening axis (Fig. 8). There is no obvious component of horizontal north-south shortening in these data.

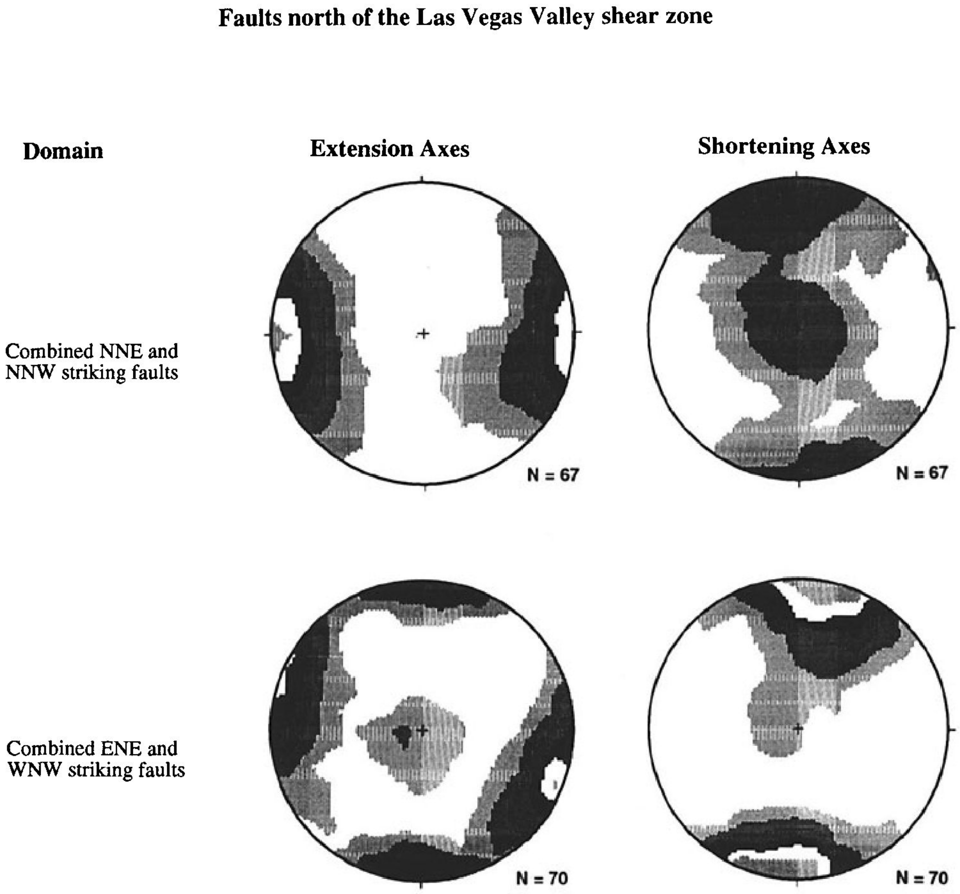


Figure 7. Lower-hemisphere, equal-area projections showing orientation and kinematic data for combined north-northeast– and north-northwest–striking faults (row 1) and for combined east-northeast– and west-northwest–striking faults (row 2) north of the Las Vegas Valley shear zone. Column 1: contoured diagram of extension axes. Column 2: contoured diagram of shortening axes. Contour interval = 2σ (after Kamb, 1959).

East-Northeast-Striking Faults. East-northeast-striking faults vary in dip from northwest to southeast. Most are left-slip faults with a normal component of displacement; however, two faults are clearly reverse (Fig. 8). Given the limited data set, it is difficult to ascertain the significance of inferred kinematic axes. Nevertheless, the kinematic data are consistent with broadly west-northwest extension and subhorizontal, north-south shortening (Fig. 8).

Northwest-Striking Faults. Because of limited data, all faults that plot in the northwest quadrant are combined. The more northerly striking faults are normal faults; the more westerly striking faults are either pure right-slip faults or left-slip faults with a normal component (Fig. 8). Because of diffuse maxima and the limited data set, significance of the kinematic analysis (Fig. 8) is uncertain.

Combined North-Northeast- and North-Northwest-Striking Faults. We combined data from these fault sets to evaluate the possibility that north-northeast- and north-northwest-striking faults could represent a single set of kinematically coordinated, conjugate faults. The composite extension direction defined by the combined set is 288°; the shortening direction is subvertical (Fig. 9). These data suggest that north-northeast- and north-northwest-striking faults south of the Las Vegas Valley shear zone may represent a single set of conjugate normal faults.

Combined East-Northeast- and West-Northwest-Striking Faults. Combined plots of east-northeast- and west-northwest-striking faults (Fig. 9) define a diffuse extension

