Heterogeneous Neogene Strain and its Bearing on Horizontal Extension and Horizontal and Vertical Contraction at the Margin of the Extensional Orogen, Mormon Mountains Area, Nevada and Utah

U.S. GEOLOGICAL SURVEY BULLETIN 2011

Heterogeneous Neogene Strain and its Bearing on Horizontal Extension and Horizontal and Vertical Contraction at the Margin of the Extensional Orogen, Mormon Mountains Area, Nevada and Utah

By R. ERNEST ANDERSON *and* THEODORE P. BARNHARD

U.S. GEOLOGICAL SURVEY BULLETIN 2011

New evidence for extension-normal contraction

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1993

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For sale by the USGS Map Distribution
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Anderson, R. Ernest (Roy Ernest)
Heterogeneous neogene strain and its bearing on horizontal extension and horizontal and vertical contraction at the margin of the extensional orogen, Mormon Mountains area, Nevada and Utah / by R. Ernest Anderson and Theodore P. Barnhard.
p. cm.—(U.S. Geological Survey bulletin ; 2011).
Supt. of Docs. no.: I 19.3:2011.
Includes bibliographical references.
1. Faults (Geology)—Nevada—Mormon Mountains. 2. Faults (Geology)—Utah—Beaver Dam Mountains. 3. Folds (Geology)—Nevada—Mormon Mountains. 4. Folds (Geology)—Utah—Beaver Dam Mountains. 5. Geology, Structural—Nevada—Mormon Mountains. 6. Geology, Structural—Utah—Beaver Dam Mountains. 7. Geology, Stratigraphic—Neogene. I. Barnhard, T.P. II. Title. III. Series.
QE75.B9 no. 2011
[QE606.5.U6]
557.3 s—dc20
[551.8'7'0979314]
91–46657
CIP

CONTENTS

PLATES

[Plates are in pocket]

FIGURES

TABLE

HETEROGENEOUS NEOGENE STRAIN AND ITS BEARING ON HORIZONTAL EXTENSION AND HORIZONTAL AND VERTICAL CONTRACTION AT THE MARGIN OF THE EXTENSIONAL OROGEN, MORMON MOUNTAINS AREA, NEVADA AND UTAH

By R. ERNEST ANDERSON *and* THEODORE P. BARNHARD

ABSTRACT

Analysis of the distribution, geometry, and kinematics of structures of known or suspected Neogene age ranging in size from mountain blocks to outcrop scale between the southern Mormon Mountains and the Colorado Plateau shows that extensional deformation was accompanied by major vertical structural uplift and associated structural thinning (attenuation) and by extension-normal horizontal contraction. The vertical attenuation developed mainly by normal-sense displacements on steeply dipping to horizontal faults and appears to be most intense on the flanks of and above severely uplifted and tilted footwall blocks, several of which are major structural culminations that expose Precambrian crystalline basement rocks. Tilts of strata in these footwall culminations commonly exceed those in the hanging wall, suggesting convex-upward fault geometry. The faults either have curved traces concave toward the culmination or consist of two segments whose obtuse intersection angle faces the culmination. Stratigraphic throw either decreases abruptly away from the culmination axis or is fed abruptly into major transverse accommodation zones that possibly represent long-lived structural flaws. Typically, the culminations have strike lengths only two to three times their maximum throw, suggesting extreme lateral strain heterogeneity. Most are too small and have flanks that dip too steeply for isosatic uplift following tectonic denudation to be a cause of their formation. Also, in plan view, they tend to be arranged en echelon such that strain is not cumulative from one to the other along sections paralleling their kinematic axes. A major effect of hanging-wall structural attenuation adjacent to and above the culminations is to subdue the potential surface relief associated with uplift and tilting of the footwall.

In the Beaver Dam Mountains, a broad open fold and a sharply overturned monocline record, relative to the adjacent unstrained Colorado Plateau, shortening strains interpreted to be associated with footwall uplift and tilting. In this area, the localized shortening represented by footwall tilting and associated folding appears to be balanced by generally localized hanging-wall lengthening by normal faulting to give nominal to no overall horizontal extension. Explanations for such deformation in terms of far-field forces are not apparent, suggesting control by localized gravitational instabilities.

Fault geometry and slip indicators along the Castle Cliff fault at the west base of the Beaver Dam Mountains, as well as the sense and direction of slip on diversely oriented outcrop-scale faults in the northern Beaver Dam Mountains, suggest a northeast-southwest kinematic axis for extension consistent with previously published estimates for the central Mormon Mountains and directions inferred from strain patterns displayed on geologic maps of the region. The direction of fault displacement that produces the combined extension and vertical attenuation is mostly down to the southwest, but important exceptions include (1) areally significant domains of either variable tilt and displacement directions or down-to-the-east displacement and westward tilt, (2) domains of opposed-sense intense shear strain and tilting in major fault zones, and (3) dip slip on shear planes approximately parallel to bedding in domains of tilted fault blocks. These exceptions, combined with large and abrupt vertical variations in extensional strain magnitude, show that the two-dimensional extensional strain field is more

complex and heterogeneous than previously reported. More important, published reports that characterize the two-dimensional displacement field as dominated by uniform-sense displacements on a stacked system of low-angle detachment faults are greatly oversimplified and inaccurate.

The extension-normal horizontal contraction was accomplished mostly by displacements on strike-slip faults and by folding on east- to northeast-trending axes (parallel to the extension direction). Strike-slip displacements are mostly dextral on northwest- to west-striking faults and sinistral on north- to northeast-striking faults, thus recording strain broadly consistent with compressive paleostress states oriented north-south to northwest-southeast. Outcrop-to-outcrop or area-to-area comparisons show local predominance either of dextral or sinistral faults practically to the exclusion of the conjugate(?) set. Similar strike-slip deformation is common in widespread areas of Neogene igneous rocks in adjacent ranges to the north and is documented by detailed fault-slip studies in Neogene rocks ranging from central Utah to the Lake Mead area; these studies provide strong support for a Neogene age of deformation in the Mormon Mountains area.

Because much of the Mormon Mountains area was affected by compressional deformation of the Sevier orogeny, which is likely to have produced folds with northeast trends, we cautiously assign a Neogene age to extension-parallel folds. Neogene rocks are folded on northeast- and east-trending axes in exposures near Candy Peak in the southernmost Mormon Mountains. A Neogene age is inferred for northeast- to east-trending folds in the East Mormon Mountains on the basis of their close spatial and kinematic association with strike-slip faults of that age. South-directed slip on some low-angle faults, some of which resemble thrusts, is spatially and kinematically associated with the folding. Low-angle faulting with slip normal to the extension direction may be a common deformation needed to accommodate depth-variable strain associated with strike-slip faulting and folding. In the Moapa Peak area, the age of a large, complex northeast-trending fold that is broadly homoclinal is highly controversial and uncertain. Indirect evidence for a Neogene age for part of that fold includes (1) a southeast-tilted basal Neogene unconformity beneath a broad area of folded Neogene rocks, (2) similarity in fold architecture to that of nearby Neogene folds, and (3) an association locally with normal faults and a general lack of evidence for an association with reverse or thrust faults. The extension-parallel folds are best interpreted either as structures that absorb some of the on-strike strike-slip displacement or as a record of structural crowding at bends or steps in the strike-slip system. As with the strike-slip faults, extension-parallel folds similar to those in the Mormon Mountains area are common from central Utah to the Lake Mead area. The extension-normal contraction represented by these structures possibly is focused near the province boundary.

Although it is not currently possible to reliably estimate the magnitude of extension-normal horizontal contraction, structures of all sizes are pervasively involved, suggesting that the magnitude is a large fraction of the magnitude of extension. Coupled with the common large-magnitude structural thinning (vertical attenuation), the three-dimensional Neogene strain field in this region clearly includes major extension-normal constriction.

The pervasive pattern of strong uplift and tilting of footwall blocks and spatially and kinematically linked hanging-wall extension and thinning suggests that (1) convex-upward fault geometry is more common than previously recognized, (2) approximately in-place (nontranslational) uplift and block tilting about subhorizontal axes is a common but difficult-to-comprehend attribute of the deformation, (3) throughout much of the deformation the footwall was the structurally active block, and (4) large and abrupt lateral and vertical variations in magnitude of apparent extension are tied directly to the distribution of uplifted and tilted blocks. The task of assessing the magnitude of regional extension is extraordinarily difficult, and assessments that do not consider nontranslational uplift and tilting of footwall blocks or the three-dimensional strain field are likely to contain large positive errors.

INTRODUCTION

The mountain ranges surrounding Mesquite basin (fig. 1) in the Nevada-Utah-Arizona tricorner area have been mapped extensively at scales ranging from 1:12,000 to 1:50,000 over the past decade (Bohannon and others, 1983; Wernicke and others, 1985; Hintze, 1986; Skelly, 1987; Wernicke, Snow, and Walker, 1988; G.J. Axen, Harvard University, unpub. map, 1989; Axen and others, 1990; Bohannon, in press; Bohannon and Lucchitta, in press). These studies provide a firm basis for understanding the geologic history of that area. Phanerozoic history is recorded by deposition of an eastward-thinning, approximately 2-km-thick Cambrian to Permian sequence of shallow-marine terrigenous and carbonate rocks in the Cordilleran miogeocline. These rocks unconformably overlie Proterozoic crystalline rocks and are conformably overlain by more than 1.5 km of mixed terrigenous clastic, shallow-marine, and evaporite rocks of Permian and Triassic age (table 1). The area (fig. 2) embraces parts of (1) the east margin of the Sevier thrust belt (Armstrong, 1968), (2) the southern limit of the south-migrating Tertiary volcanic activity (Stewart and others, 1977), and (3) the boundary between the Basin and Range and the Colorado Plateaus provinces (Dutton, 1880; Gardner, 1941; Anderson and Mehnert, 1979). Understanding the Neogene tectonism (the chief focus of this study) must be accomplished within the context of these related tectonic features. Because the Mesquite basin area contains few Tertiary volcanic rocks and has a poorly exposed Neogene

Table 1. List of stratigraphic units and their ages referred to in this report, Mormon Mountains area, Nevada-Utah

[Modified in part from Wernicke and others (1985)]

Tertiary
Pine Valley Latite (Miocene)
Horse Spring Formation (Miocene)
Jurassic
Aztec (Navajo) Sandstone (Lower Jurassic)
Kayenta Formation (Lower Jurassic)
Moenave Formation (Lower Jurassic)
Triassic
Chinle Formation (Upper Triassic)
Moenkopi Formation (Middle? and Lower Triassic)
Permian
Kaibab Limestone (Lower Permian)
Toroweap Formation (Lower Permian)
Redbeds (Lower Permian)
Pakoon Formation (Lower Permian)
Permian and Pennsylvanian
Bird Spring Formation (Lower Permian and Pennsylvanian)
Mississippian
Monte Cristo Limestone (Upper and Lower Mississippian)
Yellowpine Member (Upper Mississippian)
Arrowhead Member (Upper Mississippian)
Bullion Member (Upper Mississippian)
Anchor Member (Upper and Lower Mississippian)
Dawn Member (Lower Mississippian)
Mississippian and Devonian
Sultan Limestone (Lower Mississippian to Middle Devonian)
Crustal Pass Member (Lower Mississippian and Upper Devonian)
Ironside Member (Middle Devonian)
Ordovician
Ely Springs Dolomite (Upper Ordovician)
Pogonip Group (Middle and Lower Ordovician)
Cambrian
Nopah Formation (Upper Cambrian)
Bonanza King Formation (Upper and Middle Cambrian)
Banded Mountain Member (Upper and Middle Cambrian)
Papoose Lake Member (Middle Cambrian)
Bright Angel Shale (Middle and Lower Cambrian)
Tapeats Sandstone (Lower Cambrian)

stratigraphic record (Anderson, 1981), study of the style, magnitude, and timing of deformation of well-developed Neogene volcanic sequences directly to the north contributes a basis for contrast and comparison. Likewise, the relatively unstrained adjacent Colorado Plateau is a reference area to which deformation in the nearby Basin and Range province can be compared and contrasted (Lucchitta, 1972; Hamblin and others, 1981; Wernicke and Axen, 1988; Axen and others, 1990).

Major advances have been made in understanding the style, distribution, and correlation of Mesozoic thrust faults of the Sevier orogeny, as a result of recent detailed geologic mapping in the Mormon Mountains (Wernicke, 1982; Skelly, 1987; and Wernicke, Snow, and Walker, 1988) and Tule Springs Hills (G.J. Axen, written commun., 1989; Axen and others, 1990). This deformation can be generalized as east-directed, thin-skinned, ramp-décollement thrusting. These events generally produced large areas with thrust-duplicated, low-dipping sequences of Paleozoic and Mesozoic strata that were ideal for recording later extensional tectonic events (for example, Guth, 1981). However, in local areas, such as the southern Mormon Mountains, this simple structural picture is complicated by the presence of parautochthonous slices beneath the main thrust and by a stack of as many as 20 thrust imbrications in Cambrian strata above the main thrust (Axen and others, 1990). A major transverse ramp and subthrust fold were proposed in the southern Mormon Mountains by Axen and others (1990), though in this report we question the existence of the ramp and the relationship of the fold to thrusting.

Filtering out the effects of Cenozoic deformation in areas of complex older deformation is difficult, but we believe that the rocks and structures of this region provide adequate information to isolate the effects of younger events. For example, autochthonous rocks that largely escaped Mesozoic deformation are sufficiently exposed in areas north of Mesquite basin so that structures formed in these rocks may be compared with those formed in nearby allochthonous rocks. Also, structures in sparsely distributed Tertiary rocks may be compared with those in pre-Tertiary rocks and thus provide important constraints on the interpretation of folds and faults in the older terrain.

North of the Beaver Dam Mountains (fig. 1), deformation of Sevier age is recorded as a single thrust of upper Paleozoic strata (unit Pz, pl. 1) atop Jurassic strata (unit Mz, pl. 1), and by a group of asymmetric subthrust folds (not shown on pl. 1) that suggest southeast-directed convergence (Hintze, 1986; L.F. Hintze, R.E. Anderson, and G.F. Embree, unpub. mapping, 1982–92). An adjacent sequence of synorogenic clastic strata more than 1.5 km thick is also present and is generally lacking north of Mesquite basin. Here, as north of the basin, the thrust structures have been intensely overprinted by Cenozoic deformation.

Tertiary volcanic and sedimentary rocks that are widely exposed in the Clover and Bull Valley Mountains (pl. 1) are intensely deformed by normal and strike-slip faults (Ekren and others, 1977; Hintze, 1986; L.F. Hintze, R.E. Anderson, and G.F. Embree, unpub. mapping, 1982–92) and dip moderately to steeply over wide areas. Scattered exposures of these rocks are also found in the northern Mormon Mountains, directly east of the Tule Springs Hills, and in the southernmost Mormon Mountains (fig. 1). In all areas, except those directly adjacent to a thrust front, the Tertiary strata have dips similar to the

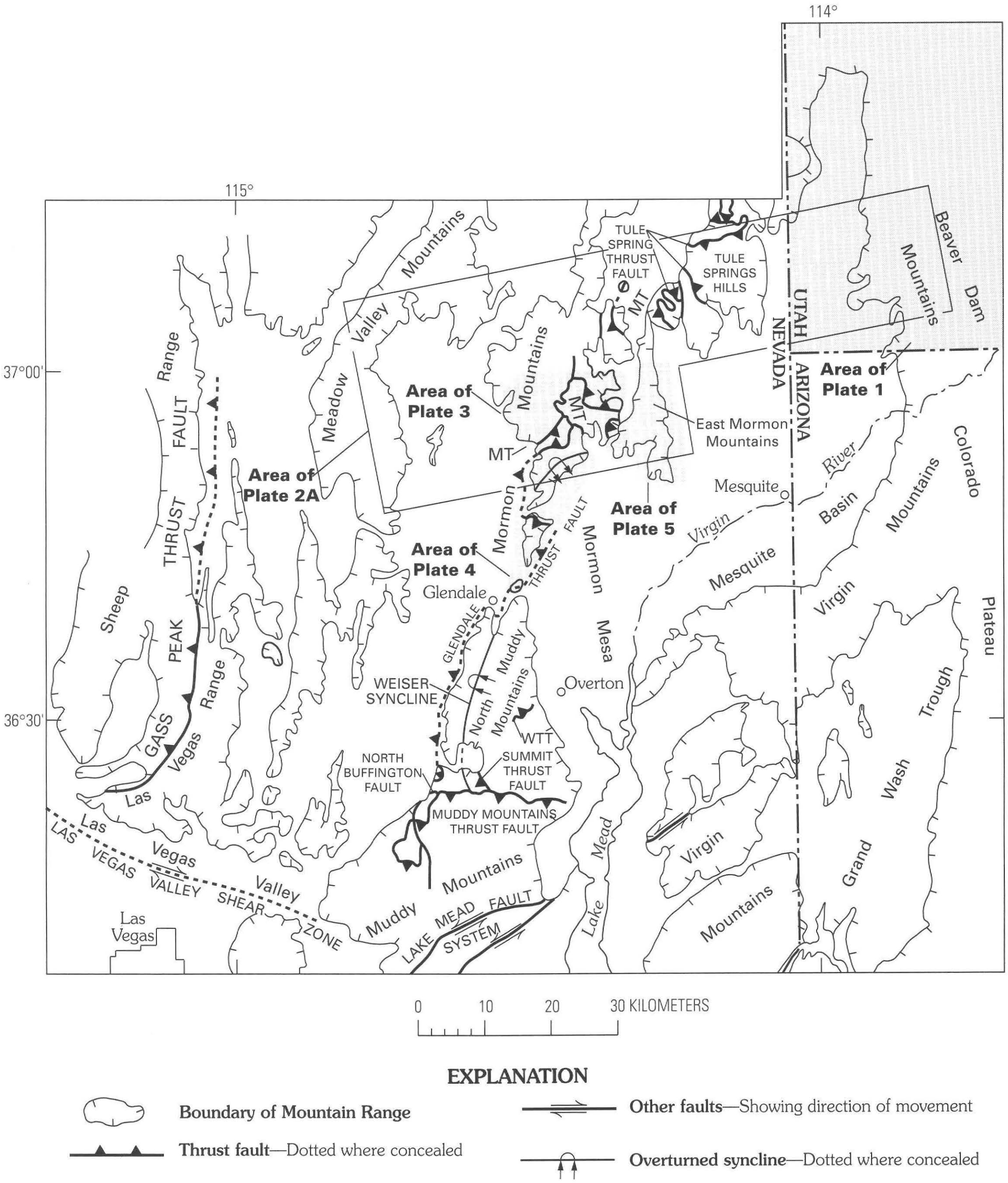


Figure 1. Location map of the mountain ranges surrounding Mesquite basin, Nevada-Utah-Arizona, showing major thrust faults and selected other structures in the region, and the location of plates 1–5. Modified from Axen and others (1990). MT, Mormon thrust fault; WTT, Willow Tank thrust fault.

subjacent pre-Tertiary strata. Similar disconformities or low-angle unconformities are interpreted from seismic-reflection data in the Mesquite basin area (Carpenter and others, 1989; Grow and others, 1990; Miller and others, 1990). Together these data indicate that neither the ramp-flat thrusts nor autochthonous rocks were differentially tilted prior to Tertiary extension (Wernicke and others, 1985; Smith and others, 1987; Wernicke and Axen, 1988), thus allowing for simplifying assumptions of pre-Tertiary structural configurations when modeling retro-deformation (Axen and others, 1990).

Studies of the Mormon Mountains and adjacent areas by Brian Wernicke and his colleagues and students led them to conclude that this area is one of several in the Basin and Range province where extensional faults of low initial dip and subregional to regional extent (detachment faults) are the first-order Neogene structures. Rocks in the upper plates of these detachment faults are cut by abundant

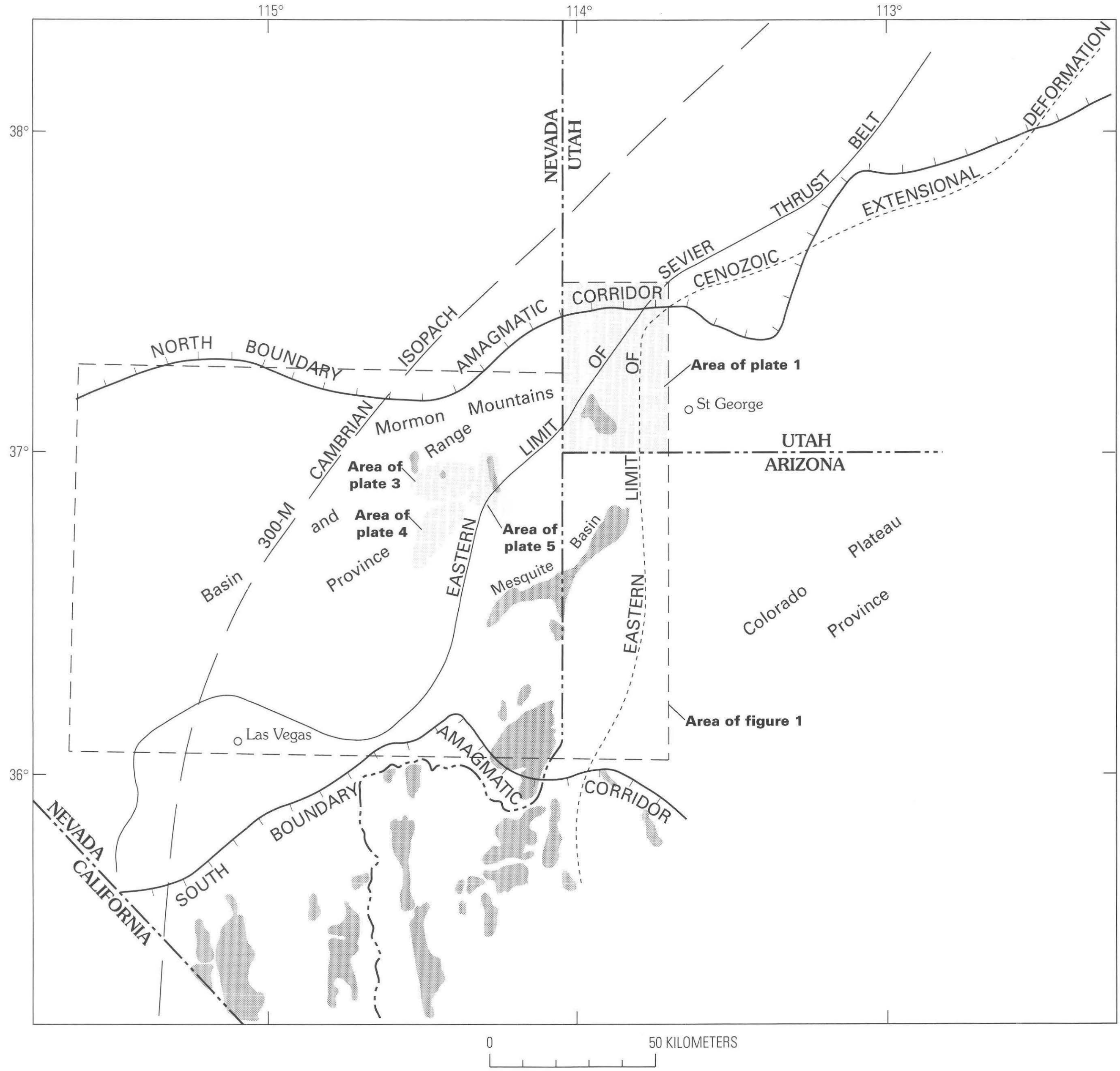


Figure 2. Location of Mesquite basin, Nevada-Arizona, relative to some major geologic-tectonic features including (1) areas of exposed Proterozoic crystalline rocks (shaded), (2) 300-m isopach for Cambrian strata (from Stewart and Suczek, 1977) marking the approximate boundary between the miogeoclinal assemblages of strata to the west and strata transitional to platform assemblages on the east, (3) approximate eastern limit of major east-directed sheets of the Sevier thrust belt, (4) boundaries of an amagmatic corridor defined by the paucity of volcanic or intrusive rocks of Tertiary age (hachures toward regions of Tertiary magmatic rocks), and (5) approximate eastern limit of major Cenozoic extensional deformation marking the boundary between the Basin and Range province and the Colorado Plateau.

domino-style and listric normal faults. Wernicke and others (1985) inferred that these normal faults chiefly served to distribute strain upward from the detachment faults, mainly through the shallow parts of the upper plates. Overall, the extensional strain of the crust is envisioned as large-scale uniform-sense (east-over-west) simple shear that is marked by three imbricate wedge-shaped slabs bounded by and penetratively extended between the Mormon Peak, Tule Springs Hills, and Castle Cliff detachment faults (Axen and others, 1990). Axen and Wernicke (1987) concluded that the detachment faults of this system were activated from west to east and that each successively lower fault carried the one(s) above it. Wernicke and Axen (1988) further concluded, on the basis of restored balanced cross sections, that the cumulative displacement on this system is 54±10 km in a direction N. 75°±10° E. These apparent displacements are large, and we suggest that there is ample evidence for far less extension. Also, the deepest exposed levels of footwall blocks only expose upper crustal rocks, rather than mid-crustal rocks that are present in many ranges in the Basin and Range province that have clearly undergone extreme extension (several papers in Crittenden and others, 1980).

Some ranges in the Basin and Range province have been recently interpreted as features that result from isostatic uplift of footwall rocks in adjustment to displacements on detachment faults (Howard and others, 1982; Spencer, 1984; Wernicke, 1985; Buck, 1988; Hamilton, 1988; Wernicke and Axen, 1988), rather than the direct result of displacements on range-bounding faults. Specifically, Wernicke (1985) and Wernicke and Axen (1988) proposed that the Beaver Dam Mountains and northern Virgin Mountains northeast, east, and southeast of Mesquite basin (fig. 1) are a type example of isostatic adjustment of a footwall breakaway zone to large-magnitude displacement on an extensional allochthon, the Castle Cliff detachment fault. Uplift of the East Mormon Mountains (fig. 1) is considered a similar response to displacement on the slightly older and higher Tule Springs detachment fault (Axen and others, 1990).

This report challenges most of these simplifying assumptions and models. It is based primarily on site-specific field studies of previously mapped faults and folds, but in some areas we have used 1:30,000-scale aerial photographs as a base for remapping and reinterpretation. Some critical structures were identified for the first time in our mapping. The field evidence indicates extremely complex crustal response to extension, complexity that can only be hinted at on geologic maps. Our focus was on aspects of extensional deformation in the brittle upper crust where the evidence is exposed for viewing, and we fully recognize that cogenetic aspects at deeper crustal levels are likely to be very different. This report has four main goals:

1. To present the results of studies of fault slip and related folds to demonstrate that Neogene strike-slip faulting is more common and more important than previously recognized. Much of our new evidence comes from detailed study of faults and fault surfaces within Paleozoic rocks, and these media are typically poor recorders of kinematic features. Faults in limestone in the region commonly contain secondary calcite, and faults in dolostone are generally marked by "exploded" tectonic breccias having self-similar particle-size distribution (commonly referred to as exploded texture) and few, if any, discrete shear surfaces. Also, exposed fault surfaces are generally coated with surface carbonate or are etched. Thus, the high proportion of exposed carbonate rocks that show only sparse striated fault surfaces makes this area poorly suited to comprehensive fault-slip studies as compared, for example, with the siliceous volcanic rocks at nearby Hoover Dam (Angelier and others, 1985) or Rainbow Canyon (Michel-Noel and others, 1990). However, we believe that the results of our fault-slip studies in widespread localities, as well as the results reported by Michel-Noel (1988), help define deformational kinematics and provide especially important evidence for previously unreported strike-slip faulting in the Beaver Dam, Clover, and East Mormon Mountains and for earlier northwest-southeast-directed transverse faulting in the southern Mormon Mountains.

2. To present some new geologic mapping and an analysis of extensive previously published mapping that indicate the following concepts: (A) Lateral heterogeneity of extensional strain is large and abrupt and must be factored into any assessment of cumulative strain magnitude. (B) Convex-upward faults are more common than have been previously recognized. They must be reconciled with interpretations that footwalls of normal faults or lower plates of detachment faults are tectonically active (Laubach, 1989; Laubach and others, in press) versus tectonically inert (Wernicke, 1981). (C) Uplifts and depressions whose axes are parallel to the extensional kinematic axis are not only more common and have a broader range of scales than has been previously recognized, but, together with the strike-slip faulting, they record structurally significant large components of constrictional strain that occurred approximately normal to the extension direction. (D) The transverse segment of the east-striking Horse Spring fault and the coextensive Davidson Peak fault are structures that accommodate for large and complex local Neogene deformation heterogeneity and are not parts of a major dextral shear zone that was active during the extensional opening of Mesquite basin, as has been proposed (Axen and others, 1990).

3. To emphasize the complexity of the Neogene deformational record and our conclusions that only by studying the three-dimensional aspects of the deformation field is there hope of understanding the complexity. There is unquestionably a significant amount of plan-view extensional-normal contraction that accompanies extensional deformation in all areas that we studied. Because this contraction is coeval with the well-documented vertical contractional aspect of extension, we use the term "constriction" to characterize these strains. Use of this term does not presume knowledge of the shape of the finite strain ellipsoid nor does it presume an absence of plane strain elements. It is used to emphasize the three-dimensional aspects of the strain field. We arbitrarily use the terms "attenuation" and "contraction" to differentiate between the vertical and horizontal elements, respectively.

4. To emphasize that convex-upward fault geometry, lateral strain inhomogeneity, and plan-view extension-normal contraction each have the effect of reducing the values of inferred extensional strain and that, collectively, recognition of these features is critical to rigorously evaluating the total extension across the region.

ACKNOWLEDGMENTS

This study was made possible by a grant from the G.K. Gilbert Fellowship Program, for which we are very grateful. Much of our work would not have been feasible and the remainder would have been significantly slowed without the enthusiastic support and cooperation provided by Brian Wernicke and Gary Axen, Harvard University. Although they disagreed with many of our results and conclusions, they have applauded our effort to build on their numerous contributions to mapping and interpreting extensionally deformed rocks, many of which they have made available to us prior to publication. We are fortunate to have enjoyed this spirit of cooperation and hope that our experience will become more commonplace among all who study extensional tectonism. We are grateful to Gerard Michel-Noel and Jacques Angelier, University of Paris, France, for providing us with the results of fault-slip studies prior to publication and for numerous discussions early in the study. Stimulating discussions with Robert Bohannon and John Grow helped us to understand the subsurface geology of the Virgin River depression.

The report was improved significantly by the reviews of Robert Scott, Ernest Duebendorfer, Robert Bohannon, and James Cole. We are especially thankful to Cole for a painstakingly comprehensive review.

BEAVER DAM MOUNTAINS

The Beaver Dam Mountains are bounded on the east by the relatively undeformed rocks of the Colorado Plateau, the northernmost part of the Grand Wash fault, and the Reef Reservoir-Gunlock fault system, and on the west by the Red Hollow and Castle Cliff faults (pl. 1). The range consists of Precambrian crystalline rocks overlain by an almost complete section of well-exposed, east-dipping Paleozoic and Mesozoic sedimentary rocks (pl. 1). The main structure of the range has been called the Beaver Dam Mountains anticline (Hintze, 1986), a northwest-trending feature defined on the basis of an elongate core of exposed crystalline basement rock (pl. 1). To us, the range structure is chiefly a northeast-dipping, internally faulted homoclinal culmination in a large region dominated by northeasterly dipping rocks resulting from Neogene deformation. This view is consistent with that of Smith and others (1987) and Wernicke and Axen (1988). Thrust faults of the Sevier orogeny have not been identified in the Beaver Dam Mountains or along tectonic strike to the northeast. It is unknown whether thin frontal thrust slices ever covered all or parts of the range, because if they did, they have been removed by erosion or by thin-skinned extensional deformation.

Because the chief concern here is with structures that formed during the regional late Cenozoic extensional deformation, it is very important to determine which, if any, of the structures in the range reflect regional compressional strain associated with the late Mesozoic Sevier or the Late Cretaceous and early Tertiary Laramide orogenies. There is considerable disagreement on this point. Hintze (1986) and Carpenter and others (1989), for example, concluded that most of the structures resulted from regionally distributed Mesozoic compressional deformation, Axen and Wernicke (1989) concluded that some of them do, and we conclude that none of them do. Whereas in this section we describe the structures of the range and, where appropriate, make note of their known or inferred age, our strongest arguments for Neogene age are in the section on "Summary and Discussion" where these structures are placed in the context of regional Neogene strain patterns. In the following section, we describe the range-bounding structures and the structures within the range.

NORTH AND SOUTH STRUCTURAL TERMINATIONS

No distinctive structural break exists between the fault-repeated northeast-dipping internal structure of the northern Beaver Dam Mountains and that of the adjacent part of the Bull Valley Mountains (pl. 1). The northern structural boundary is arbitrarily placed at a line connecting the north ends of the Red Hollow and Gunlock faults. A paraconformity between upper Tertiary and older rocks in this area shows that the main internal structure of the northern part of the range is Neogene (Hintze, 1986; Wernicke and Axen, 1988).

The southeast dip of strata directly west of the northernmost part of the Grand Wash fault (pl. 1) marks the southern termination of the main culmination of the Beaver Dam Mountains. Directly to the south, all strata west of the Grand Wash fault dip westward. Although no single transverse structure exists in this area, the dip-direction reversal, approximately at the Utah-Arizona boundary, marks the southern structural termination of the Beaver Dam Mountains.

WEST-BOUNDING FAULTS

The west-bounding Red Hollow fault (pl. 1) strikes north, has a moderately straight north-trending trace, is mostly buried, and where exposed, dips steeply toward the west. In contrast, the Castle Cliff fault has a very sinuous trace, is extensively exposed, and dips west at 10°–35°. Both faults displace strata down to the west or southwest. It is unknown whether the two faults are coextensive or if the steeper Red Hollow fault is younger and offsets the Castle Cliff fault. Regardless, the Castle Cliff fault is of most interest here because highly uplifted Precambrian crystalline rocks are extensively exposed in its footwall, and the fault can be traced southward into sedimentary cover rocks where it steepens and its displacement ends, revealing critical aspects of how strain is accommodated by it.

The sinuous Castle Cliff fault has been variously interpreted as (1) a major regional detachment fault that projects 40 km westward and dips about 11° beneath the Mormon Mountains (Axen and others, 1990), (2) part of a regional arcuate (Wernicke, 1985) or scoop-shaped (Axen and Wernicke, 1989) breakaway zone, and (3) a range-front fault of moderate (about 35°) initial dip that has been rotated to a shallow dip by isostatic uplift of its tectonically denuded footwall (Wernicke and Axen, 1988). We interpret it instead as a convex-upward zone of intense structural thinning (attenuation fault) associated exclusively with uplift and tilting of the main crystalline culmination of the Beaver Dam Mountains.

Maximum displacement on the Castle Cliff fault is near localities A and D (pl. 1) where crystalline rocks stand the highest, and Paleozoic cover rocks are faulted out of view. Directly east of Castle Cliff, at Sheep Horn Knoll, and at localities A and B (pl. 1), the Castle Cliff fault zone consists of highly fractured to brecciated and altered (locally silicified) crystalline basement rocks overlain by fault-attenuated (structurally thinned) Paleozoic sedimentary rocks. Where adequate thickness (>100 m) of the thinned Paleozoic section is preserved and exposed, such as east of Castle Cliff and at Sheep Horn Knoll, the normally 2-km-thick sequence of lower and middle Paleozoic strata is attenuated by normal-slip displacements on extremely abundant faults to less than one-tenth of its original thickness. The zone of strongly broken crystalline rock is typically a few tens of meters thick. The fault zone dips 10°–30° west, and its surface is conspicuously corrugated on a wavelength of 2–4 km (pl. 1). The corrugations are similar to regionally distributed folds displayed by the geometry of regional low-angle fault systems in the lower Colorado River extensional terrain (Frost and Martin, 1982; Teel and Frost, 1982), and they help define the kinematic direction of extension as northeast-southwest, consistent with fault-slip data gathered from planar and listric faults in the hanging wall (Smith and others, 1987). There is no general agreement as to whether such corrugations reflect the primary geometry of the faults (John, 1987; Davis and Lister, 1988) or flexing of the fault during its evolution (Cameron and Frost, 1981; Spencer, 1982).

Northwest of Castle Cliff, the hanging wall of the Castle Cliff fault consists of moderately to gently northeast-tilted syntectonic detrital sedimentary rocks and intercalated landslide blocks and sheets. The grain size of these rocks varies widely from coarse debris flow to siltstone. The landslide masses are mostly formed of structurally thinned and recrystallized Mississippian strata that can be directly correlated with structurally thinned rocks in the adjacent Castle Cliff fault zone. Clasts in the sedimentary rocks are mostly Paleozoic and Mesozoic sedimentary rocks but include sparse crystalline basement rocks and Tertiary volcanic rocks. Their broad stratigraphic range and the fault-zone source of the intercalated landslide masses indicate that these range-front deposits accumulated late in the uplift history during and after the footwall of the Castle Cliff fault had been unroofed. The presence of thin-bedded siltstones indicates an approximately horizontal postdepositional attitude, whereas the debris flows and landslide masses indicate a steep nearby mountain front. This mixed assemblage of coarse-, fine-, and landslide debris indicates rapid tilting and faulting. These sedimentary assemblages together suggest structural sagging or backtilting of the hanging wall above an active Castle Cliff fault. The current northeastern dips of the sedimentary rocks could have resulted from continued backtilting into the fault or from the kind of isostatic uplift and rotation of a tectonically denuded footwall suggested by Wernicke and Axen (1988). Isostatic uplift and rotation require that the fault was steeper during deposition of hanging-wall sediments than it is now and implies that it was inactive during uplift and tilting of its hanging-wall strata. On the basis of the paleostructural setting indicated by the interstratified coarse and fine sediments, we favor syndepositional tilting above late-stage faults of the Castle Cliff fault zone (pl. 2*B*).

Near locality G (pl. 1), the traces of most faults splay south and southeast but some splay northeast (Hintze, 1986). These fault splays distribute the displacement through a large volume of rock that forms the southeast part of the major homoclinal culmination of the Beaver Dam Mountains where the structure resembles a large southeast-plunging anticline (pl. 1). Fault-to-bedding cutoff angles range from low to high but are typically higher in the hanging wall than in the footwall of individual fault splays. Some faults that are parallel to bedding in apparently unstrained footwall rocks juxtapose hanging-wall rocks that show strong distributed structural thinning on abundant small normal faults. South of Castle Cliff, faults and bedding generally dip west, but bending of strata and reversals of bedding-dip directions are common at outcrop and larger scales, suggesting a complicated strain field (areas labeled "variable attitude" on pl. 1). As the splay faults distribute attenuation away from the main fault zone, the zone changes southward over a 5-km distance from one of gentle dips and concentrated attenuation (several tens of meters thick near Castle Cliff) to a steep fault zone a few meters wide with a stratigraphic separation of about 700 m. About 4 km farther south, the Castle Cliff fault zone terminates before reaching the Utah-Arizona border. This southward termination is within the range block, and thus the fault does not bend westward south of Castle Cliff and head back to the range front. Therefore, we dispute the interpretation that it is continuous with the northern extension of the Piedmont fault that bounds the Mesquite basin part of the Virgin River depression, as suggested by Wernicke (1985) and Wernicke and Axen (1988). Our interpretation of the relative positions of the Piedmont and Castle Cliff faults is shown in plate 1.

We infer a convex-upward subsurface geometry (pl. 2*C*) consistent with the convex westward overall trace of the Castle Cliff fault and with the shape and localized extent of positive gravity and magnetic anomalies over the culmination (Blank and Kucks, 1989). This interpretation of a downward steepening fault zone is more consistent with potential-field data than is the 11°-west-dipping detachment-fault interpretation of Axen and others (1990). The west base of the steep west flank of a 200-nT (nanotesla) positive aeromagnetic anomaly is close to the bedrock-alluvium contact, indicating structural termination near there of the raised block (Blank and Kucks, 1989). If, instead, the basement block extended westward beneath an 11°-west-dipping fault, the positive aeromagnetic anomaly should be spread westward to reflect the shallow mass of relatively magnetic crystalline basement rock. Also, gravity data (Blank and Kucks, 1989) suggest a significant structural depression beneath Beaver Dam Wash west of the Beaver Dam Mountains. We saw no evidence to suggest that the Castle Cliff fault is a continuously low angle feature that accommodated 24 km of extension, as suggested by Axen and others (1990).

The highly conjectural buried range-front structures in plate 2*C* depict a westward steepening, fault-segmented upper faulted surface on crystalline basement rocks overlain by internally faulted Paleozoic and Mesozoic sedimentary rocks, which are in turn overlain by structurally thinned Tertiary rocks and back-tilted synfaulting basin-fill strata. In the hanging wall of this frontal fault system, fault-tilted Tertiary rocks dip more steeply than underlying upper Paleozoic rocks, and the resulting strain disharmony is accommodated in intervening Mesozoic rocks, consistent with mapped relationships in the Dodge Spring quadrangle to the northwest (Anderson and Hintze, in press). The west-bounding Red Hollow fault could be the northern continuation of the Castle Cliff fault or it could be a somewhat younger and distinctly steeper fault. Its footwall consists of fault-repeated Paleozoic and Mesozoic rocks from which we obtained a large sample of fault-slip data (pl. 1) that strongly suggest northeast-southwest extension. As the fault-repeated footwall rocks of the Red Hollow fault are traced northwest parallel to their strike and toward the fault, they and the lesser faults that repeat them bend westward, producing a conspicuous fishhook pattern in plan view (Hintze, 1986, L.F. Hintze, R.E. Anderson, and G.F. Embree, unpub. mapping, 1982–92). Whether this bending reflects sinistral slip on the Red Hollow fault is unknown. The bending could be the result of normal drag on previously tilted strata, but sinistral drag is consistent with the slip characteristics of other north-striking faults in the area, as noted below.

Bedrock of the hanging wall is buried beneath alluvium of the basin below Beaver Dam Wash. Southeastward projection from bedrock exposures of the Clover Mountains (pl. 1) to the fault requires that the buried hanging wall consist of a thick sequence of northeast-tilted and fault-repeated Miocene volcanic rocks. Because this structural style is geometrically similar to the exposed footwall pattern of fault-repeated pre-Tertiary rocks, we infer that the structures east and west of the Red Hollow fault are coeval and are Miocene or younger in age. The north-trending Red Hollow fault cuts obliquely across these northwest-trending known and inferred structures. Miocene or younger throw could exceed 3 km, and the magnitude of sinistral slip is not known.

EAST-BOUNDING FAULTS

The north-striking Grand Wash, Reef Reservoir, and Gunlock fault systems (pl. 1) form the boundary between the Basin and Range province and the relatively unstrained Colorado Plateau in this area. The Gunlock and Grand Wash faults have components of down-to-the-west dip separation, and the Reef Reservoir fault has a component of down-to-the-east dip separation (Cook, 1960; Hintze, 1986), based on offsets of east-tilted stratigraphic units; and all show steep inclinations where mapped. How these faults are interconnected is poorly understood. We show them (pl. 1) as separate entities, following Hintze (1986), but we suspect that they are connected in some way. The contrasts in direction of dip separation on these quasi-continuous faults suggest either a scissors motion or complications arising from a significant component of strike-slip motion. Gently plunging striae indicate predominantly sinistral slip on the Gunlock fault, on a splay of the Gunlock that cuts Miocene volcanic rock, and on several other north-striking faults that cut Paleocene to Miocene rocks directly west of the Gunlock (pl. 1, plot 4). This type of faulting is consistent with a regional pattern of significant sinistral slip on north- to northeast-striking large- and small-displacement faults in southwestern Utah, as noted in fault-slip studies by Davis and Krantz (1986), Anderson and Barnhard (1986, 1987), Anderson and Christensen (1989), and additional unpublished data (1979–87) gathered by R.E. Anderson. A detailed study of fault-slip characteristics of the Gunlock fault and associated folds by Becky Hamond (Brigham Young University, Provo, Utah) shows that strike-slip displacements of probable Neogene age are much more common than previously recognized. We conclude, therefore, that the apparent reversals in the sense of dip separation on the Gunlock-Reef Reservoir-northernmost Grand Wash fault system are due mainly to complications induced by strike-slip displacements. The steep dip of these faults, their sense of slip, and the presence of genetically related fault-parallel folds along them indicate that little or no extensional strain can be associated with them. A Neogene age is well accepted for the Gunlock (L.F. Hintze, R.E. Anderson, and G.F. Embree, unpub. mapping, 1982–92) and Grand Wash (Lucchitta, 1972) faults and thus is inferred for the intervening Reef Reservoir segment of the fault system.