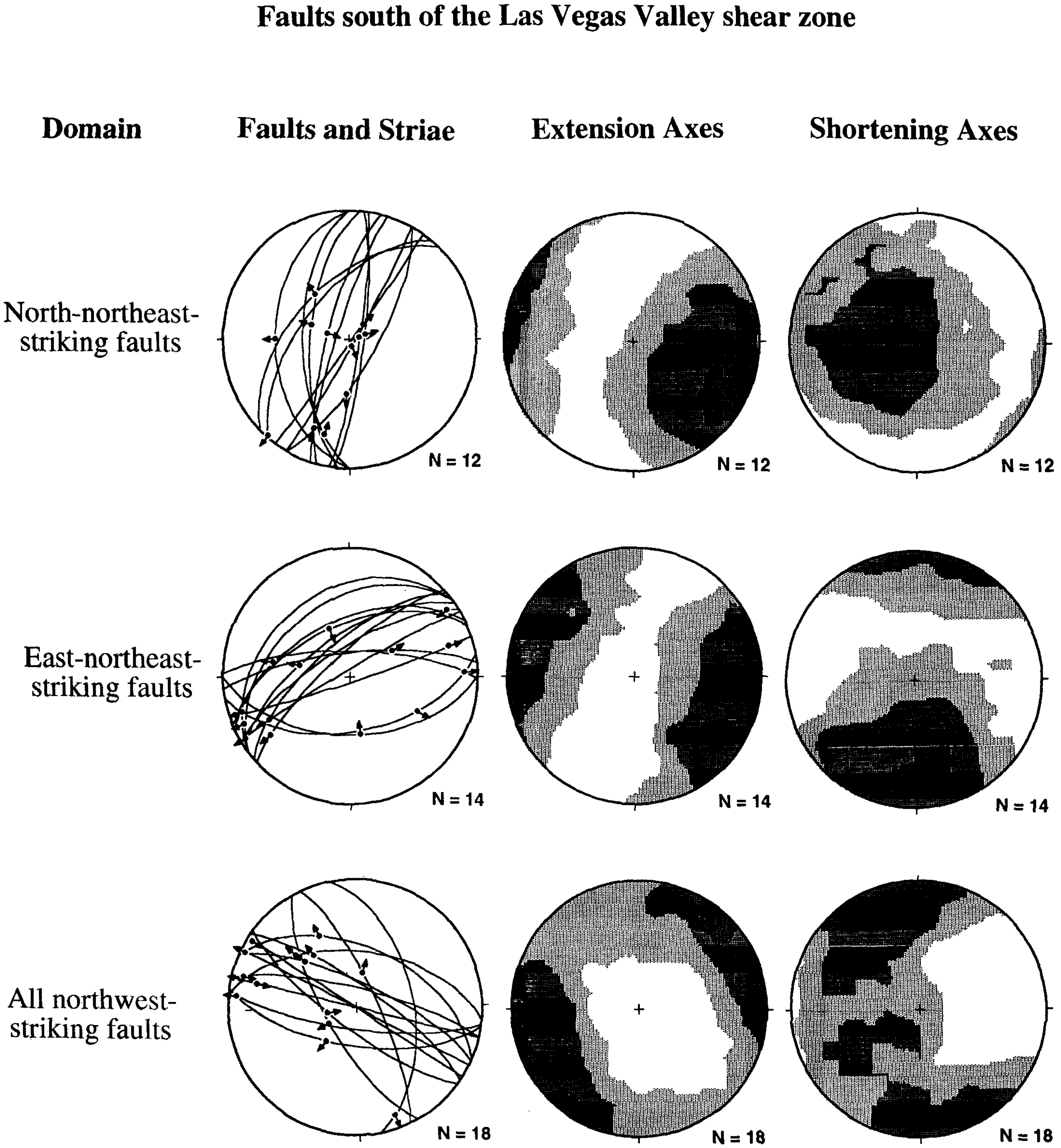


Figure 8. Lower-hemisphere, equal-area projections showing orientation and kinematic data for faults south of the Las Vegas Valley shear zone. Fault data (column 1) and kinematic analyses (columns 2 and 3) are presented in terms of 45°-orientation domains. Column 1: plots of faults (great circles), striae (dots), and slip direction (arrow shows movement of hanging wall block). N = number of measurements. Column 2: contoured diagram of extension axes. Column 3: contoured diagram of shortening axes. Contour interval = 2σ (after Kamb, 1959).

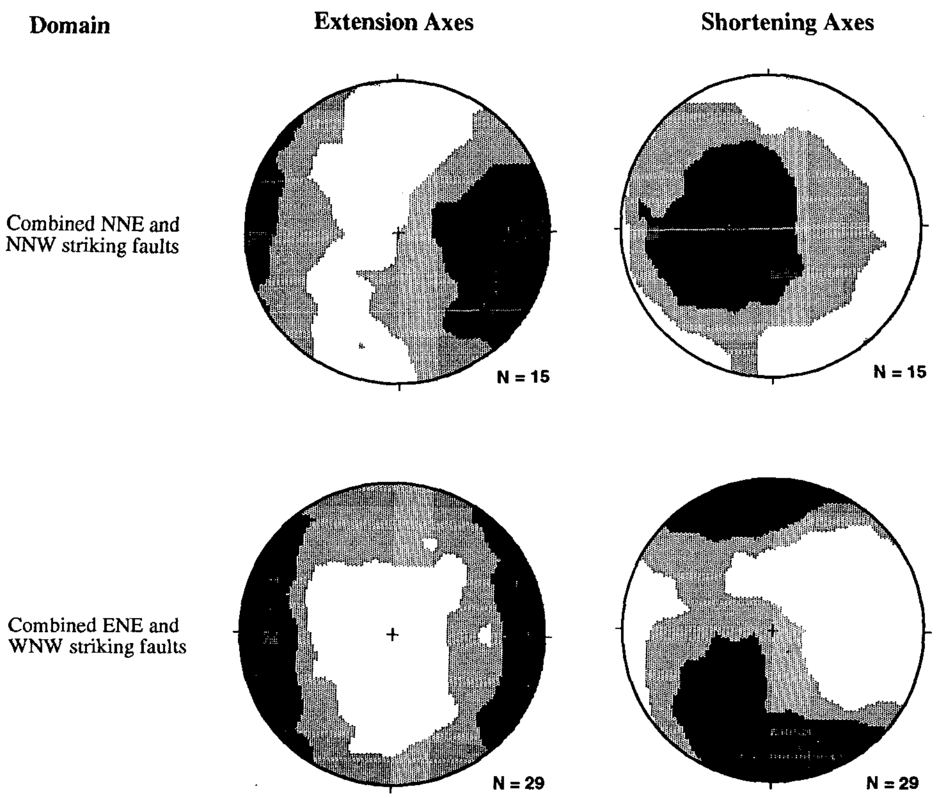


Figure 9. Lower-hemisphere, equal-area projections showing orientation and kinematic data for combined north-northeast– and north-northwest–striking faults (row 1) and for combined east-northeast– and west-northwest–striking faults (row 2) south of the Las Vegas Valley shear zone. Column 1: contoured diagram of extension axes. Column 2: contoured diagram of shortening axes. Contour interval = 2σ (after Kamb, 1959).

maximum centered on east-west and a weakly bimodal shortening axis distribution with a principal shortening axis oriented horizontal and north-south and a secondary shortening axis somewhat more steeply oriented (Fig. 9). Given the scatter in the plotted extension and shortening axes, there is no compelling reason to conclude that these two fault sets are kinematically coordinated.

Summary of Fault Kinematics. Based on the above analysis, the region north of (and including) the Las Vegas Valley shear zone appears to contain four fault sets: north-northeast-striking normal faults, north-east–east-northeast-striking left-slip faults, northwest-striking right-slip faults, and east-striking reverse faults (Fig. 10). Discrete fault sets are more difficult to define south of the shear zone. The dominant fault sets include northeast-striking, northwest-dipping normal faults and northeast-striking left-slip faults. Data from all faults north and south of the Las Vegas Valley shear zone (Fig. 11) define a statistical extension axis in both domains of about 280°. Complex patterns of shortening directions suggest a constrictional strain pattern during extension, a change in finite shortening direction during extension, or components of both.

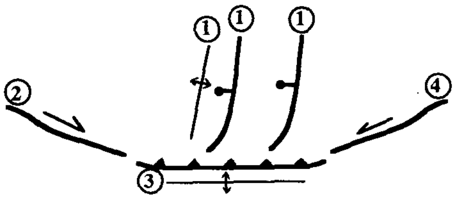


Figure 10. Sketch showing principal sets of structures in the western Lake Mead region. Numbers reflect timing of latest deformation associated with each structure as indicated by crosscutting relations observed in the field (Figs. 14 and 16). Inception of deformation on these structures is indeterminate.

Folds

North- to Northeast-Trending Folds. North- to northeast-trending folds deform rocks as young as the Bitter Ridge Limestone north of the Las Vegas Valley shear zone (Fig. 2) (Bohannon, 1983). These folds are open, upright, generally symmetrical, and variably spaced. Most of the folds are parallel to and lie in the hanging walls of north- to northeast-striking normal faults. The traces of fold axial surfaces are rotated clockwise near the Las Vegas Valley shear zone. The folds differ markedly in distribution, orientation, and geometry from the younger, east-trending folds described below.

The origin of the north- to northeast-trending folds is enigmatic. Based on their geometry, spatial distribution, and similarity in orientation and timing with north-northeast-striking normal faults, we interpret these folds as either rollover structures or extensional fault-bend folds formed in the hanging walls of normal faults (McClay and Ellis, 1987; Ellis and McClay, 1988; Xiao and Suppe, 1992). We reject explanations that these folds are related to either a shortening event or strike-slip faulting. In the first case, the fold orientation requires regional shortening that is approximately east-west. This kinematic situation is difficult to reconcile with the coeval extensional normal faulting. In the second case, formation of north- to northeast-trending folds as strike-slip–related structures requires either northeast-striking dextral faults or northwest-striking sinistral faults (Figs. 12A and 12B). Structures with these orientations and kinematics are not present in the area. An appeal to rotation of fold axes into parallelism with a north-north-east-striking left-slip strike-slip system is untenable because of the open character of most of these folds (Fig. 12C). We view the rollover or extensional fault-bend fold hypothesis as the only plausible mechanism for development of the folds.

East-West-Trending Folds. A set of east-plunging, tight folds with steep north-dipping axial surfaces is present adjacent to the Las Vegas Valley shear zone (Fig. 13). These folds are best developed within 300 m north of the Las Vegas Valley shear zone, however, they are also present south of the shear zone where rocks as young as Muddy Creek are involved in the folding. Folds are spatially

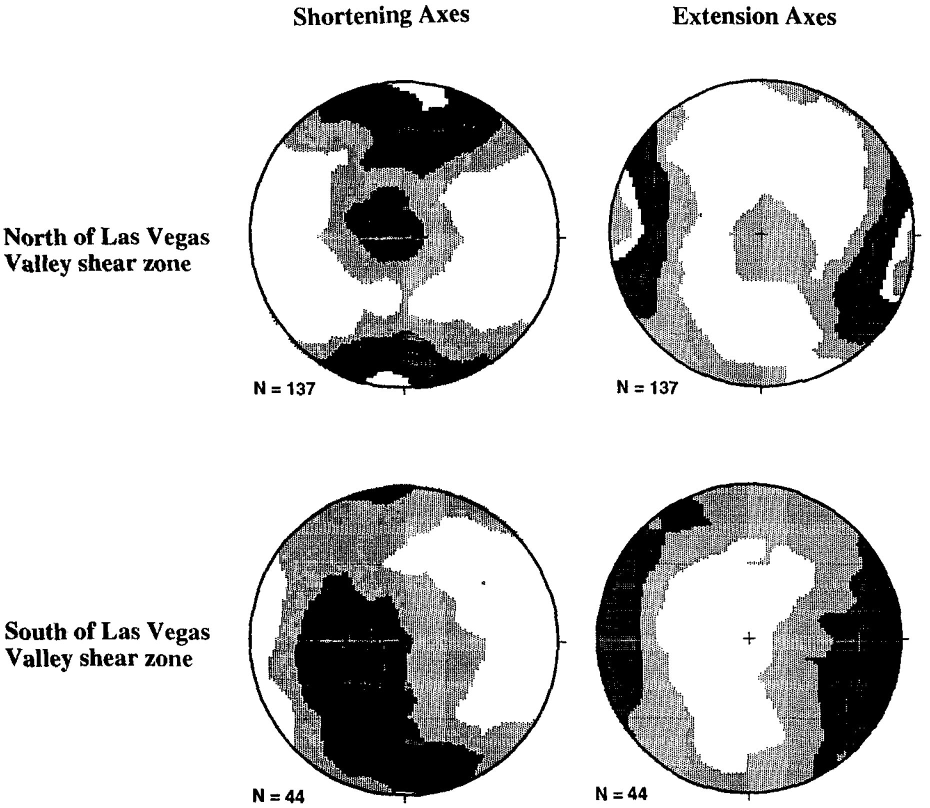


Figure 11. Lower-hemisphere, equal-area projections showing shortening (column 1) and extension (column 2) axes for all faults north (row 1) and south (row 2) of the Las Vegas Valley shear zone. Contour interval = 2σ (after Kamb, 1959).

associated with reverse faults, and crosscutting relations suggest that these two structures are contemporaneous.