STRUCTURES WITHIN THE BEAVER DAM MOUNTAINS

The chief structures, aside from the homoclinal culmination, within the Beaver Dam Mountains are (1) the Pahcoon Flat fault, (2) the Jackson Wash fault and the family of northwest-striking faults that feed into its southern part, and (3) the Shivwitz syncline (pl. 1). These structures are described below. Other structures include (1) a bedding-parallel fault in the basal Paleozoic clastic strata, (2) a few north- and northwest-striking high-angle faults northeast of the exposed crystalline rocks (including the West Mountain Peak fault of Hintze, 1986), and (3) northwest-striking dextral faults. Faults of the first two categories show minor stratigraphic throw ranging from a few meters to about 100 m and apparently account for only a small amount of extension. Previously unrecognized large-displacement dextral faults are at localities C and D (pl. 1). At locality C, a steep fault offsets the Sevier-age Square Top Mountain thrust (Hintze, 1986) by about 4 km. Map-scale faults of similar attitude and slip sense displace upper Miocene sedimentary rocks at locality E (pl. 1) and are common in upper Tertiary volcanic and intrusive rocks in many parts of the Clover Mountains (pl. 1, plots 1*A*, 1*B*). At locality D (pl. 1), the axis of the northeast-trending structural corrugation that contains the attenuated slab of Paleozoic rocks at Sheep Horn Knoll is offset dextrally about 1 km on a northwest-striking fault. Basin-margin upper Tertiary sedimentary rocks exposed in roadcuts directly west of locality D (pl. 1) are cut by similarly oriented dextral faults that are too small to show at the scale of the illustration. The trace of the dextral-slip fault at locality F is too parallel to bedding traces to evaluate its slip magnitude but, on the basis of a 50-cm-wide gouge zone excavated at one locality, the displacement could be quite large. These sparse map-scale dextral-slip faults are widely represented as outcrop-scale minor faults in Tertiary rocks in areas directly north and northwest of the Beaver Dam Mountains (pl. 1, plots 1*B* and 2). Displacement on the dextral faults is coeval with displacement on generally north- to northeast-striking sinistral faults (Anderson, 1981). Despite the coevality, some slip incompatibility is indicated by overlapping strike distributions of faults with contrasting senses of slip (compare 340°–360° sectors of plots 1*A*, 2, 3, and 4, pl. 1). Such slip incompatibility limits the use of the strike-slip data for paleostress analysis, but the cumulative strain represented by this faulting is an important element of Neogene regional deformation. The faulting implies north-south to northwest-southeast contractional strain that is generally normal to kinematic axes of extensional deformation (pl. 1, plot 5).

The Pahcoon Flat fault (pl. 1) is the most enigmatic structure in the range. It consists of a northwest-striking north part that is mostly buried beneath alluvium of Pahcoon Flat and a north-striking southern part that cuts downsection southward in both hanging-wall and footwall strata. On the basis of its trace across topography, the dip of the fault appears to decrease northward and is as little as 35° SW. directly south of Pahcoon Flat (pl. 1). As described above for the Reef Reservoir–Gunlock fault pair, the sense of apparent displacement on the Pahcoon Flat fault changes from east-side-down south of locality H (pl. 1) to west-side-down farther north, but, unlike those faults, we are aware of no data that suggest the reversal results from strike-slip movement. Northward from the point where the slip sense reverses (locality H, pl. 1), the stratigraphic separation increases abruptly and appears to be spatially and mechanically related to an increase in east dip of footwall rocks. About 2 km north of locality H, the footwall strata are overturned for at least 8 km northwest to the junction of the Pahcoon Flat fault with the Jackson Wash fault (pl. 1). The contrast in dip magnitude between hanging-wall and footwall strata is large and abrupt (pl. 1, cross section *A–A′*). Though the fault has a trace length of only 10 km, it has at least 2.2 km of normal-sense dip separation in upper Paleozoic strata.

Axen and Wernicke (1989) suggested that the footwall overturning occurred above a blind thrust but we disagree. Because the direction of presumed thrusting is northeast approximately normal to the southeast-directed thrusting characteristic of nearby areas to the north (L.F. Hintze, R.E, Anderson, and G.F. Embree, unpub. mapping, 1982–92), and because the overturning seems to be spatially and genetically linked to normal dip-slip displacement on the Pahcoon Flat fault, alternatives to a blind-thrust explanation should be sought. Because the Pahcoon Flat fault is coextensive with the Jackson Wash fault, those alternatives should consider both structures.

The Jackson Wash fault strikes generally north-south, dips steeply to gently west, and forms a structural link between the Pahcoon Flat fault and an area of sinistral-slip faulting on northeast-striking faults in the southwesternmost part of the Bull Valley Mountains (pl. 1). Striae and offsets of strata along its northern trace indicate sinistral slip of about 2 km. In its southern part, several medium- to large-displacement strike-slip and dip-slip faults transfer their displacement into it but do not cross it. Those faults represent a large amount of extensional strain in the hanging wall of the southern Jackson Wash fault. Because the footwall in that area is common to both the Jackson Wash and Pahcoon Flat faults, those faults must be mechanically coupled. The area of overturned footwall rocks is a structural culmination similar to but much more tilted than the main crystalline-rock culmination of the range. The southern Jackson Wash fault and the northern Pahcoon Flat fault combine to form a convex-westward trace somewhat similar to that of the Castle Cliff fault. We assume that prior to erosional removal, the extended rocks in the hanging wall of the Jackson Wash fault shown in cross section *A–A′* (pl. 1) projected southeastward along strike to form an intensely attenuated sheath above the footwall culmination shown in cross section *B–B′* (pl. 1). We suspect that the horizontal components of hanging-wall extension and footwall contraction across these faults balance one another in terms of kinematics and magnitude, and that the faulting mainly accommodates diapir-like uplift and overturning of the footwall and vertical attenuation of the hanging wall (fig. 3). This deformation is somewhat analogous to that in a well-exposed footwall uplift in the East Mormon Mountains described in the "Summary and Discussion" section (p. 38, fig. 20). The abrupt lateral change in throw is an example of strong lateral strain inhomogeneity. As this strain signature diminishes southward, it is balanced by a southward increase in uplift and tilting of the main crystalline-rock culmination of the range. If strain magnitude is summed parallel to the northeast-southwest kinematic axis (pl. 1), the strain tends not to be cumulative on the Castle Cliff and Pahcoon Flat faults. Similar conclusions are drawn below for major structures in the southern Mormon Mountains.

The north-plunging Shivwits syncline has a 15-km-long axial trace directly west of and parallel to the Gunlock and Reef Reservoir faults. Those faults form the ultimate east limit of the syncline, and, therefore, genetic and (or) mechanical associations are suggested. With our current understanding of sinistral slip on the Gunlock fault, it is reasonable to interpret the flexing that produced the syncline as a product of combined sinistral and normal drag. This interpretation is weakened by the fact that locally the fold is the predominant structure relative to fault displacement, and thus a drag origin is unreasonable. For example, in the area between the west-side-down Gunlock fault and the east-side-down Reef Reservoir fault, strata that form the east limb of the syncline are quasi-continuous with unfolded strata farther east. A minor amount of trace slip is the only observable fault displacement across this zone. Also, the Shivwits syncline is expressed as a negative deflection of regional gravity contours (Blank and Kucks, 1989), but the Gunlock and Reef Reservoir faults lack significant gravity expression, which is consistent with the view that the fold is a separate feature and that strike slip may be more important than the dip slip on those faults.

It is perhaps most reasonable to interpret the Shivwits syncline as a structure that is bounded on the east by faults but is genetically related to uplift of the main part of the Beaver Dam Mountains. We develop this interpretation in the "Summary and Discussion" section. Though the youngest rock in the Shivwits syncline is the Lower Jurassic

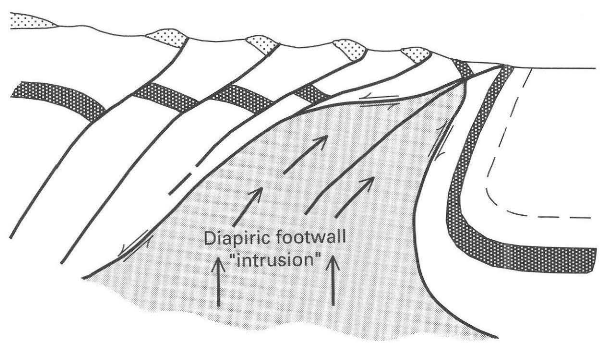


Figure 3. Dimensionless sketch showing the suggested relationship between structural crowding resulting from diapiric upwelling of the footwall block and mechanically linked structural extension and structural attenuation in the hanging-wall block.

Navajo Sandstone (Hintze, 1986), we infer a Neogene age for this fold because of its close spatial and mechanical association with the Neogene Gunlock fault and the uplifted Beaver Dam Mountains, and also from its similarity to other north-trending Neogene uplift-fold-fault combinations in the region. One such combination is formed in the downdropped block of the Hurricane fault near Pintura, Utah, 40 km to the northeast where the Miocene Pine Valley Latite is downwarped in a faulted fold that is at least as large as the Shivwits syncline (Cook, 1957; R.E. Anderson, unpub. mapping, 1980) and is sandwiched between the fault and the uplifted Pine Valley Mountains block. The similarity of these demonstratable Neogene structures to the Shivwits syncline increases our confidence not only in the age assignment but also in our inference of a genetic and mechanical link between the Shivwits syncline, its east-bounding faults, and the crystalline-rock culmination of the range. As a consequence of their pairing and form, these structures preclude significant extensional strain normal to their trace, as noted above.

MORMON MOUNTAINS

We have studied only the southern part of the Mormon Mountains (fig. 1), where our principal interests have been to (1) evaluate the ability of pre-Tertiary thrust faults and thrust-related features to constrain the sense and magnitude of Cenozoic deformation; (2) gain an improved understanding of the distribution, style, and magnitude of Neogene deformation; and (3) evaluate the conceptual model of the proposed Moapa Peak shear zone of Axen and others (1990). This feature was suggested to be a major east-west-trending dextral-slip shear zone and flexure with a combined dextral-sense offset estimated at 10–15 km. The southern Mormon Mountains are divided into two map subareas (pls. 3 and 4). An area of overlap should aid in relating the geology of one map area to that of the other.

PALEOGENE STRUCTURAL SETTING

The southern Mormon Mountains area was affected by Mesozoic Sevier thrusting (fig. 2) and preserves critical evidence of a contrast in the geometry of subthrust structures. To the south in the Muddy Mountains, the predominant structure is a major subthrust syncline (Longwell, 1949; Bohannon, 1983a, b), whereas the area north of Moapa Peak (pl. 3) is characterized by a ramp-flat geometry with upright and little-deformed autochthonous strata (Wernicke and others, 1985; Axen and others, 1990). Axen and others (1990) interpreted the steep to overturned Paleozoic rocks near Moapa Peak as folding spatially and genetically associated with thrusting, which, if true, means that the critical contrast in subthrust geometry would have to be structurally resolved in a narrow 2–3 km zone northwest of Moapa Peak.

THRUST FAULTS, FOLDS, AND TRANSVERSE FAULTS OF PROBABLE MESOZOIC AGE

The spatial and genetic relationships among thrust faults of the Mormon-Glendale thrust systems and the relation of those structures to steep and overturned rocks near Moapa Peak are complex and significantly uncertain. Some structures previously mapped as regional thrusts are reinterpreted here as transverse faults and associated folds. Because all of these structures have been used by previous investigators to constrain the sense and magnitude of Cenozoic deformation in this area (Wernicke and Axen, 1988; Axen and others, 1990), the following sections describe critical aspects of them so that the strength of the constraints can be evaluated.

MORMON THRUST FAULT AND HIGHER THRUST FAULTS

Between localities A and B (pl. 3), the Mormon thrust fault dips gently south and southeast and separates Mississippian rocks of a footwall flat from upper-plate Cambrian rocks. North and east of locality B, the upper plate is downfaulted against the lower plate on the Horse Spring fault, but the thrust re-emerges directly north of locality C, where Mississippian rocks also form the footwall. Between B and C, the thrust apparently maintains a uniform structural level in lower-plate Mississippian rocks. In that area, either the Mormon thrust fault or the structurally higher Glendale thrust fault accommodate extensive imbricate stacking in upper-plate Cambrian rocks. Between localities C and D, the thrust is also downfaulted out of view on variably striking steep faults that are parts of the Horse Spring fault system. Where it emerges at D, Pennsylvanian rocks form the lower plate, indicating a slight structural climb in the footwall from C to D.

If the thrust faults exposed at localities A and D (pl. 3) are the same Mormon thrust, then it is largely buried between those localities. The thrust fault at locality E placed thrust-imbricated Upper and Middle Cambrian rocks of the Bonanza King Formation atop upright Upper Cambrian Nopah Formation (Skelly, 1987) and was labeled the Glendale thrust by Axen and others (1990). If this thrust correlates with the Mormon thrust as suggested by Axen and others (1990), then it must cut several thousand feet downward in its footwall between localities A and E, and a greater distance upward between localities E and D. If tilts of strata of probable Tertiary age are removed from the autochthonous Cambrian through Devonian rocks east of locality E, the rocks are restored to subhorizontal post-thrusting attitudes. As such, they provide no insight into how the thrust cuts upward in lower plate rocks from localities E to D. In the following paragraphs we show that thrusts were modified during extension and that previously mapped short traces of regional thrusts farther south in the Mormon Mountains are best interpreted as transverse tear faults. These combined observations show that both location and geometry of regional thrusts in the southern Mormon Mountains are so poorly known that using them to constrain Tertiary deformation is risky at best.

In addition to the Mormon thrust fault, Axen and others (1990) mapped a structurally higher thrust that forms the floor for a stack of as many as 20 northwest-dipping imbricate sheets of Cambrian and Ordovician rock (labeled "thrust-imbricated" rocks on pl. 3). They used the orientation and position of this thrust-imbricated stack as a principal constraint on the magnitude of Tertiary dextral bending and shear in this area and suggested that this thrust was reactivated as a low-angle normal fault (labeled the "Petroglyph detachment fault (PD)" on pl. 3) during Tertiary extensional deformation. Major parts of the detachment fault are very gently inclined, remarkably planar, and subparallel to bedding in the lower plate (pl. 3 and fig. 4). Our work shows that rocks directly above the detachment fault were intensely deformed by younger-over-older faults (not shown on pl. 3), most of which merge into or terminate at the detachment fault but some of which cut the detachment fault. Based on our observations, the Petroglyph detachment represents a major subhorizontal strain boundary above which complex structural discordancies seem to imply intense upward-decreasing structural thinning of the previously thrust imbricated upper plate. Outcrop-scale fabrics in the fault zone indicate a principal kinematic axis that is oriented northwest-southeast, approximately the same as the tilt-direction azimuth of the overlying stack of thrust imbrications. On the basis of poorly developed striations, subordinate motion occurred orthogonal to that direction. Because the Petroglyph detachment fault accommodates very strong upper-plate thinning, we interpret all fabrics in the fault zone to be Neogene. Although the amount of Neogene horizontal translation on the detachment fault is not known, it is probably large enough to restrict or even preclude use of the current orientation and (or) position of the thrust-imbricated stack above it as a pre-extensional piercing point to constrain Tertiary retrodeformation.

Between the reactivated floor thrust fault (Petroglyph detachment) and the underlying Mormon thrust fault, 100–150 m of relatively little deformed Cambrian dolostone of the Banded Mountain Member of the Bonanza King Formation are preserved. Where these dolostone units are in tectonic contact with subthrust Mississippian rocks, they form sheets of exploded breccia similar to the breccia characteristically associated with hanging-wall blocks of low-angle Tertiary normal faults (Axen and others, 1990). We also observed very common pockets of highly indurated clastic sedimentary rock consisting of generally fine grained upper-plate dolostone debris that was deposited in solution cavities in lower plate limestone. Delicate bedding features in these cavity fillings suggest protracted sedimentation. The breccia and cavity fillings suggest that the Mormon thrust was also reactivated during extensional deformation and that large volumes of water flowed freely through the fault zone. The two reactivated thrusts are approximately parallel and are currently at an anomalously low structural (and topographic) position relative to autochthonous rocks that are strongly folded in the main ridge to the south that contains Moapa Peak. To explain the paradox that the subthrust fold at Moapa Peak stands much higher than and ends abruptly near the ramp-flat thrust assemblage (pls. 3 and 4), Axen and others (1990) proposed a combination of (1) a group of blind thrust faults that splay upward from beneath the Mormon thrust into the area beneath Moapa Peak, and (2) a footwall tear or ramp against which the footwall fold (Weiser syncline of Axen and others, 1990) terminates northward. Neither they nor we could identify the tear, and in the absence of subsurface data, the concept of blind thrusts remains speculative. We conclude that the low structural level north of Moapa Peak results from a combination of intense Neogene tectonic attenuation by thrust reactivation, brecciation, and intense normal faulting, and corresponding Neogene uplift of the Moapa Peak block. Some of the strong folding along Moapa Peak ridge may also be Neogene, as is discussed in the sections on "Folded and Faulted Tertiary Rocks in the Candy Peak Area" and "Summary and Discussion."

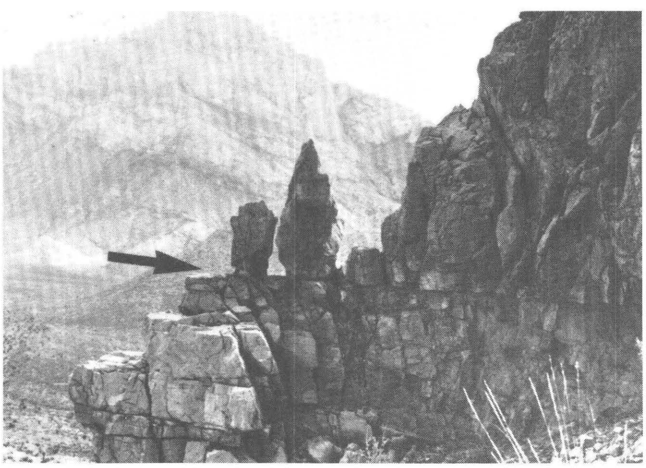


Figure 4. Typical planar, gently dipping aspect of the Petroglyph detachment fault (arrow), southern Mormon Mountains, Nevada, separating evenly bedded, little-deformed silty dolostone of the Middle and Upper Cambrian Banded Mountain Member of the Bonanza King Formation in the lower plate from dark, intensely deformed Cambrian dolostone in the upper plate. View toward the south.

HOMOCLINE AT MOAPA PEAK AND POSSIBLE BLIND THRUST FAULTS

In the North Muddy Mountains (fig. 1) south of the area of plate 4, a major north-striking, east-vergent, recumbent subthrust fold, the Weiser syncline, is the typical geometrically uniform, laterally continuous subthrust structure according to Longwell (1949) and Bohannon (1983a, b). Within the area of plate 4, the precipitous northeast-trending ridge that includes Moapa Peak and parallel satellite ridges to the south consist of steep upright to overturned Paleozoic and Mesozoic strata. These rocks form a well-exposed southeast-facing fold limb with large (>3 km) structural relief and mild to strong, but laterally discontinuous, internal folding and faulting (Skelly, 1987). Axen and others (1990) suggested that this large structure is Mesozoic in age and is either the extension of the subthrust Weiser syncline or is a zone of emerging blind thrust faults that is triangular in cross-sectional shape (a typical "triangle zone" of oil company parlance). They further suggested that the Moapa Peak ridge area was rotated clockwise by dextral shear in late Tertiary time. In this section, we describe our observations of the structure and its complex internal substructures and question its origin as a subthrust fold. Because we saw only one limb of this large southeast-facing structure, we refer to it simply as a homocline. We acknowledge that subsidiary structures within it make it different from a simple homocline.

The homocline contains internal folds that vary in size over four orders of magnitude. Most of these folds have narrow hinge zones and plunge uniformly southwest (fig. 5). They apparently formed by a combination of flexural slip and shear. Mapping by Skelly (1987) showed that large-scale folding within the homocline tends to be laterally discontinuous so that folding in cross sections differs markedly from place to place along the homocline (fig. 6; Skelly, 1987, pl. 2). Further evidence of along-strike contrast in strain distribution is that parts of the homocline are mainly upright, whereas adjacent on-strike

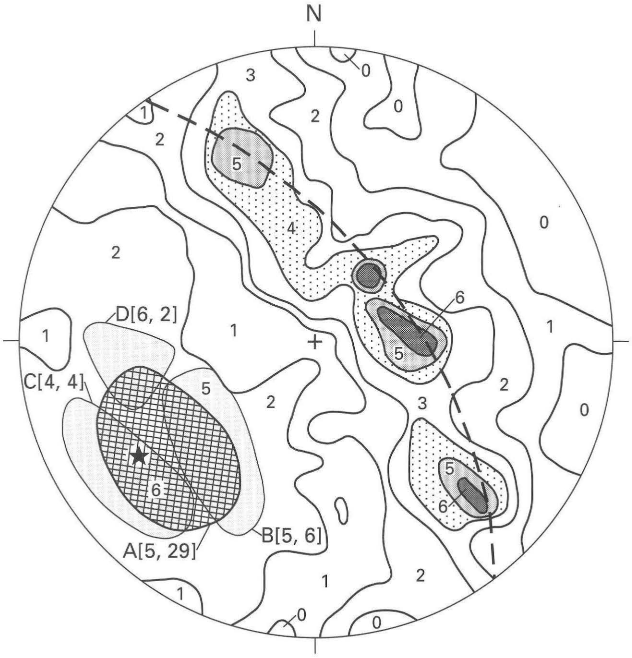


Figure 5. Schmidt-projection stereographic plot of frequency distributions of poles to bedding from the Moapa Peak ridge area, Mormon Mountains, Nevada, between localities C and H (pl. 4) showing the mean fold-axis position (star). Modified from Skelly (1987). Contours bound areas of 0, 1, 2, 3, 4, 5, and 6 percent density per 1 percent of the entire hemisphere based on 386 measurements of bedding attitudes. Only the three most dense areas are patterned, the darkest representing 6 percent. Line marks plane through high-density areas, and star is pole to that plane. The patterned areas surrounding the star are fields of fold axes determined in this study from four dispersed data-collection sites in the Moapa Peak ridge area (letters correspond to data-collection sites on pl. 4). Fold dimensions extend through four orders of magnitude. The numbers in brackets are, respectively, (1) the number of fold axes at each site determined by the stereographic analysis of systematically measured fold-limb orientations, and (2) the number of fold axes at each site that were measured directly at the outcrop. N, north.