Spatial coincidence of folds with the east-striking segment of the Las Vegas Valley shear zone strongly suggests a kinematic connection. Three possibilities are that the folds and associated reverse faults (1) formed at a restraining bend in the right-slip shear zone, (2) reflect localized shortening or a component of constrictional strain during extension, or (3) were formed as a result of far-field stresses at the apex of the wedge bounded by the Las Vegas Valley shear zone and Lake Mead fault system (for example, Cakir and Aydin, 1990). We evaluate these models below.

Structural Chronology

All structures described above deform rocks as young as the 12.0-Ma Lovell Wash Member. Because we cannot determine when these structures began forming, some of these structural sets may have been active contemporaneously; however, unambiguous crosscutting relationships exist that permit development of a structural chronology based on the *most recent phase* of movement of each set (Figs. 14, 15, and 16). We discuss below the following sequence of deformation, from oldest to youngest: (1) North-northeast-striking normal faults and northeast-trending folds, (2) right-slip faults associated with and including the Las Vegas Valley shear zone, (3) east-northeast- to west-northwest-striking reverse faults and associated folds, and (4) northeast–east-northeast-striking left-slip faults.

Evidence for early normal faulting and associated folding is indirect, but compelling, based on the following observations: (1) Normal faults and folds are rotated clockwise near the Las Vegas Valley shear zone, suggesting that these structures partly predate displacement along the shear zone. (2) Young east-trending folds plunge consistently east (Fig. 13). The simplest way to accomplish this

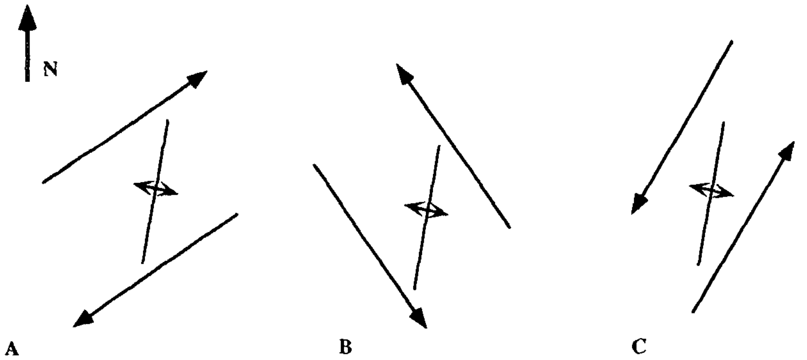


Figure 12. Relation of north- to northeast-trending folds to hypothetical wrench-fault systems. (A) A N45°–60°E-striking dextral wrench system could produce N15°E-trending folds. Dextral faults of this orientation are not present in the region. (B) A N15°–30°W-striking sinistral wrench system could produce N15°E-trending folds. Sinistral faults of this orientation are not present in the region. (C) North-striking sinistral wrench system could produce N15°E-trending folds, provided folds were rotated strongly into near-parallelism with the shear couple. This would produce strongly appressed folds, which are not observed.

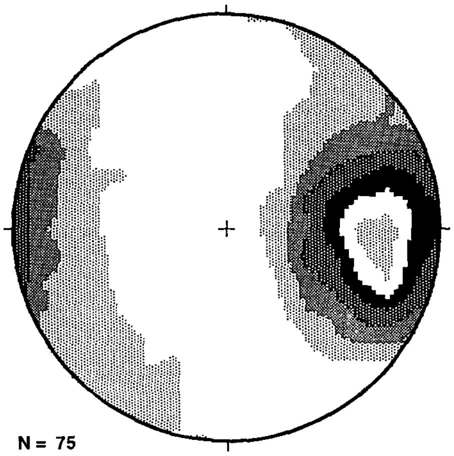


Figure 13. Lower-hemisphere, equal-area projection of fold axes directly north of the Las Vegas Valley shear zone. Contour interval = 2σ (after Kamb, 1959).

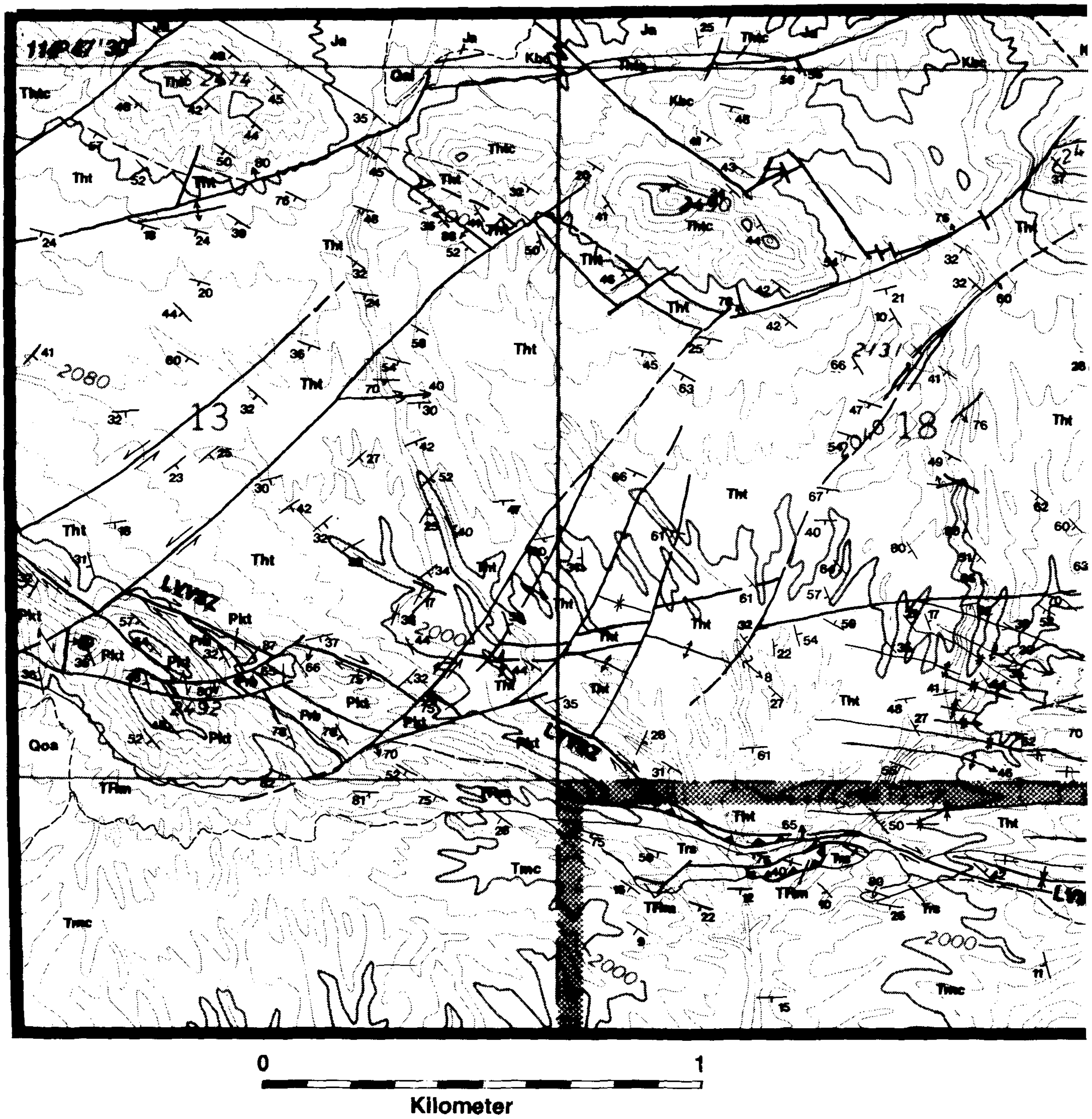
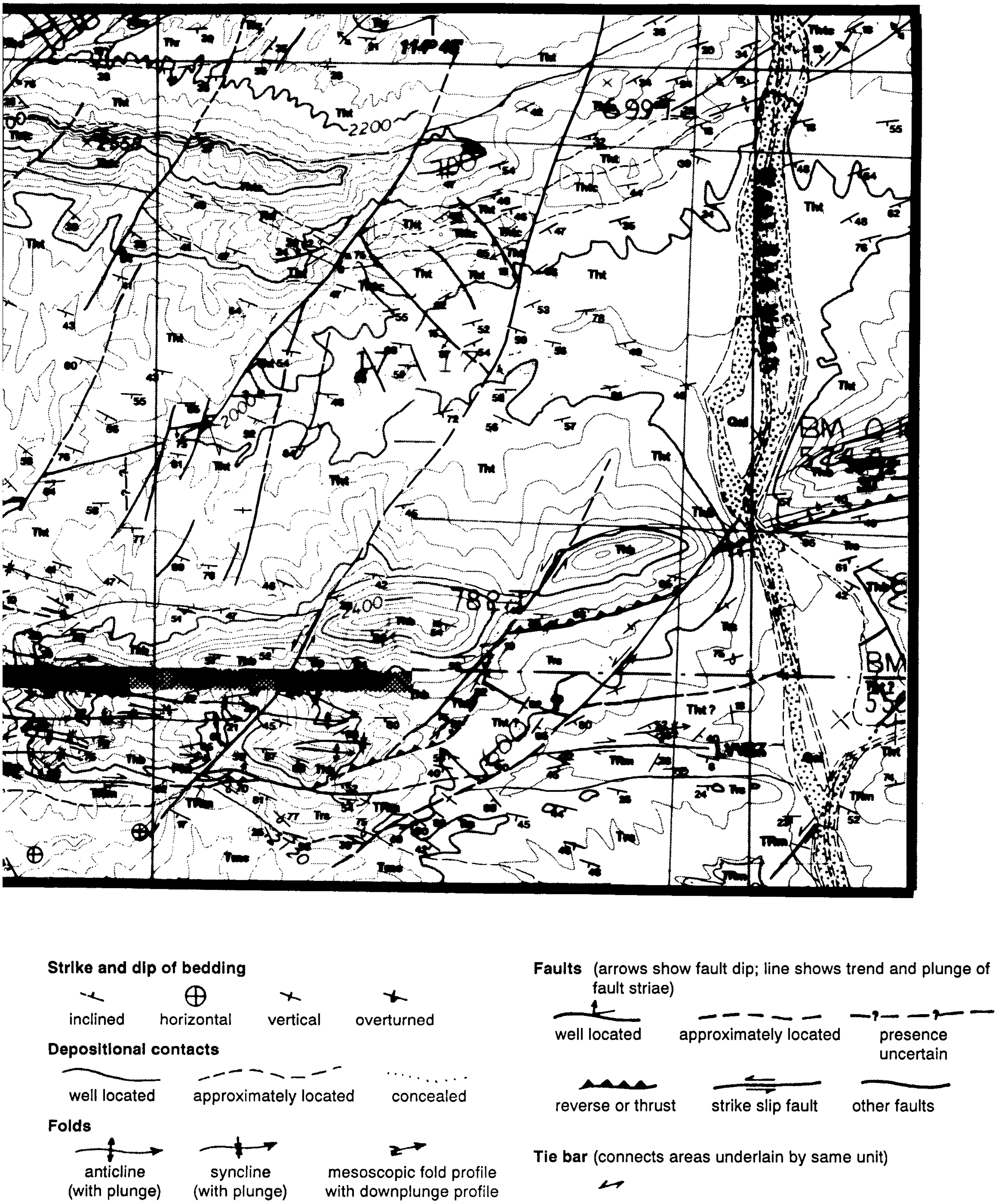


Figure 14. Geologic map at the east end of the Las Vegas Valley shear zone (LVVSZ). Map shows critical crosscutting relations between right-slip LVVSZ, east-trending folds and reverse faults, left-slip faults, and stratigraphic units that bracket the timing of these structures. Field relations of these structures relative to stratigraphic units of known age provide the basis for the structural chronology presented in Figure 15. Area of Figure 14 includes eastern part of Government Wash and western part of Callville Bay 7.5′ quadrangles. The mapped stratigraphic units include, from youngest to oldest, Qal, alluvial deposits; Qoa, older alluvial deposits; Tmc, Muddy Creek Formation (8.5–5.8 Ma); angular unconformity; Trs, Red sandstone unit (11.9–8.5 Ma); local unconformity; Thb, Bitter Ridge Limestone Member (13.5–13.0 Ma) (Horse Spring Formation); Tht, Thumb Member (17.2–13.5 Ma) (Horse Spring Formation); Thtc, Thumb Member, conglomerate facies; Thr, Rainbow Gardens Member (24–18 Ma); angular unconformity; Kbs, Baseline Sandstone (sandstone facies); Kbc, Baseline Sandstone (conglomerate facies); unconformity; Ja, Aztec Sandstone; TRm, Triassic rocks (Moenkopi and Chinle Formations); Pkt, Kaibab and Toroweap Formations; and Prb, Permian red beds. (Note duplication where cut.)