EXPLANATION

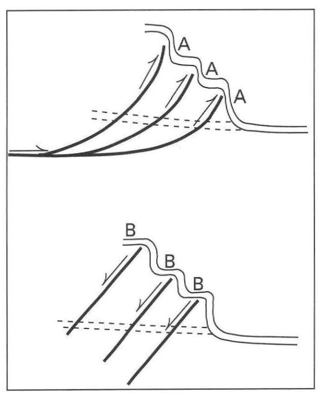
QTa	Alluvium (Quaternary and Tertiary)
TRc	Chinle Formation (Upper Triassic)
TRm	Moenkopi Formation (Middle? and Lower Triassic)
Pkt	Kaibab Limestone and Toroweap Formation (Lower Permian)
Pr	Redbeds (Lower Permian)
Pp	Pakoon Formation (Lower Permian)
PIPb	Bird Spring Formation (Lower Permian and Pennsylvanian)
	Monte Cristo Limestone (Upper and Lower Mississippian)
Mmyb	Yellowpine and Bullion Members
Mmy	Yellowpine Member
Mmb	Bullion Member
Mmad	Anchor and Dawn Members
Mma	Anchor Member
Mmd	Dawn Member
MDs	Sultan Limestone (Lower Mississippian to Middle Devonian)
MDsc	Crystal Pass Member
Dsi	Ironside Member
Oes	Ely Springs Dolomite (Upper Ordovician)
Op	Pogonip Group (Middle and Lower Ordovician)
Op2	Unit 2
Op1	Unit 1
€n	Nopah Formation (Upper Cambrian)
	Bonanza King Formation (Upper and Middle Cambrian)
€bb	Banded Mountain Member
€bb2	Unit 2, Banded Mountain Member

- - - - - Bedding traces

Contact—Dashed where inferred, dotted where projected above ground surface

Fault—Dashed where inferred. Barbs show relative motion. T, motion towards viewer; A, motion away from viewer

Thrust fault—Sawteeth on upper plate



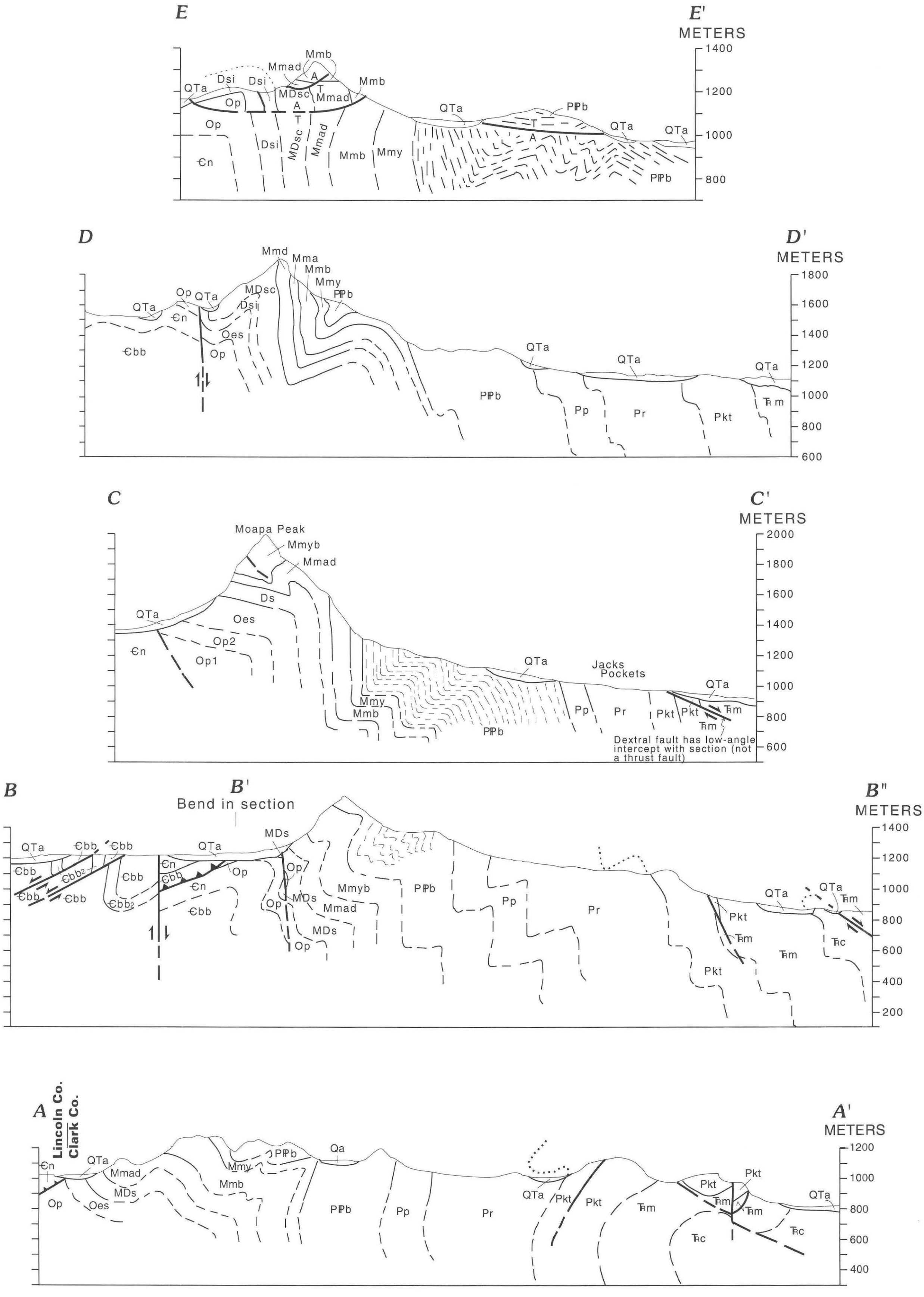
EXPLANATION

Contact

Fault—Barb shows relative motion

Position of bed before uplift and faulting

Figure 6 (facing column and facing page). Serial cross sections through the Moapa Peak ridge, Mormon Mountains, Nevada, showing the generalized form of internal folds and faults within the southeast-facing homocline. Locations of sections are shown on plate 4. The sections illustrate extreme disharmony along strike in the form of the overall structure (compare the mushroomlike form in section *A–A′* with the comparatively simple homocline in section *C–C′*). Parts of sections *B–B′* and *D–D′* are modified from Skelly (1987). All cross sections include some stratigraphic and structural details not shown on plate 4. The fold at Moapa Peak (section *C–C′*) is illustrated on figure 8. The diagram shows possible contrasting relationships between the internal kink-type folding and inferred shear either as thrust-related reverse faulting (upper sketch) or as gravitational collapse (lower sketch). The gravitational collapse model implies collapse during uplift. Stratigraphic thinning would be expected in steep limbs (A) if the folding is associated with reverse faulting, but in shallow limbs (B) if associated with gravitational collapse, consistent with field evidence.


E
E'
METERS
1400
1200
1000
800
QTa
Dsi
Op
Mmad
Mmb
MDsc
PPb
Ꞓn
Mmy
D
D'
METERS
1800
1600
1400
1200
1000
800
600
Mmd
Mma
Ꞓbb
Oes
Pp
Pr
Pkt
Ꞓn
C
C'
METERS
2000
Moapa Peak
Mmyb
Ds
Op2
Op1
Jacks Pockets
Dextral fault has low-angle intercept with section (not a thrust fault)
B
B'
B"
Bend in section
MDs
Ꞓbb2
A
A'
Lincoln Co.
Clark Co.
Qa
Oes
400
200

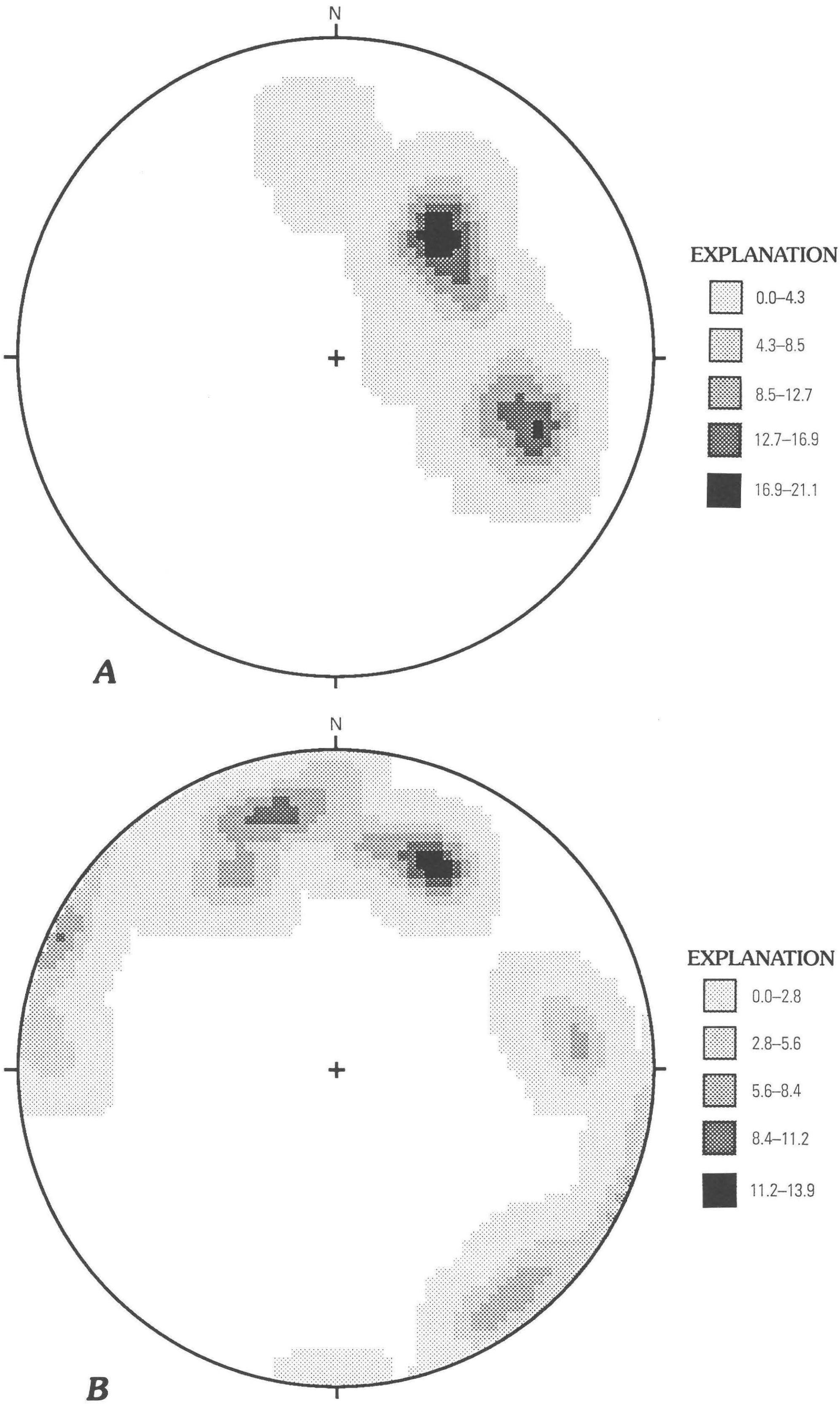


Figure 7. Schmidt-projection stereographic plots of frequency distributions for poles to fold limbs from the Moapa Peak ridge area, Mormon Mountains, Nevada. North-facing limbs of anticlinal folds (*A*, 31 limbs) generally dip less steeply than south-facing limbs (*B*, 32 limbs). Individual fold limbs are represented by as many as five poles to bedding. Values are in percent. N, north.

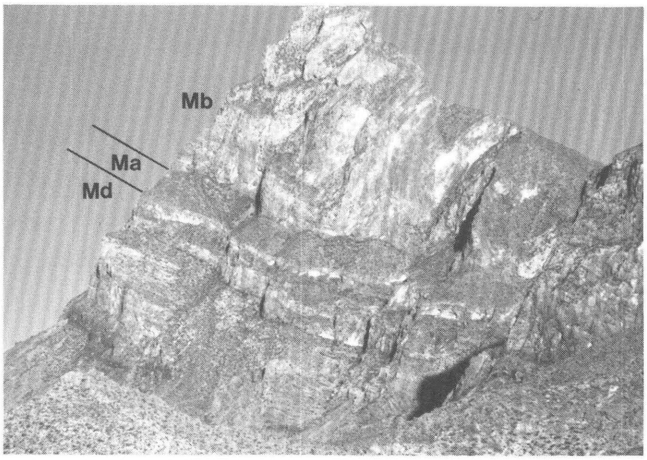


Figure 8. Moapa Peak, showing the form of a fold in Mississippian Monte Cristo Limestone, Mormon Mountains, Nevada. Md, Dawn Member; Ma, Anchor Member; Mb, Bullion Member. Note that the axial plane dips to the south (right), unlike most folds in the Moapa Peak ridge area that have axial planes that dip to the north. View to the east.

parts are mainly overturned (pl. 4). We found similar lateral contrasts among smaller scale folds. Good examples of along-strike lateral strain discontinuity are directly east and southeast of Moapa Peak where there are two conspicuous northeast-trending structural culminations—one that exposes Devonian rocks at locality A and another that exposes Mississippian rocks at locality B (pl. 4). These culminations are slightly en echelon and are separated by a northeast-elongate sag or syncline where they overlap. The culminations are high-amplitude, short-wavelength, short-trace-length folds that are similar in architecture to the homocline in which they reside. The along-strike strain variation tends to have been absorbed by transverse shear folds and transverse faults that show major strike-slip components and suggest that to some extent the folds are compartment folds.

The north-facing limbs of most subsidiary folds in the homocline have shallow dips and are more intensely sheared and thinned than the commonly steep to overturned south-facing limbs (fig. 7). The axial surfaces of these folds dip north and northwest. Many folds with these characteristics are shown in the cross sections on figure 6, which illustrates that the net effect of folding was to increase the breadth of the homocline by forming a cascade of steps and risers. Owing to their narrow hinge zones, they resemble kink folds. We did not see and Skelly (1987) did not report any examples of thrust-mode translations of the sharp hinges or of the steep to overturned limbs, as might be expected (Boyer and Mitra, 1988) if the folds absorbed thrust-related reverse-fault displacements as suggested by Axen and others (1990, fig. 9). Although the absence of such translations does not preclude a thrust-related origin, it allows for alternative interpretations, one of which is diagramed in figure 6.

A few subsidiary folds in the homocline have axial surfaces that dip to the southeast, suggesting some additional strain disharmony as, for example, at Moapa Peak (fig. 8; fig. 6, cross section *C–C′*). However, despite these indications of antivergent folding and along-strike strain discontinuity, either a single episode of folding or polyphase folding in coherent stress fields is suggested by the fact that only small differences in the orientation of fold axes (fig. 5) exist throughout most of the homocline.

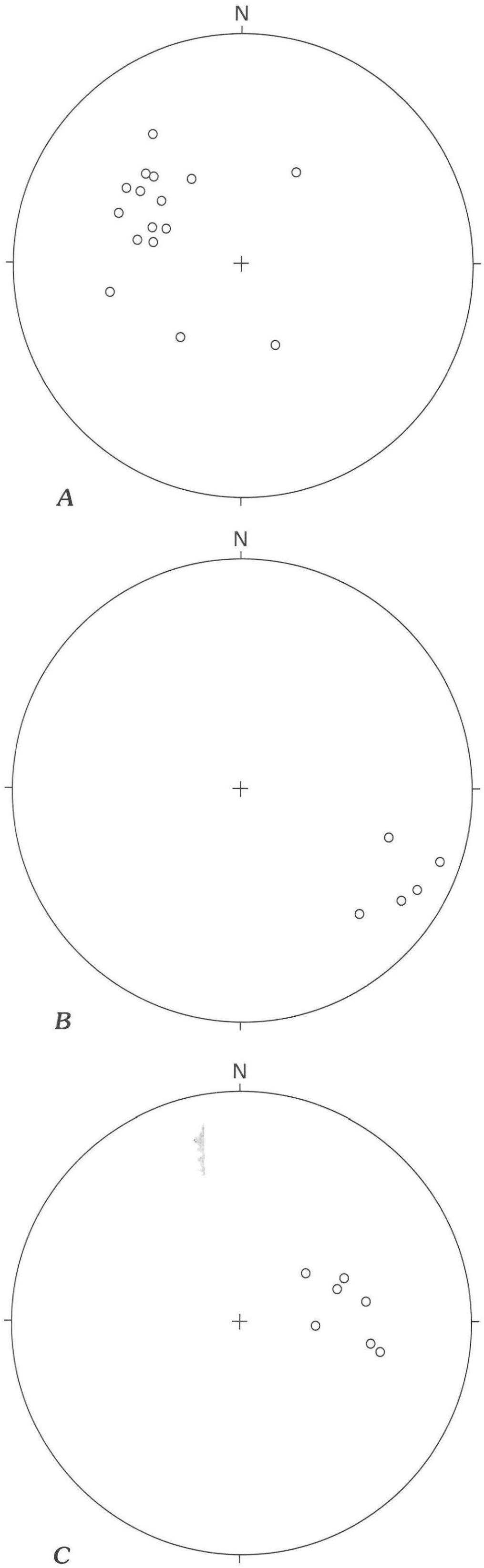
The northeast end of the Moapa Peak ridge contains structures that appear to be important for understanding the origin of the homocline. The area between localities G and H (pl. 4) consists of Ordovician through Mississippian rocks that dip southwest and are cut by several normal faults with down-to-the-northeast displacements. These rocks form part of a west-tilted domain (pl. 3) where the style of tilting and fault repetition suggests a Tertiary age for the deformation. As the fault-repeated rocks are traced southeastward along strike, they bend sharply downward on northeast-trending flexure axes into steep to overturned southeast dips that are conformable with and part of the main homocline. The downward bending is at different structural levels and at different places, depending on which normal-fault block it is in, and forms a cluster of sharp-axis homoclines. The sharp downward bending is seen at least as far south as locality I (pl. 4), where the rocks involved are Mississippian, and bedding-parallel shear planes in the steep south limb indicate up-to-the-north sinistral displacement. This displacement contrasts strongly with the dextral shear inferred for similarly oriented structures by Axen and others (1990). A north-trending cross section (fig. 6, cross section *E–E′*) shows the pattern of downward bending. This flexing does not seem likely to have formed as part of a subthrust fold coextensive with the Weiser syncline because (1) the traces of axial planes are 1–2 km southeast of the nearest known thrust; (2) the intervening rocks are upright (they would probably be subhorizontal except for Tertiary tilting); and (3) the observed folds are homoclinal or anticlinal, not synclinal. If the downward bending were actually associated with thrusting, the thrust faults would have to be blind and would have to be in the shallow subsurface as very steep reverse faults of the type illustrated by Axen and others (1990, fig. 9). Such an arrangement of structures would be dramatically different in style from the Weiser syncline, and any regional thrust structure that could produce the reverse faults in the proposed triangle zone would have to be much deeper than the Mormon-Glendale thrust. A genetic link between this folding at Moapa Peak and structurally higher thrust faults, such as has been documented for the Weiser syncline in the Muddy Mountains, is therefore highly unlikely. Instead, the homoclinal downward bending may be in some way related to the younger-on-older faults that displace the axial zones of the cluster of homoclines.

TRANSVERSE SHEAR ZONES AND ASSOCIATED DRAG FOLDS

The southwestern part of the homocline is modified by two major sets of transverse structures. Near locality J (pl. 4), conspicuous counterclockwise bending affects one of the major subsidiary folds in the homocline. This bending appears genetically linked to a variably west to southwest dipping complex transverse fault zone that can be traced discontinuously from near locality J to locality C (pl. 4). West to southwest dips of main strands of this fault zone range from 35° to 87°. Directly northeast of locality J, offsets of strata and fault-plane striae indicate normal-sinistral and sinistral displacement that is consistent with the sinistral-sense counterclockwise bending in the footwall. A complex synformal anticline north of locality J, mapped and illustrated by Skelly (1987, pl. 1, figs. 18, 19), may also be related to the transverse faulting and associated drag. Directly east of locality D and at localities C and K (pl. 4), striations on gently dipping fault and fracture surfaces have an average northwest-southeast azimuth (pl. 4, plots 5 and 6); kinematic indicators directly east of locality D show top-to-the-southeast (mainly normal and normal-sinistral) displacement. We interpret the displacements on these gently dipping planes as structurally coupled to the main sense of slip on the transverse fault system that passes through localities C, D, and beyond to the north. Because this major transverse structure does not affect rocks in the ridge between localities E and F (pl. 4), we infer that it bends sharply eastward near locality C and connects with a major fault-fold structure that produces conspicuous plan-view repetition of Permian and Triassic strata southwest of Jacks Pockets (between localities K and L, pl. 4). The generalized form of that structure is shown on figure 6 (cross section *A–A′*). Though faults are present, the structure results mainly from the steeply inclined rocks having been folded back on themselves in a synformal anticline and antiformal syncline pair, the axial planes of which dip about 14° southeast (Skelly, 1987). Here, as in the area directly to the west, the principal yielding sense is top-to-the-southeast (cross section *A–A′*, fig. 6). The axes of many minor folds associated with this deformation (group A, fig. 5) are coaxial with the homocline and its other internal folds, and this geometric consistency suggests a genetic association with the homocline. We suggest that the transverse shear zone and its associated steep-axis drag folding is coextensive with and kinematically and mechanically coupled to this top-to-the-southeast faulting and refolding. Together the structures form an arcuate structural zone along which the main homocline is sinistrally offset (pl. 4).

A second major transverse fault-fold structural pair that cuts and offsets the homocline is directly northeast of Candy Peak (pl. 4) where a buried northwest-striking fault must be present below the alluvium between closely juxtaposed Cambrian and Mesozoic (units Js and T̄Rc, pl. 4) rocks (Skelly, 1987). Autochthonous basal conglomerate and sandstone of the Upper Triassic Chinle Formation and the overlying Lower Jurassic Moenave Formation are severely overturned toward the northeast and strike toward the northwest, probably as a result of counterclockwise rotation relative to the northeast-striking homocline (locality N, pl. 4). Allochthonous Cambrian rocks southwest of the buried fault form a thrust-imbricated stack that is folded into the west-plunging Candy Peak syncline (pl. 4). This structure is an open syncline on the west where the axis plunges about 30°, the wavelength is greater than 2 km, and the limb dips are typically 40°–50° (Skelly, 1987). It closes eastward, and in the easternmost exposures strata along its axis dip 37°–75° W. where they are unconformably overlain by Tertiary limestone that dips gently east (pl. 4). If the Tertiary limestone is restored to horizontal, the average western plunge of the syncline at the unconformity is about 70° (plot *B*, fig. 9). Thus, the syncline closes and its axis steepens closer to the buried northwest-striking fault, and these relations suggest to us that the two structures are related. The Cambrian rocks in the south limb of the syncline dip about 50° northwest. They are structurally coextensive with moderately northwest- to west-dipping strata that extend at least 8 km southward to Interstate 15 (pl. 4). In that structural context, it is the strike of the rocks in the north limb of the Candy Peak syncline that is anomalous and suggests counterclockwise rotation adjacent to the buried fault. As with the Mesozoic rocks northeast of the buried fault, the change in strike near the fault is consistent with sinistral drag. A dextral sense of drag of the Mesozoic rocks (Axen and others, 1990) is precluded. The structures are similar to those along the other transverse fault near locality J (pl. 4) and are best interpreted as transverse tear faults that developed late in the history of formation of the homocline. They and the main part of the homocline formed prior to deposition of the Tertiary limestone. Both transverse structures were mapped by Axen and others (1990) as the Glendale thrust fault, and tentatively correlated with the Mormon thrust fault. We note that the only remaining surface trace of the Glendale thrust fault north of Interstate 15 is in a small exposure near that highway (pl. 4) and that the nearest exposure of the Mormon thrust fault is 20 km to the north. These far-separated limited exposures of thrust faults are inadequate for controlling palinspastic reconstructions of Cenozoic deformation.