Strike and dip of bedding
inclined
horizontal
vertical
overturned
Depositional contacts
well located
approximately located
concealed
Folds
anticline (with plunge)
syncline (with plunge)
mesoscopic fold profile with downplunge profile
Faults (arrows show fault dip; line shows trend and plunge of fault striae)
well located
approximately located
presence uncertain
reverse or thrust
strike slip fault
other faults
Tie bar (connects areas underlain by same unit)

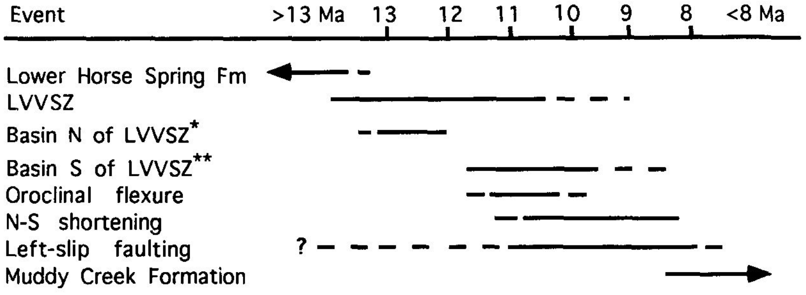


Figure 15. Chronology of major structures in the western Lake Mead area based on field observations of crosscutting relations between units or structures of known age. Dashed lines indicate uncertainty in timing. LVVSZ = Las Vegas Valley shear zone. *Refers to post-lower Horse Spring Formation basin north of the LVVSZ. **Refers to post-lower Horse Spring Formation basin south of the LVVSZ.

systematic plunge is to fold strata with a preexisting, regional eastward tilt developed by slip on west-dipping normal faults. (3) Development of White and Boulder basins (Bohannon, 1984; Duebendorfer and Wallin, 1991) at 11.9–10 Ma suggests active normal faulting during that time. We suggest that northeast-striking normal faults partly preceded but largely coincided with major displacement along the Las Vegas Valley shear zone.

The Las Vegas Valley shear zone and associated right-slip faults were clearly active at the time of deposition of the youngest units of the Horse Spring Formation and the red sandstone unit. The shear zone cuts the red sandstone unit but is lapped over by the Muddy Creek Formation, indicating activity between 11.9 and 8.5 Ma (Fig. 14). The inception of movement is poorly and only indirectly bracketed between 13.5 and 12.0 Ma by the youngest rocks with the total clockwise rotation (Thumb Member) and control over facies distributions in rocks of the upper Horse Spring Formation.

East-striking reverse faults and associated tight folds clearly deform rocks of the red sandstone unit (Fig. 14). This relationship requires that north-south shortening postdated extension-related basin development. The Las Vegas Valley shear zone may have been reoriented during shortening to a dip of 40°–60° north, an unusually low angle for a major strike-slip fault. South of the Las Vegas Valley shear zone, several small reverse faults place Triassic strata or the red sandstone unit over the Muddy Creek Formation (Fig. 16). Slip dies out up-section within the Muddy Creek Formation, suggesting that reverse faulting was waning during Muddy Creek time. Northeast- to east-northeast-striking left-slip faults consistently cut all folds and fault sets in the area, including the Las Vegas Valley shear zone. These faults also cut rocks of the Muddy Creek and, therefore, were active in part after 8.5 Ma. Timing of inception of left-slip faulting in the western Lake Mead area is unknown.

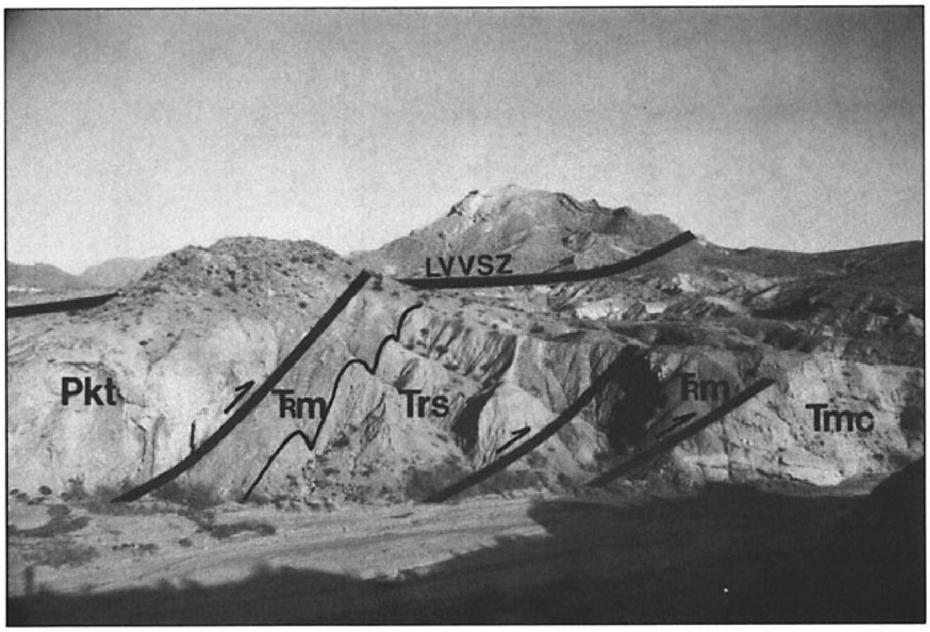


Figure 16. Photograph looking east, nearly parallel to strike of the Las Vegas Valley shear zone, showing contractional structures. Note folds in Bitter Ridge Limestone on peak near center of the photograph. Heavy lines indicate faults; arrows indicate relative sense of movement. Light line shows overturned unconformity between Triassic Moenkopi Formation (left) and Miocene red sandstone unit (right). Bedding attitudes dip steeply north and are overturned. Moenkopi is thrust over Muddy Creek Formation at extreme right side of photo; just out of view, younger Muddy Creek sediments lap over reverse fault. Pkt = Permian Kaibab-Toroweap Formations, TRm = Triassic Moenkopi Formation, Trs = Miocene red sandstone unit, Tmc = Miocene Muddy Creek Formation. View is ∼200 m across in foreground.

DISCUSSION

Implications for Tectonic Models

Any tectonic model for middle- to late-Tertiary deformation in the northwestern Lake Mead area must honor the following kinematic and timing data: (1) Rocks as young as the 12.0- to 13.0-Ma Lovell Wash Member show evidence for all episodes of deformation described above. (2) Between ∼12 and perhaps 10 Ma, extension, probably along a combined the Saddle Island-Las Vegas Valley shear zone system, produced Boulder basin (Duebendorfer and Wallin, 1991). (3) The narrow, 300-m corridor of east-plunging folds and east-striking reverse faults adjacent to the Las Vegas Valley shear zone suggests that contraction was a local phenomenon. Contractional structures postdate all red sandstone unit deposition and most displacement along the Las Vegas Valley shear zone and accommodate <1 km of shortening. (4) Left-slip faulting and possible associated normal or oblique-slip faulting outlasted all other deformational events.

Existing Models

We summarize and evaluate three published models for origin and kinematics of major fault systems in the western Lake

Mead area. The first two are dynamic and involve either north-south–directed compression (Model 1) or a reorientation of principal stress axes during the middle to late Miocene (Model 2). The third model is kinematic and proposes a constrictional strain field during Tertiary extension (Model 3).

Model 1 postulates a remote north-south maximum principal stress direction during Miocene (Cakir, 1990; Cakir and Aydin, 1990) and interprets observed structures in the context of the Coulomb fracture criterion. The model explains development of north- to northeast-striking normal faults as the result of east-west tension, the east-west–trending folds and reverse faults as the result of north-south compression, and the strike-slip faults as conjugate shears. By viewing all structures as dynamically related, the model requires that all structures formed and were active contemporaneously.

We consider this interpretation as unlikely for the following reasons: (1) Our data suggest significant diachronous movement on all faults present in the area. (2) The model does not and cannot explain the formation of north-northeast-trending folds. (3) The two major strike-slip fault zones intersect at an angle of ~130°. This is far larger than the angle predicted by simple Coulomb fracture theory and that observed for conjugate shears in natural settings. (4) It is not clear why far-field stresses would produce localized deformation at the apex of the wedge bound by the Las Vegas Valley and Lake Mead fault systems rather than more pervasive shortening structures within the wedge. (5) The model approximates uniaxial shortening and does not account for the large-magnitude lateral translations that are documented in the Lake Mead area (for example, Anderson, 1973; Bohannon, 1979).

Model 2 invokes reorientation of principal stress directions (for example, Zoback and others, 1981; Angelier and others, 1985) to explain observed differences in timing between the two major strike-slip fault zones (Rowland, 1989). In this model, the Las Vegas Valley shear zone was active when the maximum compressive stress was oriented N20°W, and the Lake Mead fault system operated when the maximum compressive stress was oriented N30°E. Because Model 2 invokes a rotation of the maximum compressive stress axis around a due-north orientation, it is broadly consistent with the development of structures associated with both north-south shortening and east-west extension.

Model 2 is based on strict Coulomb failure theory and addresses only the strike-slip faults in the area. We reject this model for the following reasons: (1) There is no evidence that major strike-slip faults must form in response to regional stresses in accord with the Mohr-Coulomb theory. Strike-slip faults in both compressional and tensional regimes can form subparallel to the tectonic transport direction, where they function as tear or transfer faults (for example, Rich, 1934; Davis and Burchfiel, 1973; Wernicke and others, 1982). (2) The paleostress determinations themselves are suspect, both in terms of orientation of principal stress axes and timing of rotation. Angelier and others (1985) determined paleostress orientations in an area <1 km^2; hence, the regional applicability of their determinations is questionable. In addition, these authors do not address the timing of the inferred change of paleostress direction. (3) Finally, by failing to incorporate the development of east-west-trending folds and reverse faults, the model incompletely describes the geometry and kinematics of the region; i.e., it is not comprehensive.

Anderson and Barnhardt (1993) present regional evidence for significant north-south shortening during Tertiary extension. They argue that coeval north-south shortening, vertical structural attenuation, and east-west extension are manifestations of a regional constrictional strain field and that the vertical and north-south horizontal contractions combine to form constrictional strains whose magnitudes approximately balance east-west extension (Model 3). Our detailed, but areally more limited, data set suggests that north-south shortening clearly *post-dated*, rather than coincided with, large-magnitude east-west extension. Furthermore, the documented east-west extension in the northwest Lake Mead area is nearly an order of magnitude greater than the maximum possible north-south shortening recorded in the rocks of the area. While we acknowledge the importance of north-south shortening, our data show that these strains are neither contemporaneous with nor of sufficient magnitude to represent true constrictional strain coincident with east-west extension.

Our Model

The models discussed above fail to address adequately either the timing of development of principal sets of structures or the kinematic role of documented detachment faults in the western Lake Mead region. We propose a model whereby major strike-slip faults function largely as transfer faults between differentially extending terranes, and contractional structures reflect the south-directed "flow" of rocks into an area of high-magnitude extension. Our model views north-south contraction as a *response* to large-magnitude extension in the northern Colorado River extensional corridor.