To summarize, the southwestern part of the homocline is modified by a complex mixture of transverse faults and associated steep-axis drag folds and by physically connected(?) low-angle faults and associated shallow-axis drag folds. These structures probably formed relatively late during development of the homocline. It is not known whether they represent tears in the Mesozoic system of compressional structures or whether they are simply a zone of structural accommodation for along-strike contrasts in strain within the homocline. In either case, the homocline cannot



be interpreted as the limb of a giant subthrust fold. The cascade folds that characterize Moapa Peak ridge may have formed within a triangle zone in which large-magnitude reverse faulting was absorbed (as speculated by Axen and others), but we believe that the observed thinning of gently inclined north limbs argues against this model and in favor of normal-fault related folding (cross section *C–C′*, fig. 6). Our studies in the southern Mormon Mountains show most of all that so little is known of the location or geometry of regional thrust faults and related structures that they generally cannot be used as piercing points to constrain the sense or magnitude of Cenozoic extensional deformation.

STRUCTURAL SETTING RELATIVE TO CENOZOIC FEATURES

The southern Mormon Mountains are well within the Basin and Range province (fig. 2) but are within an east-west corridor that generally lacks exposures of Tertiary volcanic and plutonic rocks (Anderson, 1981). They form a structural bridge between the Miocene detachment faults and domelike uplift of the central Mormon Mountains and the deep Neogene basins along the Virgin River to the south (Grow and others, 1990). The Mormon Peak detachment fault has an inferred minimum displacement of 8 km but a potential displacement of more than 20 km based on palinspastic reconstruction (Axen and others, 1990). It is interpreted as the oldest and highest of three major detachment faults in the central Mormon Mountains (pl. 3), lying above the Tule Springs and Castle Cliff detachments of Axen and others (1990). Upper-plate rocks consist chiefly of pieces of the former Mormon thrust fault, preserved as

Figure 9 (facing column). Stereographic plots of poles to bedding in pre-Tertiary units near Candy Peak, Mormon Mountains, Nevada, corrected for Tertiary tilting. *A*, Poles to bedding in Navajo Sandstone beneath south-dipping Tertiary limestone at locality P (pl. 4) east of Candy Peak, showing the result of 30°–54°corrections for southern tilt. Some measured attitudes at the outcrop indicate overturned strata but all correct to top-side-up attitudes, representing pre-Horse Spring age tilting. *B*, Poles to bedding in the Nopah Formation midway between localities P and M (pl. 4) along the axis of the Candy Peak syncline, showing the result of 6°–37° corrections for eastern tilt. *C*, Poles to bedding in overturned Mesozoic strata northeast of Candy Peak at locality N (pl. 4), showing the result of a uniform correction for 20° eastern tilt (based on the average attitude of Tertiary limestone midway between localities P and M (pl. 4); all attitudes still show overturned strata following the tilt corrections. The overturning predates the Tertiary tilting and is believed to have resulted from structural crowding and sinistral-sense (counterclockwise) bending of beds that were initially upright and had moderate southeast dips similar to the corrected attitudes in *A*. N, north.

scattered scablike erosional remnants on top of a remarkably regular detachment-fault surface. This surface defines a structural dome that must be either contemporary with or younger than movement on the detachment fault (Wernicke and others, 1985). This domelike structure is reflected in both the physiography and the Bouguer gravity field of the main part of the Mormon Mountains (Shawe and others, 1988). Reynolds and Lister (1990) and Asmeron and others (1990) suggested that the doming of detachment faults can result from magmatic inflation. Gans (1987) emphasized the general association between magmatism and extension in the Basin and Range province. Although the Mormon Mountains are in a generally amagmatic corridor (Anderson, 1981), geologic and geophysical data suggest a possible buried Tertiary pluton beneath the dome (Shawe and others, 1988).

We confined most of our studies to the southern part of the Mormon Mountains on the south flank of the dome and south of the mapped extent of relics of allochthonous rocks above the Mormon Peak detachment fault. This area is presumed to be structurally below that detachment and within rocks that are mostly autochthonous with respect to the Mormon thrust fault. The Tule Springs detachment fault, the middle of the three detachment faults, was interpreted by Axen and others (1990) to extend at least as far south as the Horse Spring fault (pl. 3), which they believe is genetically and kinematically linked to the Tule Springs detachment fault. Only the Castle Cliff fault, the youngest and lowest of the three detachments, has been interpreted to extend beneath all of the southern part of the Mormon Mountains. We question these interpretations but defer discussion of these and other long-distance fault projections to the "Summary and Discussion" section of the report.

STRUCTURES OF KNOWN OR SUSPECTED CENOZOIC AGE

Our initial purpose in studying the Mormon-East Mormon Mountains area was to improve the understanding of the major dextral-slip Moapa Peak shear zone (first reported by Olmore, 1971, and recently restudied by Axen and others, 1990) and its relationship to (1) the reported system of stacked detachment faults to the north, and (2) Neogene development of the basin to the south that Axen and others (1990) referred to as the Mormon Mesa basin. The results of fault-slip studies reported by Michel-Noel (1988) and our early field studies led us to question the existence of the Moapa Peak shear zone and to focus our study on its major reported components. This section of the report describes and discusses Cenozoic structures that were interpreted by Axen and others (1990) as critical elements of the oroclinal bend and Moapa Peak shear zone, and dextral displacement that they ascribed to but which we do not recognize. The structures include (1) folded and faulted Tertiary strata in the Candy Peak area, (2) strike-slip faults in the Candy Peak area, and (3) the Horse Spring fault and associated structures.

FOLDED AND FAULTED TERTIARY ROCKS IN THE CANDY PEAK AREA

The Candy Peak area (pl. 4) contains the only known Tertiary rocks in the southern Mormon Mountains. These rocks are above autochthonous Mesozoic strata and allochthonous lower Paleozoic strata, and thus are an important constraint on the relative magnitude and style of pre-Tertiary and Tertiary deformation. Contact relationships between the Tertiary and older rocks are complex, however, and lead to some ambiguities regarding control data for palinspastic restorations. We describe the Tertiary rocks and their structures and conclude that the structures reflect Neogene regional contractional deformation.

Rocks that probably correlate with the Miocene Horse Spring Formation (Bohannon, 1983a; Skelly, 1987) are widely exposed east and southeast of Candy Peak (pl. 4). The poorly exposed base consists of a few meters to a few tens of meters of coarse conglomerate that contains angular carbonate and sandstone clasts in a red sandy matrix. The conglomerate is overlain by as much as 500 m of well-exposed, predominantly fine-grained, wavy- to flat-bedded, laminated to indistinctly bedded lacustrine limestone and algal limestone that locally contains layers with conspicuous chert nodules. These limestone units are folded on east-trending, shallow-plunging axes for at least 5 km (pl. 4) south of the basal contact (Skelly, 1987) (pl. 4 and fig. 10). Folds tend to be more open in the south than in the north where some are overturned (fig. 10*A*) and where disharmonic folding is common (fig. 11). Most folds are short, discontinuous, or arranged in slightly en echelon fashion. Where short or discontinuous, they commonly terminate against steep north-striking faults. We interpret the folds as compartment folds between the short tear faults that serve as negative stretching faults (Means, 1989) to accommodate for the shortening strain (fig. 12). The cross-sectional form of the folds (illustrated in east-facing views on figs. 10, 11, and 12) shows the well-documented disharmonic nature of the structure and the overall aspect of a south-facing homocline. Thus, the Tertiary rocks south of Candy Peak show features that are similar in many ways to the northern part of the larger homocline in Paleozoic-Mesozoic rocks at the Moapa Peak-Jacks Pockets area (compare fig. 11 with the northern part of cross section *A–A′*, fig. 6). Cambrian rocks are folded into the core of some folds (fig. 10*B*).

Most of the contact between Tertiary limestone and thrust-imbricated allochthonous Cambrian dolostone (Skelly, 1987) is either a steep, sharp fault or a moderately to gently dipping zone marked by tectonic breccia that is a few meters thick and has a conspicuous subhorizontal to gently inclined fabric that superficially resembles

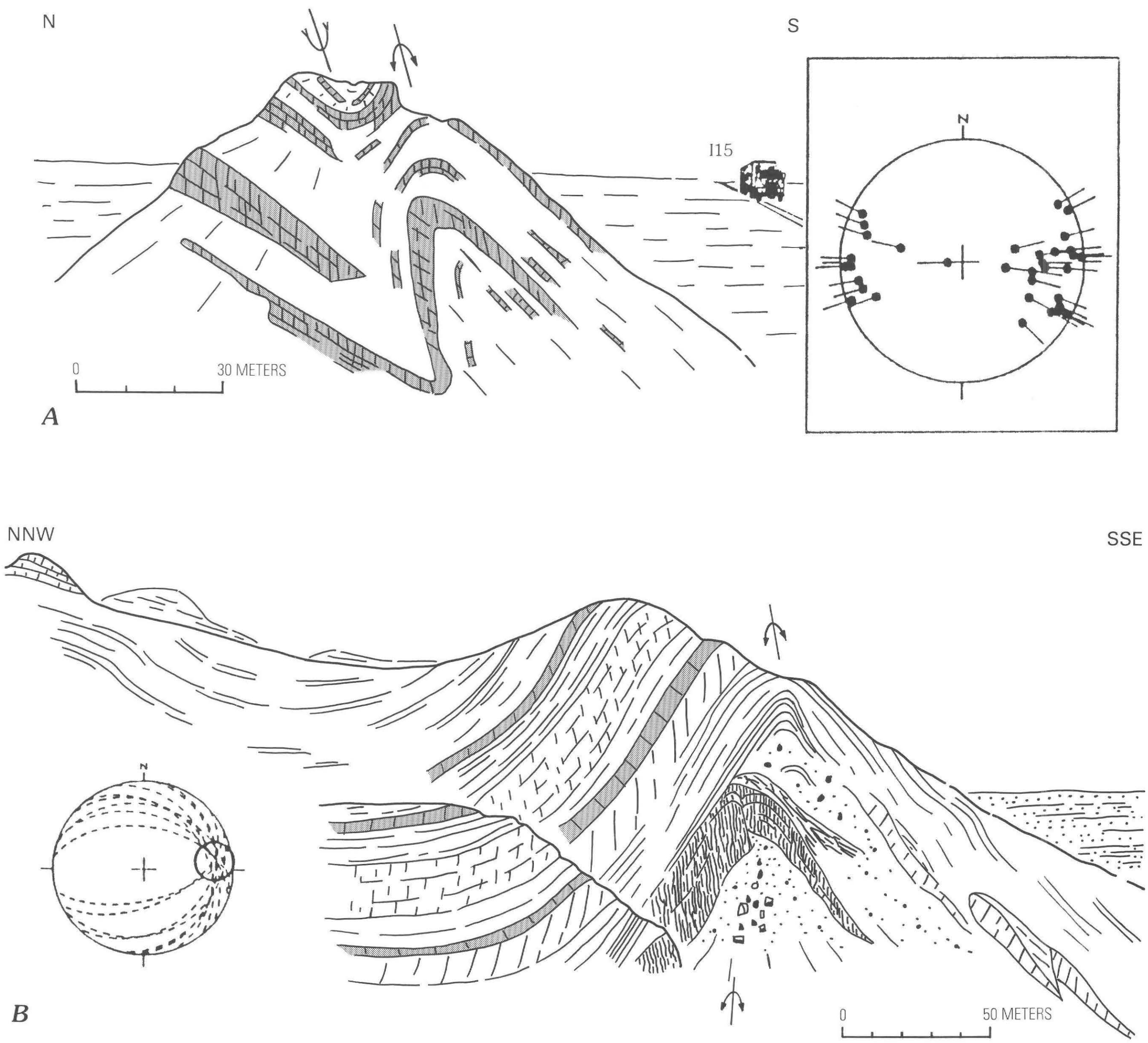


Figure 10. Field sketches of folds in Tertiary limestone in the Candy Peak area, Mormon Mountains, Nevada. From Michel-Noel (1988). *A*, View toward the east from a point directly south of locality P (pl. 4) shows overturned beds and structural disharmony; inset shows a stereographic plot of representative data for fold axes. N, north. *B*, View toward the east (1 km east of locality M, pl. 4) shows Cambrian dolostone (close vertical ruling) folded into the core of a Tertiary anticline; inset shows a stereographic plot of fold-limb data.

sedimentary rock stratification. This breccia is widely exposed, and breccia detritus is also found in places where the contact is not exposed. Widespread dislocation at the contact is therefore indicated, and thus the base of the Tertiary rocks and angular discordances across it cannot generally be used for palinspastic restorations. Critical exceptions where the depositional base of the Tertiary is intact are present, however, along the axis of the Candy Peak syncline and in the north slope of an east-trending ridge east of Candy Peak (locality P, pl. 4). In several small exposures at the latter locality, the Lower Jurassic Aztec Sandstone is steeply overturned to the north and is unconformably overlain by basal Tertiary conglomerate that dips 30°–50° to the south. Removal of the Tertiary dip restores the Aztec Sandstone to upright attitudes that are quite variable (fig. 9*A*), but much of the variation probably results from large-scale crossbedding that is typical of the Aztec but not recognizable in the small exposures. The predominance of restored northeast strikes (fig. 9*A*) suggests that these Jurassic strata belong to the same structural domain as the northeast-striking homocline between Moapa Peak and Jacks Pockets (see the section on "Homocline at Moapa Peak and possible blind thrust faults") and that they have not undergone the counterclockwise sinistral drag that affected the Mesozoic strata 1 km away to the northwest (locality N, pl. 4). We believe that the relationships at

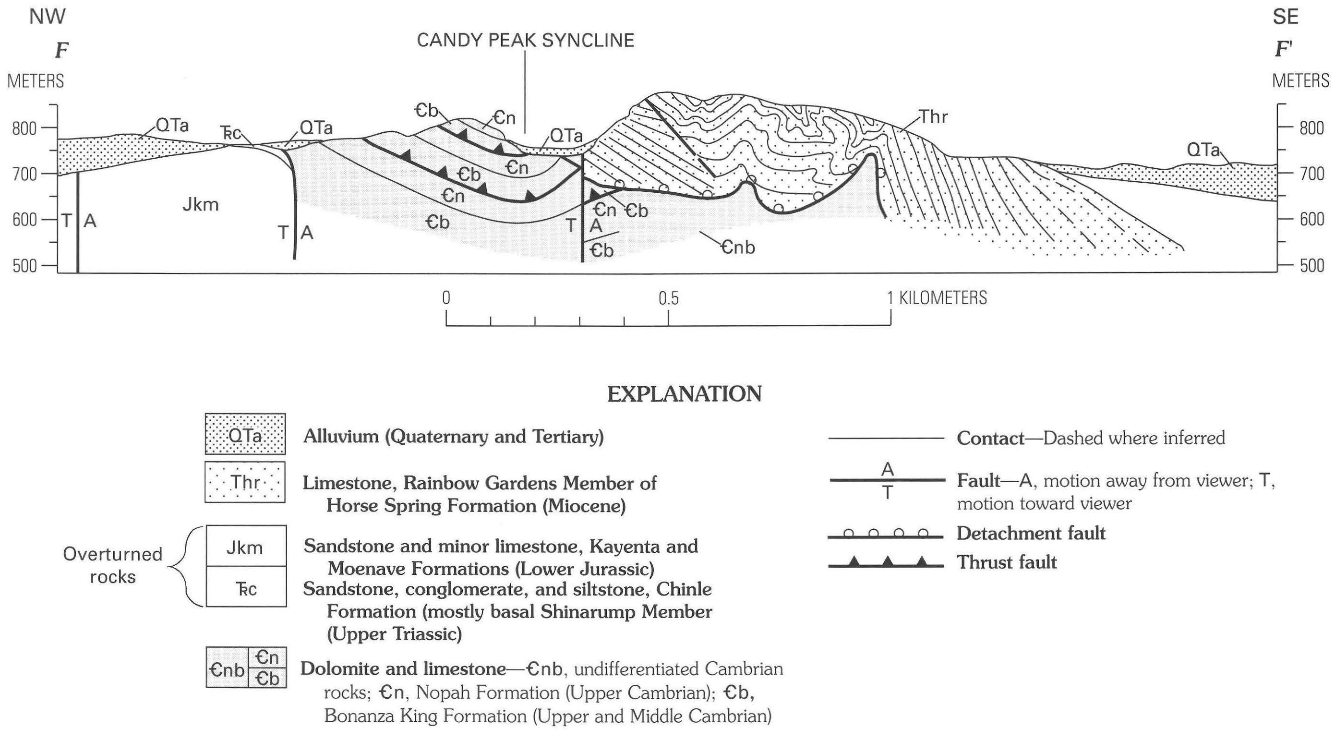


Figure 11. Cross section showing the form of the Candy Peak syncline in Cambrian rocks and adjacent folds in limestone beds of the Miocene Horse Spring Formation, Mormon Mountains, Nevada. Note that the thrust faults are folded (Skelly, 1987). Line of cross section is *F–F'* on plate 4. The Tertiary limestone, estimated to be at least 500 m thick, is truncated by a tectonic contact (detachment fault) from the underlying Cambrian dolostone units. Form lines in Tertiary limestone units show bedding traces that are tightly controlled by many attitude measurements along the section line and by extrapolation from field photographs. Note overall similarity of the folded limestone form with that of the Mississippian rocks in cross section *A–A'*(fig. 6).

locality P (pl. 4) involving the Tertiary unconformity indicate that a significant part of overturning of strata in the Aztec Sandstone, which is similar to that in the Moapa Peak homocline, is clearly Tertiary in age.

Axen and others (1990) interpreted the Tertiary folding in the Candy Peak area to be the result of second-order structural crowding in the axial part of a major dextrally coupled Neogene oroclinal bend (described below). However, in keeping with the interpretation of Skelly (1987), we interpreted the Tertiary folds as evidence of north-south shortening that is part of a regional pattern of extension-related north-south contractional strain (Anderson, 1990). Rocks of similar age in central Utah (Anderson and Barnhard, 1987) show analogous evidence.

Strong similarities in the size, shape, and distribution of small folds were noted in Tertiary strata east and southeast of Candy Peak and in structures of less than mapping scale in Triassic strata between localities E and L and Pennsylvanian strata east of locality J (pl. 4). As emphasized above, the overall cross sectional shape of the Moapa Peak homocline and the structure in Tertiary rocks east of Candy Peak are quite similar, possibly indicating common genesis. If only half of the 30°–50° of Neogene south tilting in the ridge at locality P (pl. 4) is characteristic of the main homocline, the associated uplift would explain the anomalously high structural position of that part of the autochthon relative to the adjacent allochthon. In the "Summary and Discussion" section, we contrast the model of Axen and others (1990) with our alternative interpretation involving Tertiary deformation for at least part of the structure in the homocline.

STRIKE-SLIP FAULTS IN THE CANDY PEAK AREA

Axen and others (1990) suggested that a northeast- to east-striking dextral-slip fault forms the southern boundary of the Moapa Peak shear zone and projects toward the alluvial gap directly north of Candy Peak (midway between localities M and F, pl. 4). North- to northeast-striking faults investigated in areas north and south of the alluvial gap are sinistral (pl. 4, plots 3 and 4) and resemble the widely distributed sinistral-slip faults of Tertiary age in the region. Those faults directly south of the gap displace the north limb of the Candy Peak syncline southward and thus are younger than the syncline. A northeast-striking map-scale fault that cuts Tertiary limestone directly southeast of Candy Peak clearly has sinistral slip, based on drag

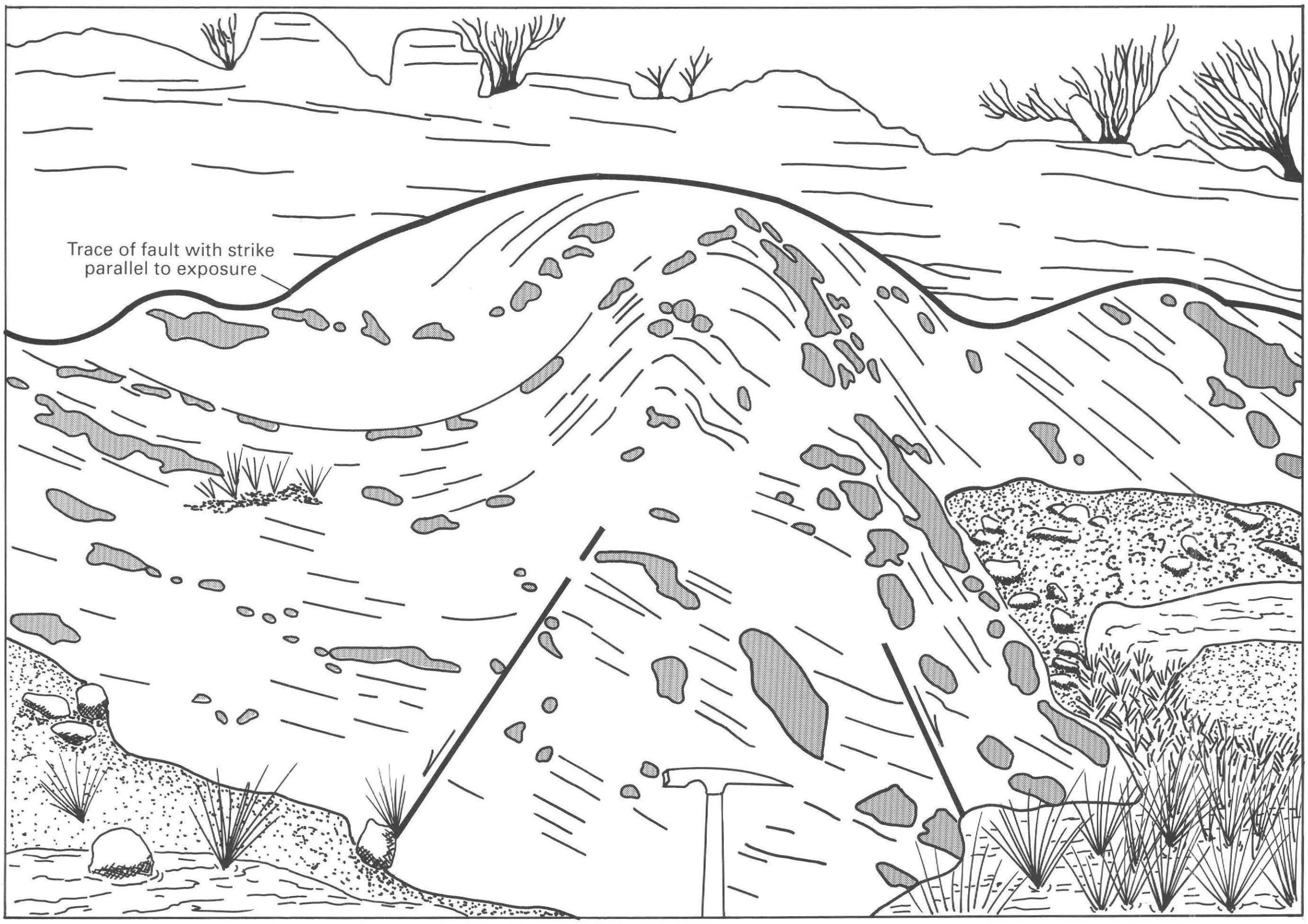


Figure 12. Sketch from a photograph of deformed upper Tertiary limestone showing traces of bedding and nodules of chert (dark). View to the east from a point about 2.5 km south of locality M (pl. 4). Heavy lines are faults; barbs show direction of movement. The small east-trending fold (foreground) terminates against a high-angle north-striking accommodation fault, the trace of which is approximately parallel to the photograph. North-striking faults in the Candy Peak area vary widely in size, but all accommodate unevenly distributed north-south constrictional strain similar to the accommodation interpreted for some of the largest faults in the region.

of strata and striations (pl. 4, plot 3). Thus, the proposal by Axen and others (1990) that a nearby parallel Tertiary fault buried beneath the alluvium has had major dextral slip would be kinematically incompatible and highly unlikely. Also, any significant amount of dextral slip on such a fault north of Candy Peak would worsen an existing apparent offset between overturned Permian strata of the homocline and equivalent overturned strata interpreted by Axen and others (1990) as a once-continuous structure south of Interstate 15 (fig. 13). If a northeast-striking fault lies buried beneath the gap, we would expect it to have sinistral offset rather than dextral and to be younger than the northwest-striking sinistral tear faults and associated drag structures described above.

To summarize, in the Candy Peak-Moapa Peak area there is much uncertainty about the location and geometry of thrust faults and the age and tectonic significance of major and minor folds. These uncertainties preclude using thrusts as reliable factors in palinspastic reconstructions of Cenozoic deformation. The uncertainties, together with similarities in the strain field between areas of Tertiary and pre-Tertiary rocks allows for interpretation of many of the folds and strike-slip faults in pre-Tertiary rocks as structures formed by constrictional forces coeval with and oriented orthogonal to Neogene extensional forces. The indicated constrictional strain has many features in common with systems of Neogene strike-slip faults and folds that are widely distributed between Las Vegas and central Utah.

HORSE SPRING FAULT AND ASSOCIATED STRUCTURES

The area surrounding the Horse Spring fault (pl. 3) contains autochthonous and allocthonous rocks of the thrust system. The autochthonous rocks range from Proterozoic through Pennsylvanian and were little deformed and essentially horizontal prior to late Cenozoic tilting during extensional deformation (Wernicke and others, 1985).

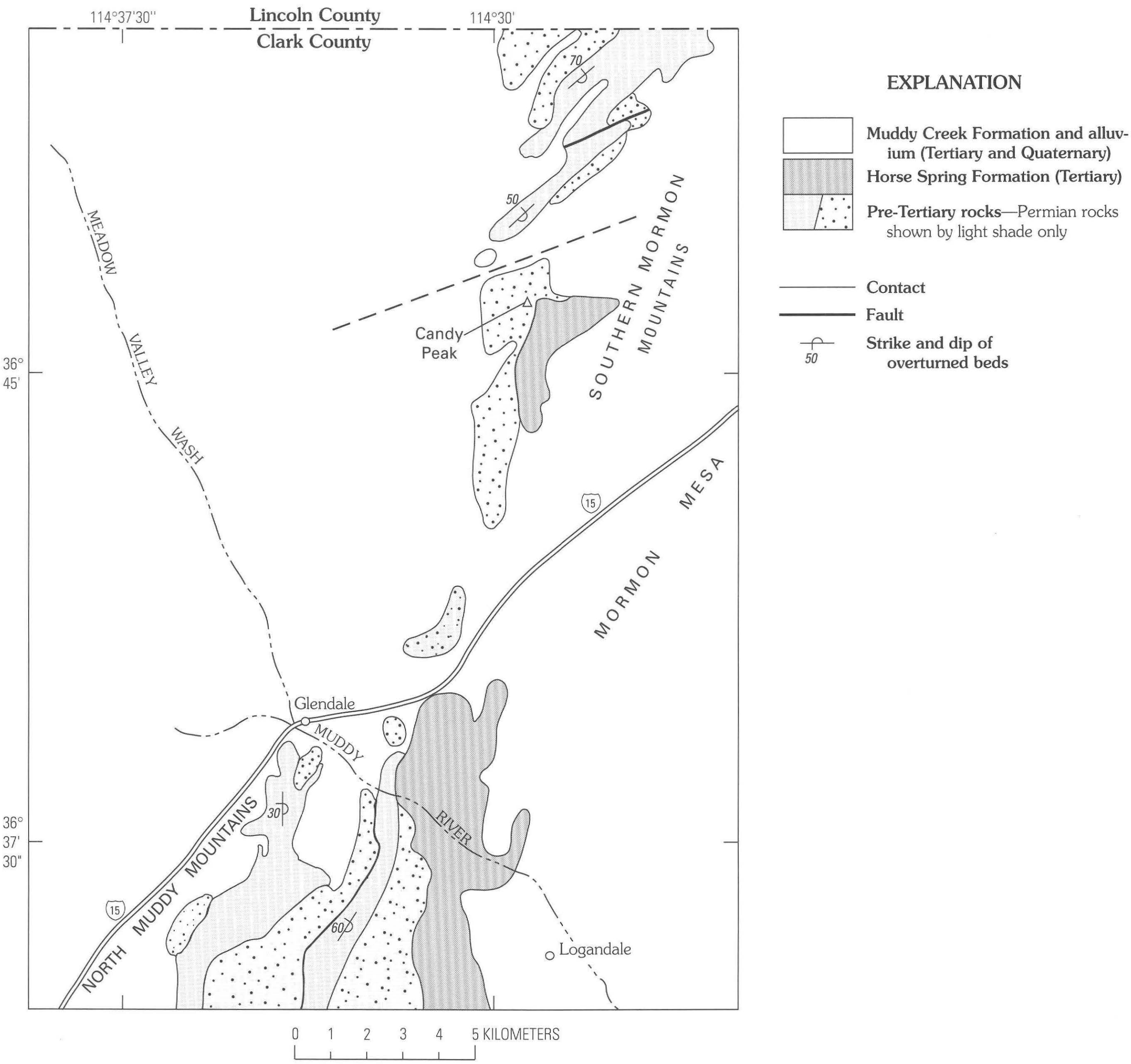


Figure 13. Sketch map of the North Muddy Mountains and southern Mormon Mountains, Nevada, showing distribution of overturned Permian rocks in relation to the alluvial gap, north of Candy Peak, which was proposed by Axen and others (1990) as the area into which the dextral-slip Moapa Peak shear zone projected (heavy dashed line). If the structurally similar Permian sections are segments of a once-continuous outcrop band, then they would appear to be offset in a sinistral sense. Restoration of any significant dextral displacement along the trend proposed by Axen and others (1990) would only enlarge the current misalignment of the Permian rocks.

The Horse Spring fault consists of two main segments that intersect near Wiregrass Spring (pl. 3) where the fault makes an approximate 115° bend. The northern segment strikes about north and is part of a large structural domain of east-dipping strata and down-to-the-west faulting that Wernicke and others (1985) denoted "the east imbricate fault zone." We refer to it as the east-tilted domain (pl. 3), and it is postulated to be above the Tule Springs detachment fault by Wernicke and others (1985). The southern segment of the Horse Spring fault is a complex zone that strikes east-southeast across the local structural grain, and, throughout much of its length, it separates the east-tilted domain from a domain of west-dipping strata and down-to-the-east faulting that we call the west-tilted domain (pl. 3). Both domains include rocks of the thrust allochthon and autochthon, though in widely differing proportions.

Because Tertiary rocks are absent from both domains, the distribution and magnitude of Tertiary tilting must be assumed from repeat patterns of strata that are normally associated with Tertiary extensional deformation. Because the transverse segment of the Horse Spring fault coordinated reversals in both tilt of strata and fault displacement, we call it an accommodation zone (Bosworth and others, 1986; Rosendahl, 1987; Faulds and others, 1990). We discuss below selected aspects of the northern fault segment and associated faults, then the accommodation-zone segment.

Directly north of Wiregrass Spring in the east-tilted domain, the west-northwest-dipping Horse Spring fault has a normal separation of about 3 km. Within 6 km to the north, the separation is an order of magnitude less and is distributed on several small faults (pl. 3). No transverse faults have been mapped that allow for transfer of the large displacement to other structures. The mapped relationships indicate strong lateral strain inhomogeniety. Hanging-wall rocks of the Horse Spring fault dip east 10°–20°, whereas footwall rocks dip more steeply at 20°–50° eastward. Wernicke and others (1985) correctly interpreted the dip discrepancy as evidence for a convex-upward shape of the Horse Spring fault as shown on plate 2*B*.

East of Hackberry Spring (pl. 3), also in the east-tilted domain, the unnamed fault (UF, pl. 3) is another large-displacement southwest-dipping normal fault whose footwall strata dip conspicuously steeper (about 50° E.) and are less internally deformed than gentle but variably inclined hanging-wall strata. The hanging wall also includes a gently east dipping erosional remnant of the Mormon thrust-fault system (pl. 3), which, because it is in a nonramping position, provides further evidence of mild post-thrust tilting of the hanging-wall rocks. The mapped geologic relationships strongly suggest a convex-upward shape for the unnamed fault; as with the convex-upward northern segment of the Horse Spring fault, dip separation is greatest near the accommodation zone (about 2 km) and decreases abruptly to the north and separates into several small-displacement faults. Thus, both major west-dipping, convex-upward faults in the east-tilted domain show strong lateral strain inhomogeneity.

The kinematic axis for extensional deformation in the east-tilted domain was probably oriented west-southwest (Wernicke and others, 1985). The large-separation parts of the Horse Spring fault and the unnamed convex-upward fault are crudely en echelon, and thus the apparent extensional strain associated with them, though probably of similar azimuth, is not cumulative. That is, a hypothetical northeast-southwest cross section drawn parallel to the kinematic axis and through the maximum-displacement part of the Horse Spring fault would intersect the unnamed fault where its displacement is minimal. We recognize this fault geometry and strong strain inhomogeneity as common features in this part of the Basin and Range province and conclude that they have profound implications regarding the distribution and magnitude of extensional strain as emphasized in following sections of this report. Wernicke and others (1985) characterized the east-tilted domain as a zone of domino-style extensional faulting that developed in the upper plate of the late Cenozoic Tule Springs detachment fault. Our analysis of the kinematics and the geometry of faulting indicate conditions that were far more complex than this simple characterization. As we show in following sections of this report, the structures separating the southern Mormon Mountains and East Mormon Mountains do not include gently dipping planar detachment faults extending through the area that are analogous to the proposed Tule Springs detachment fault, which should project into that area from the north. Instead, the structures have large components of strike slip, laterally variable displacement, and complex shapes similar to the major structures that transfer their displacement into the presumed Tule Springs detachment fault. The simple model of the east-tilted domain as a passive allochthon above a detachment fault fails to account for real three-dimensional relationships among faults and fault blocks. Thus, we conclude that the relationship of this deformation to any regional detachment fault extending through the area is suspect. Specifically, we do not recognize the Tule Springs detachment fault in the part of the East Mormon Mountains we studied (vicinity of locality Y, cross section *A–A′*, pl. 2*C*).

In order to understand the distribution of extensional deformation between the central and southern Mormon Mountains, it is important to determine whether the transverse segment of the Horse Spring fault is the northern boundary of a major zone of dextral shear that accommodates subregional contrasts in extensional strain as suggested by Axen and others (1990), or whether the fault is a structure that coordinates and accommodates local strain variations as we claim. To a large extent, the argument for subregional strain accommodation hinges on the presence or absence of major dextral displacement on the fault, and the argument for local accommodation hinges in part on whether structural tilts south of the fault are late Tertiary in age.

Between Wiregrass Spring and Hackberry Spring (pl. 3), the transverse segment of the Horse Spring fault strikes approximately east and dips 45°–75° south, and its footwall contains the thrust autochthon of Proterozoic crystalline rocks and overlying Cambrian clastic rocks. Carbonate rocks in the hanging wall directly to the south are extensively brecciated; most strike at a high angle to the zone and dip steeply southwest. There is no indication of strong dextral-sense bending or uniform zone-parallel dextral shear in these rocks on either side of the fault. Striated fractures are sparse, but a few striae were measured (pl. 3) mainly from microfaults in Cambrian sandstone in the footwall. The striae orientations are consistent with predominantly normal and normal dextral slip, and such displacement would be expected to accommodate the uplift and east tilting of the footwall block.

Directly northeast of locality B (pl. 3), the Horse Spring fault divides into two main strands that envelop a fault-parallel band of strongly deformed Mississippian rocks that are part of the thrust autochthon. The band of disruption within the fault zone can be traced east-southeast to a position north of locality D (pl. 3), east of which it is covered by alluvium. As this band is approached from either north or south, a progression from relatively broad, uniformly tilted blocks into narrow, complexly faulted and nonuniformly tilted blocks is apparent. Between the two main strands of the Horse Spring fault, this deformation becomes quasipenetrative and is shown by intense stratigraphic attenuation of units and brittle smearing of contact relationships (fig. 14). Bedding inclination generally increases as the fault spacing decreases, and the faults consistently place younger or structurally higher rocks on older or structurally lower rocks. This transverse part of the Horse Spring fault is further complicated by interplay or competition between faults of opposed displacement sense that originate in the opposing tilt domains of plate 3.

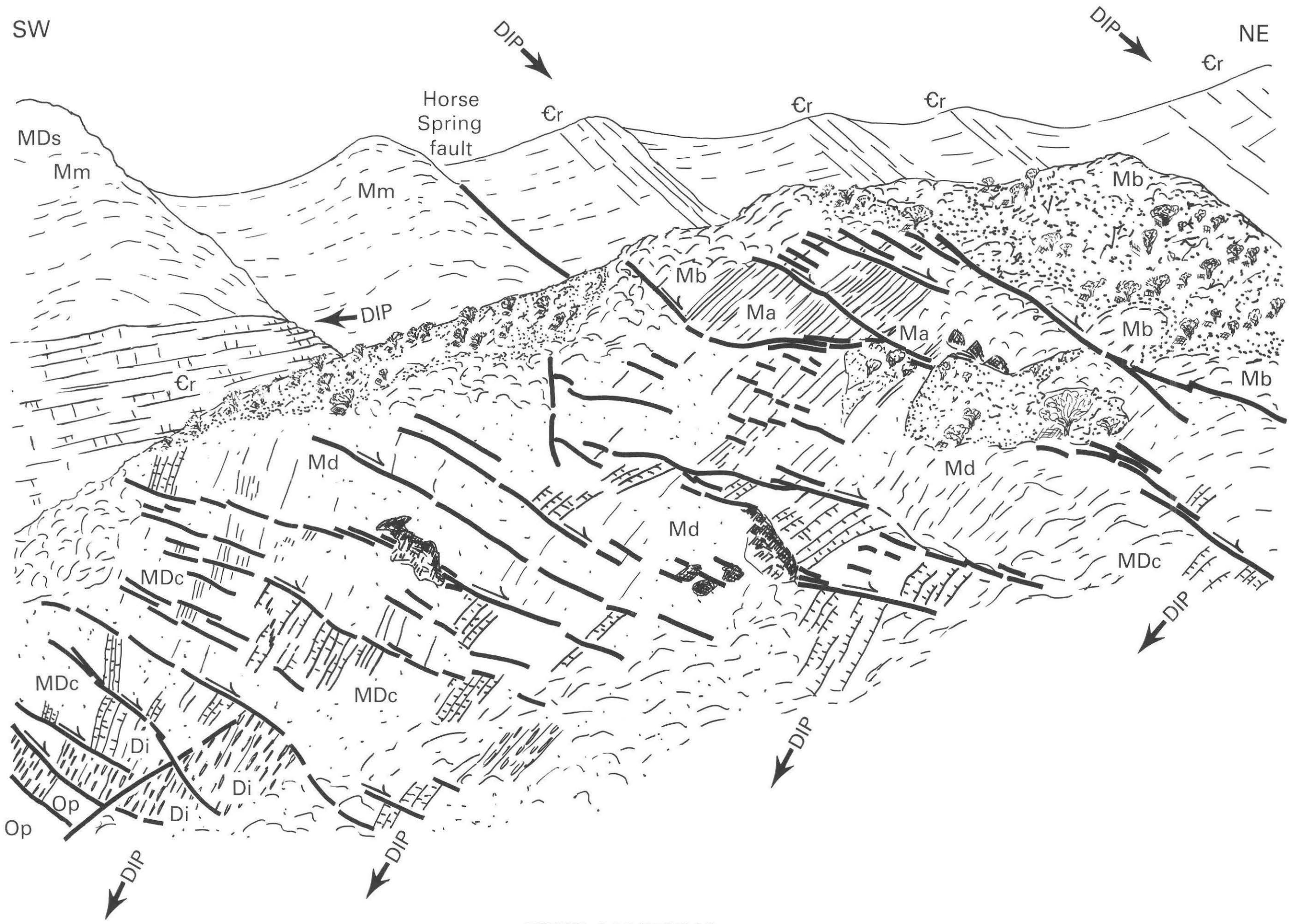
Wernicke and others (1985) likened the complexity in the hanging wall along the transverse segment of the Horse Spring fault to "chaos structure" that develops in extensional deformation either as normal faults merge downward into detachment faults or by stratigraphic slicing from footwall and hanging-wall blocks along the base of an extensional allochthon. The extended hanging-wall allochthon south of the transverse segment of the Horse Spring fault was interpreted to carry elements of the Mormon thrust-fault system westward relative to rocks north of the fault in the east-tilted domain (Axen and others, 1990). According to this interpretation, the transverse segment serves not only as a dextral tear in the extensional allocthon but also as an accommodation for eastward-increasing amounts of extension as normal-fault displacements feed into it from the north (from the footwall). Axen and others (1990) suggested that this geometry results in eastward-increasing dextral displacement along the transverse segment, so we searched for evidence of uniform dextral shear along that part of the Horse Spring fault but found considerable diversity instead.

As the transverse segment is approached, changes in bed orientation give the appearance of vertical-axis rotations that resemble dextrally coupled shear-related drag features. However, some beds in each domain show the opposite sense of rotation, the fault zone shows no uniform lateral shear sense, and uniform attitudes of strata in some places can be traced through the zone with no suggestion of drag associated with lateral shear. Near the Petroglyphs (pl. 3), Mississippian rocks athwart the Horse Spring fault zone are strongly deformed, and their dips range from gentle to steep. Large-magnitude vertical separations were documented on diversely oriented faults, but there is no single fault extending through these rocks and thus no major fault with large-magnitude dextral separation. Sharp bends and sinuous traces are common features of individual faults in the transverse segment of the Horse Spring fault zone, which, if they are interpreted as shear-related folded faults, would not indicate uniform dextral shear but rather a confusing mixture of dextral and sinistral shear.

The Davidson Peak fault in the southern part of the East Mormon Mountains (pl. 5) was interpreted by Axen and others (1990) as forming the eastern continuation of the northern boundary of their proposed dextral shear zone. In a following section on "Davidson Peak fault," we present evidence similar to that presented here for the Horse Spring fault, indicating that no major component of dextral displacement has occurred on the Davidson Peak fault.

The area south of the transverse segment of the Horse Spring fault includes (1) folded rocks directly above the Mormon thrust, (2) northwest-dipping thrust-imbricated rocks above the Petroglyph detachment fault, and (3) west-dipping autochthonous Cambrian and Ordovician rocks between Moapa Peak and locality D (pl. 3). The latter rocks are cut by hundreds of faults (not shown on pl. 3) with displacements of a few centimeters to more than 100 m. Most are dip-slip normal faults that fall into two categories: (1) down-to-the-east east-dipping faults that cut bedding at high angles, and (2) down-to-the-west faults that are approximately parallel to west-dipping bedding. Though the strata dip west, successively younger rocks are found in a traverse eastward because normal throw on the shingled east-dipping faults has been greater than the stratigraphic effect of tilting. These structures are typical of those associated with Neogene extension and attenuation in nearby areas (Wernicke and others, 1985; Axen and others, 1990), and we therefore interpret them to be of Neogene age. The current predominantly northwest dip of the thrust-imbricated zone was interpreted by Axen and others (1990) to be thrust-related, but we believe the tilting could be Neogene because (1) northeast along strike of the imbricated rocks, autochthonous rocks that clearly were tilted and fault-repeated during Neogene extensional deformation (fig. 14) are structurally concordant with the imbricated rocks (fig. 15); and (2) faulting and tilting directly above the Petroglyph detachment fault is probably Neogene, as noted in a preceding section.