We follow the early suggestion of Anderson (1973) that Miocene deformation in the Lake Mead area was dominated by large-scale westward translation of blocks away from the Colorado Plateau. We suggest that extension south of the Las Vegas Valley shear zone was associated largely with the Saddle Island fault (Weber and Smith, 1987; Duebendorfer and others, 1990), occurred between 13 and ~10.0 Ma, and is recorded by sedimentary rocks of the red sandstone unit. Coeval extension occurred north of the Las Vegas Valley shear zone but was of lesser magnitude as shown by modest stratal tilts and the more limited extent of red sandstone-age deposits. North-south shortening clearly postdated deposition of the red sandstone unit. The constrictional model, which requires contemporaneous shortening and extension, would require intraformational unconformities within the red sandstone unit, which are not seen. The spatial coincidence between the highly extended western Lake Mead region and locus of greatest documented shortening strains suggests a kinematic relation between the extension and contraction. The difference in timing, however, between the two deformational events argues that north-south contractional strain may be a *consequence* of extension rather than a cause (Cakir and Aydin, 1990) or "equal partner" (Anderson and Barnhardt, 1993) in the regional strain picture.

Our observations, data, and interpretations are consistent with the suggestion of Wernicke et al. (1988) that substantial differential extension between two regions can induce gravitational flow of crustal material from the thick, less-extended terrane toward the thinner and more highly extended terrane. As emphasized by Block and Royden (1990) and modeled by Kruse and others (1991), the driving mechanism for crustal flow is simply the lateral pressure gradient created by differential near-surface loads between any two crustal columns. The viscous flow model developed by Wdowinski and Axen (1992) to calculate isostatic rebound associated with tectonic denudation clearly predicts a horizontal flow component of material from undenuded crust toward tectonically denuded crust (Fig. 17). Although they

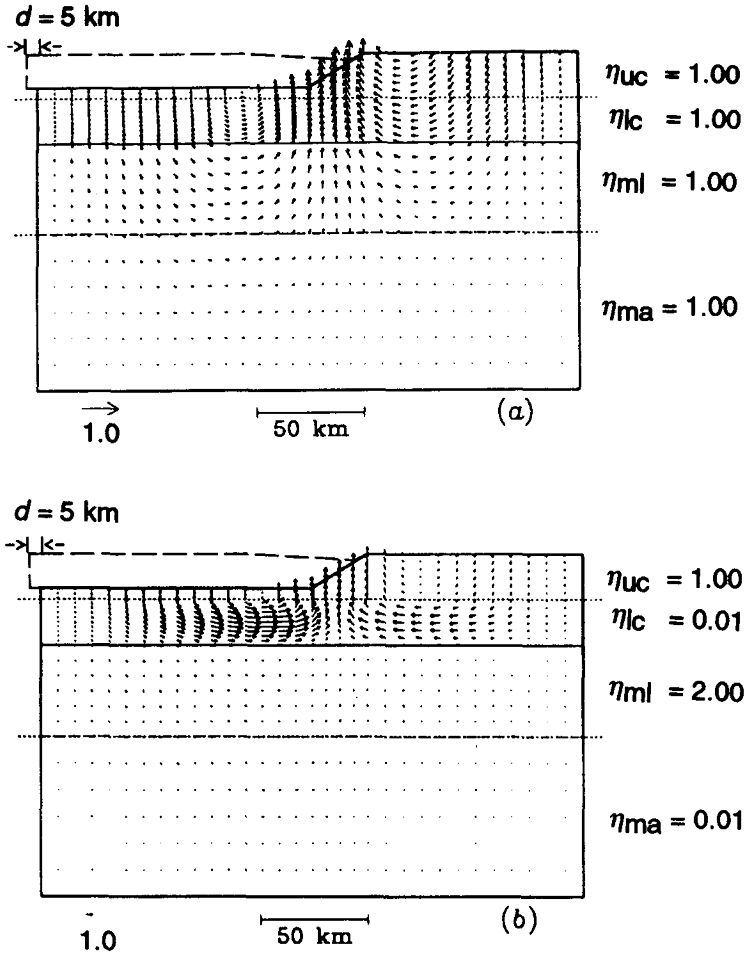


Figure 17. Flow field within the crust and mantle in response to tectonic denudation (Fig. 4 in Wdowinski and Axen, 1992; see that article for discussion). Top = velocity field for constant viscosity. Bottom = velocity field for more realistic viscosity structure (Wdowinski and Axen, 1992). Note flow of material from undenuded toward denuded terrane in upper and lower crust. Sections are constructed with tectonic transport from left to right. We suggest that similar flowage must occur across transverse structures that separate highly extended from weakly extended terranes. In this case, the tectonic transport direction would be away from the observer (into the page). Flowage of material across transverse structure toward highly extended block could produce localized contractional deformation near the transverse structure—in this case, the Las Vegas Valley shear zone.

modeled extension-parallel, two-dimensional flow, similar pressure gradients should develop *perpendicular* to the extension direction where major transverse structures or "lateral breakaways" form the boundary between weakly (thicker) and highly (thinner) extended terranes (Fig. 17). Wdowinski and Axen (1992) concluded that "structural crowding" at a breakaway is largely a function of detachment dip, with steeper detachments producing more structural crowding and footwall deformation. We note that the Las Vegas Valley shear zone, as the northern boundary of the northern Colorado River extensional corridor, was active as a steeply dipping, strike-slip fault that bounded differentially extended terranes. Thus, the extreme, but highly localized contractional deformation in the western Lake Mead area might be explained by the high-angle character of this "lateral breakaway." This model explains both the relative timing of extension and contraction in the western Lake Mead area and the modest degree of observed north-south shortening strains relative to documented large-magnitude east-west extension recorded in the region.

SUMMARY AND CONCLUSIONS

The earliest post-Horse Spring Formation structures in the region are north-northeast-striking normal faults, associated extensional fault-bend folds, and right-slip faults associated with the Las Vegas Valley shear zone. These structures operated in a kinematically coordinated fashion to accommodate approximately due east-west extensional strain between 13.0 and 10.0 Ma. North-south shortening clearly postdated the main phase of extension in the western Lake Mead area. North-south shortening may reflect localized southward flow of crustal material into the region of extreme extension at the northern end of the Colorado River extensional corridor. Left-slip faults associated with the Lake Mead fault system represent the youngest structures in the region and may be related to extension to the northeast in the Mesquite Basin–Virgin River depression region (Wernicke and others, 1988; Bohannon and others, 1993). The Las Vegas Valley shear zone and Lake Mead fault system neither initiated nor functioned as conjugate shears related to a single regional paleostress direction.

ACKNOWLEDGMENTS

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