To summarize, we interpret the northern segment of the Horse Spring fault as a convex-upward normal fault that accommodated a laterally variable amount of uplift and rotation of its footwall. We interpret the transverse segment of the Horse Spring fault as having had a similar function for its footwall (including accommodating strain for other large- and small-displacement footwall faults and rotations), as well as having accommodated the downthrow and opposite-sense rotations of its hanging wall. The fault's location is probably controlled by an ancient structural flaw in the basement rocks. Wernicke and others (1985) noted that the deformation along the transverse segment of the Horse Spring fault is highly complex and extremely intense when considered in terms of the small amount of estimated lateral extension. We note that the complexity and intensity are directly related to the fault's accommodation of structural thinning and contrasting tilt directions. We are



EXPLANATION

Mm	**Monte Cristo Limestone (Upper and Lower Mississippian)**
Mb	**Bullion Member (Upper Mississippian)**
Ma	**Anchor Member (Upper and Lower Mississippian)**
Md	**Dawn Member (Lower Mississippian)**
MDs	**Sultan Limestone (Lower Mississippian to Middle Devonian)**
MDc	**Crystal Pass Member (Lower Mississippian and Upper Devonian)**
Di	**Ironside Member (Middle Devonian)**
Op	**Ordovician rocks**—Probably belonging to the Pogonip Group
€r	**Cambrian rocks**

Figure 14. Sketch showing the dip-direction discordance between Cambrian rocks of the east-tilted domain (right skyline ridge) and younger Paleozoic rocks of the west-tilted domain (foreground), about 1 km northwest of the Petroglyphs, southern Mormon Mountains, Nevada. Only the Cambrian dolostone units in the left middle distance are allochthonous above a thrust-fault surface (hidden from view) and form part of the thrust-imbricated stack in the west-tilted domain (pl. 3). Bedding and fault traces (heavy lines, barbs show displacement sense) are emphasized in the strongly deformed Devonian and Mississippian rocks in the foreground. Here, the structural lengthening associated with fault displacements (consistently top-to-the-northeast) is everywhere greater than the shortening due to tilting, so younger and younger strata are crossed on a down-structure (northeastward) traverse. This cross-strike condition is typical of areas of Neogene deformation in the region. All rocks except the east-tilted Cambrian rocks on the right skyline are in the hanging wall of the Horse Spring fault, which forms the accomodation boundary for all the intense deformation in that hanging wall.

impressed with many similarities between this accommodation zone and the Neogene Eldorado Mountain zone in the lower Colorado River extensional terrane described by Faulds and others (1990). Both zones are dominated by younger-on-older fault displacements, strong structural attenuation, some torsional strain, radical along-strike

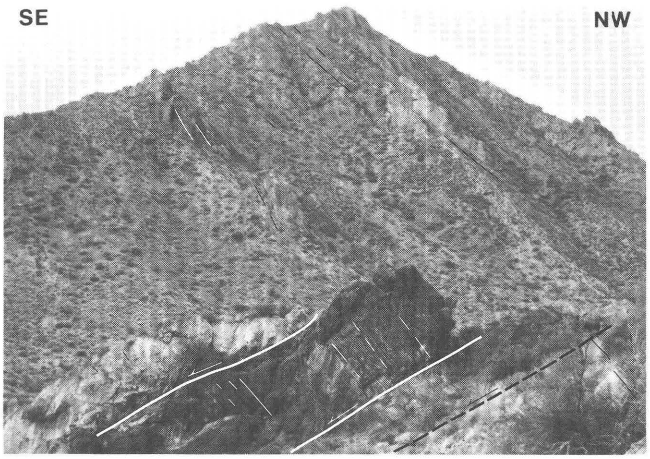


Figure 15. Similarity in northwestern dips of strata (bedding traces highlighted by fine lines) in the thrust-imbricated allochthonous Cambrian rocks (skyline ridge) and the Devonian rocks of the autochthon (foreground). View is to the southwest from 0.6 km west-northwest of the Petroglyphs, southern Mormon Mountains, Nevada (pl. 3). Dark and light rocks of the Ironside and Crystal Pass Members of the Middle Devonian to Lower Mississippian Sultan Limestone in the foreground form part of the west-tilted domain (pl. 3), which is commonly cut by down-to-the-east normal faults (heavy lines with barbs). Because the dip (about 55°) of these rocks is similar to the dip of the thrust-imbricated rocks on the skyline, we infer coeval Neogene tilting of the autochthon and thrust-imbricated allochthon during formation of the west-tilted domain.

variations in throw, and an absence of uniform-sense lateral slip.

EAST MORMON MOUNTAINS

The East Mormon Mountains are an internally faulted and folded, mostly east tilted range that is wedge shaped, broadening to the south. It is bounded by the Carp Road fault on the west and the buried Toquop Gap fault on the east (Olmore, 1971; Axen and others, 1990). All rocks in the part of the range considered here (pl. 5) belong to the thrust autochthon. As with the Mormon Mountains, major abrupt along-strike strain discontinuities exist in the range. Cambrian through Pennsylvanian rocks in the narrow northern part of the range north of the area of plate 5 were intensely deformed by complex systems of low-angle normal faults and transverse faults that collectively form a structurally complicated area referred to by Axen and others (1990) as the Toquop chaos. This intense internal deformation lessens southward into the area of plate 5. Southward to the Davidson Peak fault, the main central part of the range consists of two east-tilted structural blocks: a western triangular uplift that has a continuous stratigraphic section from Proterozoic crystalline basement through Pennsylvanian rocks, and an eastern block composed mainly of crystalline basement rocks and overlying faulted basal Cambrian clastic rocks. The two blocks are separated by the large-displacement down-to-the-west East Mormon fault (pl. 5), which terminates southward by bending sharply eastward and transferring its displacement into the east-striking Davidson Peak fault in a zone of several major fault splays. The Davidson Peak fault is the eastern strike extension of the transverse segment of the Horse Spring fault in the central Mormon Mountains and similarly is a major strain boundary for the southern part of the East Mormon Mountains.

Using the geologic map of Olmore (1971) as a guide, we concentrated our studies along major faults. We describe the north-striking faults first, the Carp Road, East Mormon, and Peach Spring faults, then the major east-striking Davidson Peak fault (pl. 5). We briefly describe some uplifts and depressions found in the southern part of the range. We conclude that these latter features, together with folds found along major faults, are extremely important in understanding Neogene strain distributions and deformational kinematics of the area. Indirect evidence for a Tertiary age for structures in the East Mormon Mountains was reviewed by Axen and others (1990).

CARP ROAD, EAST MORMON, AND PEACH SPRING FAULTS

The trace of the Carp Road fault is marked in some places by conspicuous scarps in alluvium, which indicate some Quaternary displacement (fig. 16). Probably because of this young displacement, striae are more conspicuous on this and subparallel smaller faults than on most other faults we studied. Striae on the main fault were only seen at two places and indicate normal sinistral slip, whereas striae on subsidiary faults show predominantly sinistral slip (pl. 5, plot 1). East of locality A (pl. 5), the surface trace is concave westward, the fault dips an average of 77° W., and the fault separates weakly deformed east-tilted rocks in the footwall from strongly deformed rocks in the hanging wall. Structures in the hanging wall include an east-striking normal fault and a steep-limbed syncline cut by many faults, some of which are east striking and of large displacement (not shown on pl. 5). Because these east-striking structures have no counterparts in the footwall, the strain represented by them must terminate at the Carp Road fault. Northeast of Carp Summit, lower Paleozoic rocks in the footwall bend westward (counterclockwise) from their normal northern strikes, and this change suggests that the long-term slip on the Carp Road fault is sinistral (pl. 5 and fig. 16), consistent with the Quaternary(?) striae. We interpret the hanging-wall folding (the predominant structure) to have resulted either from structural crowding near the right-stepping bend in the Carp Road fault or from drag associated with components of sinistral slip. The presence of a fold and a normal fault in the deformed hanging-wall block is somewhat analogous to relationships at locality N (pl. 5) described in detail in the section on "Uplifts and Depressions in the Southern East Mormon Mountains." The stratigraphic separation on the

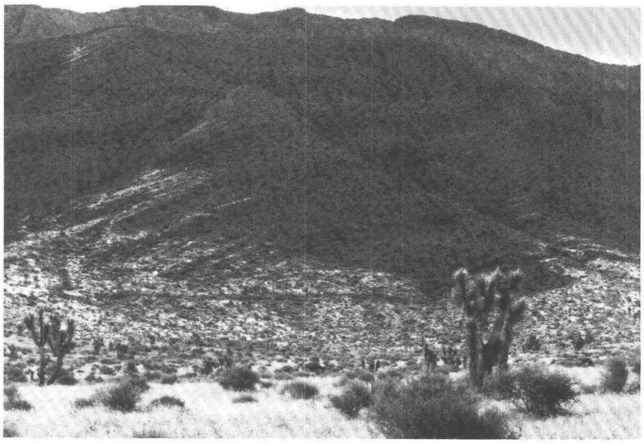


Figure 16. A sharply defined Quaternary scarp along the Carp Road fault at the west base of the East Mormon Mountains, Nevada. View is to the southeast. The scarp is 2–3 m high and was formed partly on bedrock and partly on alluvium but is not visible on the Holocene(?) fan surface to the right of the large Joshua tree. We suspect that net slip since deposition of the older alluvium was at least equal to twice the scarp height because nearby striae indicate a 20° southern rake. Cambrian dolostone beds low in the range strike north (color banding visible in shade at right) and bend northwest into the fault trace, as shown by the back-lighted strata in the left part of the view. This bending (about 35° change in strike) is consistent with sinistral slip on the Carp Road fault.

Carp Road fault at the latitude of locality A is highly variable and ranges from nil to more than 150 m, depending on what part of the folded hanging-wall block is in contact with the footwall. The separation increases to the southwest and is a maximum of about 1.8 km near locality B where Mississippian rocks of the hanging wall strike into exposed Precambrian crystalline rocks of the footwall. We interpret the strong strike discordance between faults and beds in this locality also to have resulted from strike-slip movement on the Carp Road fault.

At and southwest of Carp Summit (pl. 5), the Carp Road fault separates structurally thinned, west-tilted variably dipping rocks in its hanging wall from less thinned, east-tilted rocks in its footwall. Footwall strata dip 30°–60° E. and are conspicuously steeper than hanging-wall rocks, geometric relations that suggest that the southern part of the Carp Road fault has a convex-upward shape. Throw on the Carp Road fault increases dramatically southward in a fashion similar to the Horse Spring fault and its unnamed companion described above. We assume that the southern part of the Carp Road fault is convex upward to considerable depth because the 8-km-broad East Mormon Mountains block is characterized by dips steeper than in the adjacent part of the Mormon Mountains block (pl. 2).

Axen and others (1990) concluded that the Carp Road fault at its southern end feeds most of its displacement into the Davidson Peak fault by bending abruptly eastward. Further, they interpreted the wedge-shaped area between these two faults as a footwall culmination. We concur in their interpretation and conclude that the culmination acted as a buttress against which structural crowding of the hanging wall occurred in association with sinistral slip on the Carp Road fault.

The East Mormon fault is a complex west-dipping sinistral-normal structure that broadens from a single mapped trace in the north to a complex zone of several major splays in the south (pl. 5). Locally, Pennsylvanian rocks are dropped down against Precambrian crystalline rocks with a stratigraphic separation of about 2 km. It has an average mapped trace of about 350°, but segments of the fault that have large displacement also have a broad range of strikes (pl. 5, plot 2*A*), especially in the south. Good exposures at several places indicate that the fault dip decreases southward from 33°–55° in the north to 12°–41° in the south. Some main-fault planes contain striae that indicate that the youngest displacements include a major component of sinistral strike slip (pl. 5, plot 2*A*) even though the west-side-down stratigraphic throw is large. Minor faults and fractures in the hanging wall adjacent to the main fault also have diverse attitudes (pl. 5, plot 2*B*), and whereas some are sinistral, most are dip slip. Dip-slip minor faults generally displace hanging-wall rocks either down to the west or south.

Near a radio tower directly south-southwest of locality F (pl. 5), the trace of the main fault that separates Precambrian crystalline rocks from strongly attenuated Paleozoic carbonate rocks has a conspicuous convex-eastward bend, which apparently led Olmore (1971) to interpret the structure as a low-angle fault. Axen and others (1990) named this structure the "radio-tower fault" and reported that it is cut by the East Mormon fault, which was inferred to be a steeper, younger fault (see also Wernicke and others, 1984). Our investigation shows that, although the dip of the main fault varies, the convex-eastward radio-tower fault is part of the East Mormon fault whose strike changes systematically from 322° through 37° to 55° as the bend is traversed from north to south. The hanging wall here is a west-plunging scoop of Devonian and Mississippian rocks that show the effects of intense brittle attenuation. The East Mormon fault, as defined by us, is the major fault zone that exposes Precambrian crystalline rocks in its footwall, and we do not recognize a separate radio-tower fault. Other curved segments of the fault trace to the north also appear to be continuous with the main fault, which obviously has a complex three-dimensional shape (represented by strike diversity in pl. 5, plot 2*A*). We do not claim that crosscutting faults are not common because they are, and many exposures show that steep faults displace more gentle faults. This relationship is best interpreted as the result of either a deformational continuum (Morton and Black, 1975) or of ramp-flat fault geometry (Laubach, 1989; Root, 1990; Laubach and others, in press).

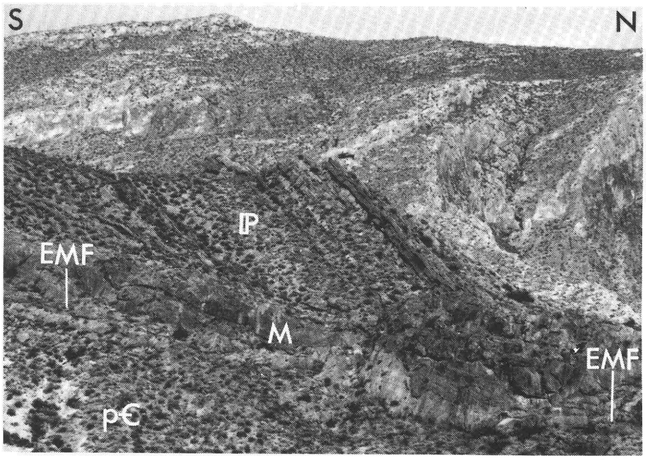


Figure 17. View across the west-dipping East Mormon fault (EMF), East Mormon Mountains, Nevada. View is west from a point between localities F and G on plate 5. Surface trace of the fault is in the foreground where poorly exposed Precambrian crystalline rocks (p€) in the footwall (largely covered by colluvium) are structurally overlain by cliff-forming bands of structurally thinned (penetratively deformed) Mississippian limestone (M). North-dipping, distinctly bedded Pennsylvanian limestone (IP) in the middle distance strikes directly into the fault zone and is truncated by it, a structural relationship noted at several other localities along north-striking faults in the range. Striated fault surfaces to the north and south of this view indicate an important component of sinistral slip on the East Mormon fault. The skyline is the crest of the East Mormon Mountains whose east flank is primarily a dissected dip surface on Mississippian limestone.

Footwall-hanging wall tilt relations across the East Mormon fault are generally not known because unrestorable Precambrian crystalline rock makes up the footwall along the entire southern trace. At locality L (pl. 5), however, Cambrian strata directly above the nonconformity are tilted 65° or more eastward and are thus about twice as steep as rocks in the adjacent hanging wall 2 km to the west. The dip discrepancy suggests that this part of the East Mormon fault, west of locality L, is convex upward, like several other major sinistral-normal faults in this region.

The structure of the hanging wall of the East Mormon fault is varied and complex and includes a major fault-parallel open syncline mapped by Olmore (1971). The hanging wall also shows sharp flexing of beds into the trace of the East Mormon fault and common down-to-the-east normal faults. These two features are discussed below.

Directly west of locality E, bedding in Pennsylvanian limestone is sharply rotated in a counterclockwise fashion from the normal north-striking, east-dipping attitudes that are characteristic of the main range block to northeast and north dips, and inclinations that increase toward the fault. Bedding thus forms a shallow, open, east-trending fold (not shown on pl. 5). These hanging-wall structures were not seen east of the fault that must therefore accommodate the strain. The sense of bending is consistent with sinistral slip on the fault. A similar structural relationship is seen between localities F and G (pl. 5) where Mississippian and Pennsylvanian strata bend toward the fault and are truncated by it (fig. 17). Previously described similar structures at locality A and at Carp Summit, above the Carp Road fault, and bedding relations at locality M (pl. 5) suggest that north-striking faults in the range have much in common in terms of hanging-wall folds that are truncated at the fault and are spatially and causally related to the faults. We interpret the hanging-wall folding and bending mainly as drag structures associated with sinistral and normal-sinistral displacements on the main north-striking faults. As such, they show that the sinistral-slip striae represent an important component of the Neogene deformation rather than a trivial late-stage event. The hanging-wall folds are analogous to those found along large-displacement, oblique-slip extensional faults of early Mesozoic age in the Fundy rift basin, Nova Scotia (Olsen and Schlische, 1990).

Between localities H and D, the hanging wall of the East Mormon fault is composed of structural slabs of Devonian and Mississippian rocks that are structurally thinned internally by extremely abundant younger-on-older faults similar to those along the Castle Cliff detachment fault in the Beaver Dam Mountains (pl. 1), described above. At several localities, outcrop-scale bedding offsets and internal deformation fabrics in these intensely faulted rocks show down-to-the-east displacement sense that seems incompatible with the principal down-to-the-west throw on the East Mormon fault zone. One of these (fig. 18) is directly west of locality C (pl. 5). We recognized similarly intense down-to-the-east faulting in rocks directly above the Mormon Peak detachment fault in the east-central Mormon Mountains (indicated by opposed-sense barbs at localities marked by X in cross section *A–A′*, pl. 2*C*). This antithetic-sense shear is where the normally west dipping Mormon Peak detachment fault is back tilted to an east dip. Reynolds and Lister (1990) summarized data indicating that domed-upward detachment faults are cut by antithetic shear zones where the detachments are backtilted in the domes. They concluded that the antithetic shear zones are genetically related to doming and form late in the doming history. Although this is a possible explanation for the antithetic shear along the Mormon Peak detachment fault, field relationships show no clear-cut evidence that the shearing is late stage and displaces the main detachment fault. Instead, we interpret the opposed-sense shear directly above these faults as evidence of an early phase of extensional deformation, the roots of which have been structurally eroded by excisement tectonics of the type described by Davis and Lister (1988). At outcrop scale, the deformational intensity indicated by these examples of opposed-sense faulting matches that associated with the main-sense down-to-the-west displacement direction. Because the opposed-sense faulting and tilting are similar in style and magnitude to and

Figure 18. South-facing exposures within the hanging wall of the East Mormon fault, East Mormon Mountains, Nevada. Location is directly west of locality C (pl. 5). *A*, Geologist stands on the moderately west dipping fault that places moderately east dipping limestone of the Lower Permian and Pennsylvanian Bird Spring Formation (PIPbd) against the strongly deformed footwall of Upper Mississippian Bullion Member of the Monte Cristo Limestone (Mmb). Bedding in footwall is indistinct owing to intense deformation. Early formed calcite veins (light streaks) form a tectonic band low in the exposure. The displacement sense of the early formed veins is predominantly top-to-the-east. Nearby exposures show a similar displacement sense of intensely deformed and translated bedding elements. *B*, Detailed view of shear fabric in lower part of exposure.

share common structural levels with the main-sense deformation, we interpret both to represent a single protracted tectonic event. Structural thinning was accomplished by the opposed-sense fracture systems and the subsequent excisements of the roots. Previous workers may have overlooked the significance of this mechanism in favor of models of large-magnitude, uniform-sense displacements.

The Peach Spring fault strikes 340° in its northern part where it diverges from the East Mormon fault and penetrates the footwall of the latter. The Peach Spring fault appears to have a single main trace for about 3 km southward, then fragments into numerous short northeast- and northwest-striking, west-dipping segments in its southern part where it separates footwall crystalline rocks from hanging-wall basal Cambrian clastic rocks. Olmore (1971) apparently did not recognize that a combination of diversely oriented steep faults and depositional contacts produce a sinuous trace between crystalline rocks and Cambrian basal clastic rocks in this area. Therefore, he mapped a continuous low-angle fault whose trace approximately parallels topographic contours. Sparse fault-attitude and fault-slip data (pl. 5, plot 3) indicate that the Peach Spring fault is somewhat similar to the East Mormon fault and probably has a significant component of sinistral slip. It does not represent an early episode of low-angle normal faulting analogous to that proposed by Axen and others (1990) for their radio-tower fault.

In summary, the three main exposed northerly striking faults in the East Mormon Mountains have down-to-the-west throw and large components of sinistral slip. Though the total relative magnitude of dip-slip versus strike-slip displacements is not known, we conclude that the sinistral slip components on these faults are large and are kinematically and mechanically linked to major uplifts and depressions, as noted in the following section on "Uplifts and Depressions in the Southern East Mormon Mountains." Also, we conclude that the sinistral displacements have regional tectonic significance and constitute additional examples of this shear-sense geometry that we have observed throughout the southeastern part of the Great Basin and adjacent transitional area to the Colorado Plateau. The contrasting model of diachronous faulting history in which an early episode of low-angle normal faulting (radio-tower fault and Peach Spring fault as erroneously mapped by Olmore, 1971) is followed by displacements on high-angle faults (East Mormon fault) has been emphasized (Axen and others, 1990). We recognize complex fault-slip characteristics and a complex arrangement of structures such as in the hanging wall of the East Mormon fault, and we interpret them as having formed in a single protracted episode of extension and extension-related contraction.

DAVIDSON PEAK FAULT

The throw on the east-striking Davidson Peak fault is consistently down to the south, and it separates Precambrian through Pennsylvanian rocks on the north from Pennsylvanian through Triassic strata on the south (pl. 5). Its western part is a complex zone marked by elongate slivers of Cambrian through Mississippian rock across which the maximum stratigraphic separation near locality B (pl. 5) is almost 2 km. The fault decreases in complexity and separation of strata eastward, and directly northwest of locality D (pl. 5) it separates easterly dipping Pennsylvanian and Permian strata and has a single map-scale trace with a stratigraphic separation

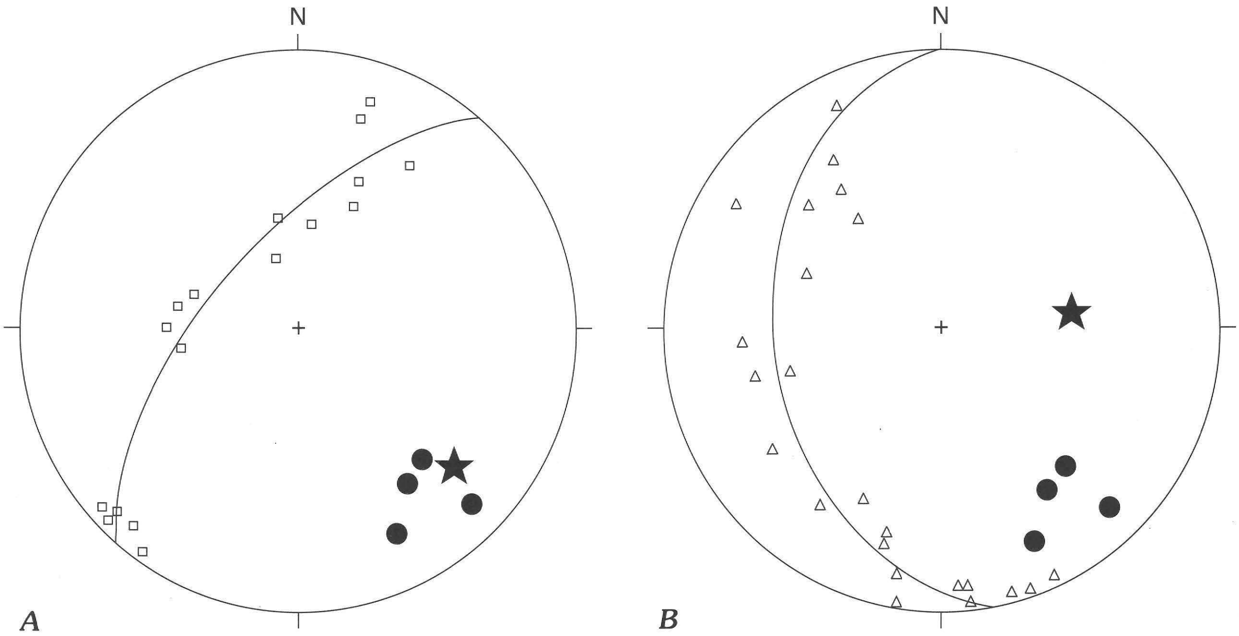


Figure 19. Schmidt-projection stereographic plots of poles to bedding (squares and triangles) from the northeastern (*A*) and southwestern (*B*) parts of a recumbent fold in the footwall of a low-angle normal fault midway between localities D and N (pl. 5), East Mormon Mountains, Nevada. Stars show locations of fold axes determined from the best-fit great circle (line) through fold-limb data. It is not apparent why different parts of what appears to be a single fold have different orientations. Similarly, it is not apparent whether the southwest-directed (*A*) or south-directed (*B*) motion on the overlying causative low-angle normal fault is the principal motion. Each type of motion is consistent with some fault-slip data from the same general locality (see pl. 5 and associated text for additional details). Solid circles show axes of outcrop-scale folds in mechanically weak Pioche Shale in the footwall of the detachment fault. Note that they parallel the axis of the northeastern part of the main subdetachment fold, a position that suggests that northeast-southwest translation may be the main strain signature.

of less than 0.7 km. Near locality D, the Davidson Peak fault intersects the East Mormon fault, which is a much more complex fault and shows much greater displacement than the Davidson Peak. East of this junction, the Davidson Peak fault zone broadens eastward and becomes a major zone of generally south dipping faults (well exposed but few striae) that cut moderately to steeply east dipping strata (pl. 5, plot 4*A*). Weakly developed striae on one gently southeast dipping fault in the zone indicate predominantly dextral slip (pl. 5, plot 4*A*). Numerous large- and small-displacement younger-on-older faults feed into this fault from above but do not cross it, indicating that it accommodated a large amount of strain in its hanging wall and could have large displacement. Overturned bedding directly above this fault (pl. 5, plots 4*A*, *B*) results from extreme extension-related tilting. Its footwall contains a south- to southwest-vergent recumbent drag fold (fig. 19) developed in structurally weak well-bedded limestone of the Middle Cambrian Papoose Lake Member of the Bonanza King Formation. The southwest-vergent part of the fold (fig. 19*A*) is kinematically consistent with the weakly developed striae on the associated main fault (pl. 5, plot 4*A*) as well as with striae on nearby minor faults (pl. 5, plot 4*B*). The south-vergent part of the fold (fig. 19*B*) is kinematically consistent with normal dip-slip displacement on the several major south-dipping strands of the Davidson Peak fault zone and with sparse striae on minor faults nearby (pl. 5, plot 4*B*). The south-vergent part of the fold is also consistent with the sinistral component of slip on the East Mormon fault, and we interpret both to be mechanically and kinematically linked. Although these data fail to provide unique kinematic solutions, they illustrate that (1) folding can occur in structurally weak rocks in the footwall of a low-angle normal fault, (2) resulting folds can be kinematically coordinated with complex slip on the fault, and (3) the combined faulting and folding reflects deformation that is coupled to normal-sinistral slip on a major block-bounding fault that feeds its displacement into the transverse fault zone.

Directly north of locality J (pl. 5), a small klippe of north-striking vertical Lower Permian rocks (Kaibab Limestone) is underlain by Pennsylvanian rocks in which the dip direction changes progressively as the Davidson Peak fault is approached from the south (details not shown on pl. 5) from 60° to 70° south-southeast to steep east (counterclockwise rotation). We interpret this klippe as an erosional remnant of the Permian section exposed in the structural block west of the north-striking normal fault (locality J). The attitudes of strata in the klippe and those of the subjacent block that indicate counterclockwise rotation are the reverse of what would be expected if the Davidson Peak fault were a major dextral shear zone, as suggested by Olmore (1971), Wernicke and others (1984), and Axen and others (1990). Attitudes of strata in the fault zone west of this klippe do not suggest dextral shear nor, on the basis of unpublished data, do fault orientations and striae within the erosionally stranded Permian rocks.

Most strands of the Davidson Peak fault are not exposed, and we were able to measure its attitude and slip sense at only two localities (pl. 5, plot 5*A*). Although dip-slip, oblique-dextral slip, or dextral slip are indicated, the data are insufficient to characterize the overall slip sense. Most small-displacement faults in the zone either strike northwest and show dextral shear or strike northeast and show sinistral shear (pl. 5, plot 5*B*) and generally support a northern component of horizontal compression similar to that determined for the area by Michel-Noel (1988). These motions appear to be kinematically inconsistent with predominantly normal and normal-dextral displacements in the eastern part of the fault zone, further suggesting complex fault kinematics along the zone. The collective evidence for radical lateral contrasts in throw and kinematically complex motion on the Davidson Peak fault zone suggests to us that, similar to the coextensive Horse Spring fault described above, the Davidson Peak has endured as an efficient structural boundary that mostly accommodated local strain variations in adjacent blocks rather than regionally accumulated strain contrasts. We suspect that its location is controlled by an ancient flaw in basement rocks.

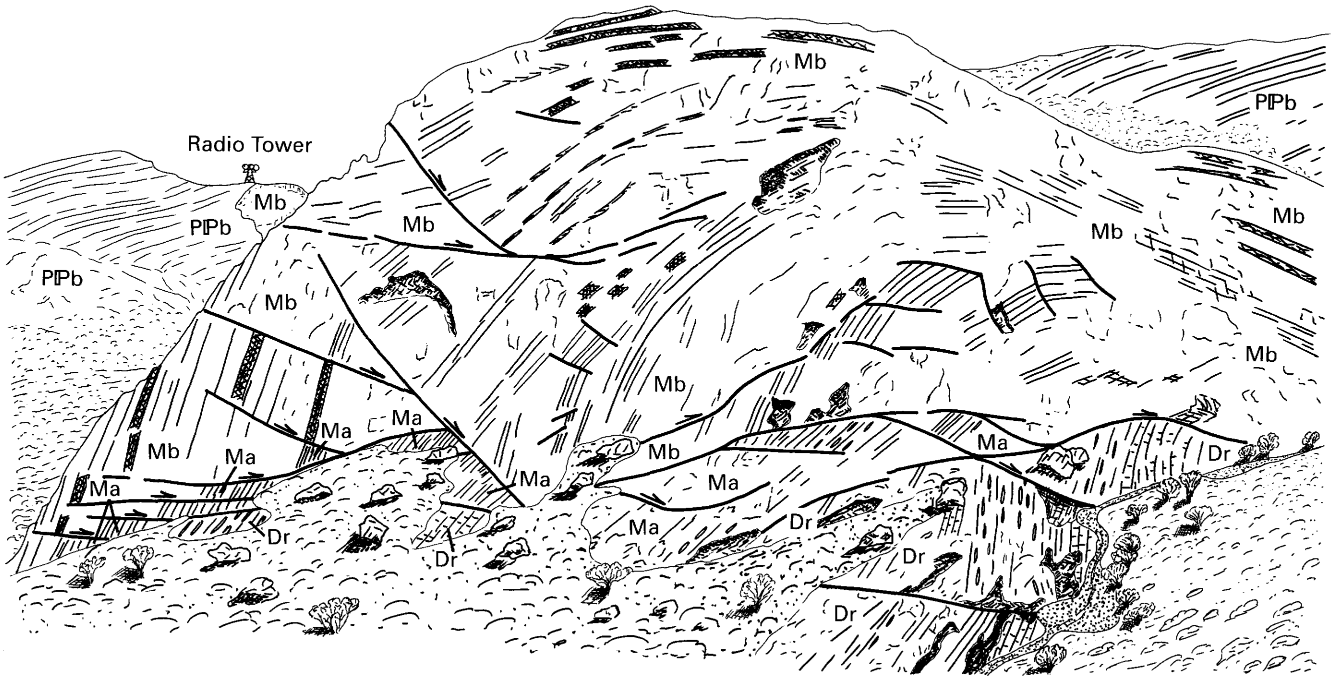
UPLIFTS AND DEPRESSIONS IN THE SOUTHERN EAST MORMON MOUNTAINS

Directly northeast of locality N (pl. 5), a conspicuous northeast-trending anticlinal feature strikes into the East Mormon fault at a high angle. Excellent exposures of its detailed internal structure (fig. 20) are in a steep-walled east-west drainage. Tilting of strata is closely coordinated with systems of faults that consistently displaced beds down toward the anticlinal axis and produce strong structural thinning across the core of the fold. The association of this structure with extensional deformation is obvious on the basis of its location in the East Mormon fault zone, the stratigraphic attenuation, and because it is in the footwall of a moderately northwest dipping normal fault. Although smaller in scale, this fold is a well-exposed example of steeper average dips of strata in a footwall block than in the associated hanging wall, and the fold shows by analogy the effects of uplift and steep tilting of footwall rocks that occur beneath convex-upward main faults, inferred in the Beaver Dam and southern Mormon Mountains as described in earlier sections of this report. As a result of the intense internal strain (fig. 20), the Mississippian rocks in the core of the antiform appear to have been intruded or emplaced diapirically, as was illustrated for the footwall rocks (fig. 3) of the Pahcoon Flat fault.

Steep to overturned attitudes of strata characterize the area of discontinuous outcrop of upper Paleozoic and Mesozoic rocks surrounding locality K (pl. 5), and these orientations define a large-amplitude, short northeast-trending overturned syncline. The axial zone is covered by sheets of crackled landslide breccia and by Neogene alluvial basin-fill deposits, and so the magnitude of vertical structural relief, though large, is not known. Reconstruction suggests rocks as young as Jurassic may occupy the center of this fold. The northeast trend and south to southeast vergence are consistent with northwest-southeast constriction such as might have occurred during the Sevier orogeny to produce a subthrust fold or fault-propagation fold. We reject the interpretation that this overturned syncline might have formed as a subthrust fold, because we saw no evidence to the northwest for a causative steeply ramping thrust or reverse fault required for thrusting to rise to such a high structural level. Although the Davidson Peak fault might mark the trace of that steep thrust, we note as compelling negative evidence the south dip of the fault, the extreme lateral variation in stratigraphic throw, and the absence of thrust-related structures in the adjacent block north of the Davidson Peak fault.

The wedge-shaped area between the Carp Road and Davidson Peak faults is a conspicuous northeast-trending uplift or culmination exposing Precambrian crystalline rocks. Axen and others (1990) interpreted the culmination to be Neogene in age. It is similar in size, amplitude, and trend to the overturned syncline described in the previous paragraph. Within the culmination near locality I (pl. 5), complex dip reversals in Cambrian dolostone units define a conspicuous synclinal keel with a northeast axis parallel to the uplift. This structure bears no obvious drag-fold relationship to the adjacent Davidson Peak fault. East of locality I (pl. 5), the dolostone units are sharply overturned and cut by northwest-striking faults that not only limit the overturning but also appear to mark the northeastern limit of this synclinal keel. Because one of the northwest-striking faults crosses the Davidson Peak fault, we infer a young age for the folding that is bounded by it. We interpret this fold to have formed simultaneously with the wedge-shaped culmination and the overturned syncline at locality K (pl. 5).

We interpret these northeast-trending folds to have absorbed some of the sinistral displacement on the East Mormon and Carp Road faults. Many faults in the overturned north limb of the syncline directly north of locality K (pl. 5) dip moderately to gently west and show top-to-the-south strike-slip displacement (pl. 5, plot 6) consistent with the suggested absorption of strike-slip displacement. The compressional features are intrinsically linked to regional extensional deformation because the kinematic axis of extension is parallel to the fold and uplift axes. We recognize similar uplifts and depressions, outcrop-scale structural keels and sails, and basins and ranges of this trend over an extremely



EXPLANATION

PIPb	**Bird Spring Formation (Lower Permian and Pennsylvanian)**
Mb	**Bullion Member of Monte Cristo Limestone (Upper Mississippian)**
Ma	**Anchor Member of Monte Cristo Limestone (Upper and Lower Mississippian)**
Dr	**Devonian rocks**

Fault—Barb shows direction of movement

Figure 20. Sketch emphasizing traces of bedding and faults, East Mormon Mountains, Nevada. View is southward from a point 1 km west of locality G, plate 5. All rocks in view are in the hanging wall of the west-dipping East Mormon fault. The east dip of Permian and Pennsylvanian limestone (unit **PIPb**) on the distant ridge shows the general tendency of hanging-wall strata to dip toward the East Mormon fault. In the foreground, a small drainage cuts transversely through a north-trending ridge, revealing in cross section an intensely faulted anticline. Only the faults that conspicuously truncate bedding are shown, and their displacement sense is consistently down to the west. Similar-sense internal strain appears to be intense in the massive carbonate rocks of the Bullion Member of the Monte Cristo Limestone (fig. 18) but is masked by recrystallization. The Devonian and Mississippian rocks in the lower part of the anticline dip east at 55°–85° (average of 70°), but the highly strained Mississippian rocks higher in the anticline dip much more gently, forming a deformed sheath that mantles the more steeply dipping rocks in the core of the fold (lower right side of sketch). This style of folding and faulting characterized by steeper average dips of strata in structurally lower elements is common over a broad range of scales in the Mesquite basin region and is therefore considered of fundamental tectonic importance. The western dip of strata in the right part of the view may reflect normal drag beneath a low-angle, subsidiary down-to-the-northwest fault (surface trace hidden by foreground ridge) that locally repeats part of the section of Permian and Pennsylvanian rocks on the skyline.

broad range of scales in the Mormon Mountains-Mesquite basin region and interpret them to be of regional tectonic significance. Axen and others (1990) interpreted uplift of the East Mormon Mountains as an isostatic response to tectonic unloading by the Tule Springs detachment fault, whereas we interpret much of the vertical structural relief as resulting from footwall absorption of north-south contraction that accompanied extensional deformation. These arguments are discussed and expanded in the following section.

SUMMARY AND DISCUSSION

This study provides a basis for challenging the three major components of the dextral-slip Moapa Peak shear zone (fig. 21) and thereby its very existence. First, the easterly striking Davidson Peak-Horse Spring fault zones lack either fault-slip or drag-fold evidence for uniform-sense large-magnitude dextral slip. Each fault zone is best interpreted as a structure that accommodated strong local contrasts in the magnitude and (or) direction of adjacent tilting, uplift, and structural thinning. Evidence for dextral slip was found at places where deformation in adjacent blocks requires its existence—so, too, evidence was found for dip slip or sinistral slip. These fault zones are similar to other accommodation zones found in extended terrains (Chapin, 1978, 1989; Faulds, 1989; Faulds and others, 1990; Morley and others, 1990) that correspond to belts of intermeshing deformation rather than to major uniform-sense strike-slip fault zones.

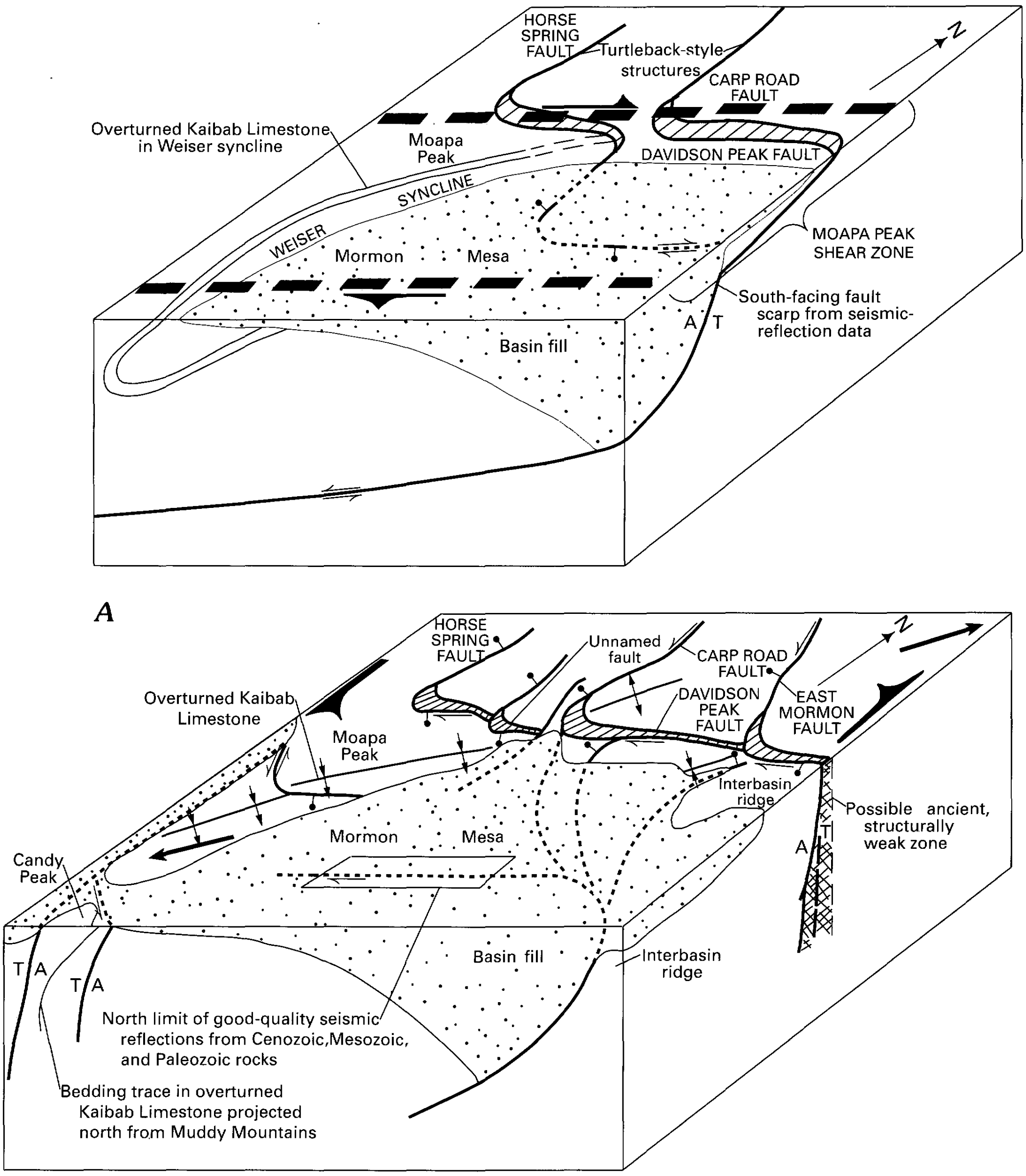
Second, the existence of the Moapa Peak shear zone requires major dextrally coupled clockwise bending of the northern part of the Weiser syncline in the Moapa Peak area. Because the steeply tilted to overturned rocks in the Moapa Peak area have no obvious spatial or mechanical relationship to mapped thrust faults and because they contain internal structures that could be related to reverse faulting (rather than to thrusting), we argue that the Weiser syncline does not extend into this area as a subthrust fold. Much of the tilting and overturning could be due to the emergent fanning of numerous reverse faults from a buried thrust fault into a triangular zone of fold-type accommodation. Some of the deformation in the Moapa Peak area could be Tertiary, as is suggested below. If the structures in the Moapa Peak area are considered to be Mesozoic in age and to record shortening strains related to blind thrusting (triangle zone), is it reasonable that the northeast structural trend results from major clockwise rotation during Neogene dextral shear? We consider it highly unlikely that the northeast trend, which lies approximately parallel to the trend of the Sevier orogenic belt for 500 km from southern Nevada to central Utah (Armstrong, 1968), results from any significant amount of rotation. We note that thrust-related shortening structures 75 km northeast of the Moapa Peak area are oriented northeast and indicate northwest-southeast shortening during Sevier time (R.E. Anderson, unpub. mapping, 1980-87; L.F. Hintze, R.E. Anderson, and G.F. Embree, unpub. mapping, 1982–92). If any Mesozoic structural trend in the region is anomalous, it is the more northerly trend of the (frontal) Weiser syncline in the Muddy Mountains, because its on-strike projection northward would place it deep within the hinterland of the Sevier orogenic belt.

The third critical component of the proposed Moapa Peak shear zone is the presence of a major dextral-slip fault zone buried beneath Cenozoic sedimentary rocks in the northern part of Mormon Mesa (fig. 21), a feature that Axen and others (1990) contended is detectable in seismic-reflection data. A component of dextral slip is likely on the geophysically imaged fault in order to accommodate extensional strain at the northern margin of one of three major buried east-tilted Cenozoic subbasins that have also been geophysically imaged (Grow and others, 1990). It is not known whether a major east-striking, through-going fault also accommodates tilting at the northern margin of the other two subbasins and thereby accumulates large dextral displacement. We prefer an interpretation that is consistent with our surface observations of the similarly oriented Davidson Peak-Horse Spring transverse fault zones, which do not accumulate such displacement. This interpretation agrees with our observations of sinistral slip in bedrock in the Candy Peak area in the southernmost Mormon Mountains (pl. 4, locality F). The alluvial gap north of Candy Peak along the western projection of the proposed Moapa Peak shear zone should show dextral slip, if it is cumulative, to be at a maximum, but structural projections across the gap (for example, Weiser syncline or overturned Permian rocks) preclude significant dextral displacement.

In summary, we found no individual or collective evidence among the main structural components for the existence of the proposed Moapa Peak shear zone; earlier fault-slip studies by Michel-Noel (1988) also were inconsistent with significant dextral slip. Apparent offset of imbricate thrust faults in the southern Mormon Mountains and contrasts in the thickness of Ordovician strata in the East Mormon Mountains were cited (Smith and others, 1987; Axen and others, 1990) as evidence for dextral slip in the shear zone. However, we conclude that elements of the thrust system are weak criteria for major structural reconstruction, because the traces of thrusts and thrust-related features are not necessarily linear, are poorly known, and, in the southern Mormon Mountains, are likely to have been modified extensively by post-thrusting deformation. Our observations that question the existence of the dextral-slip Moapa Peak shear zone are important because they open the way for alternative interpretations of deformational style and magnitude in the region.

Between the Colorado Plateau and the Meadow Valley Mountains (fig. 1), Wernicke, Axen, and Snow (1988) estimated composite extensional strain magnitude of 54±10 km in a direction 255°±10°. That large value results from structural restoration of a stack of three proposed west-vergent detachment faults that become younger to the east and have a breakaway zone or proximal boundary (Wernicke, 1990) along the Beaver Dam Mountains (Wernicke and others, 1989). The reliability of this estimate depends in part on whether the detachment faults formed and matured as planar features of great lateral extent with moderate to gentle dips and in part on whether each successively lower, younger one carried the older, higher ones along. Some of the structural features that we identify as common in this region (that is, convex-upward fault shape, lateral strain inhomogeneity, nonuniform slip sense, and plan-view extension-normal contraction) have a strong bearing on these reliability factors because they contradict the assumption of laterally cumulative strain, as discussed below.

Some major faults, such as the Gunlock, Jackson Wash, Peach Springs, East Mormon, and Carp Road faults, and many minor faults have significant components of strike slip. Major faults such as the Pahcoon Flat, Castle Cliff, southernmost East Mormon, Carp Road, and Horse Spring and other unnamed faults have footwall blocks that dip more steeply



EXPLANATION

Contact—Dashed where approximately located

Fault zone

Fault—Dotted where concealed; bar and ball on downthrown side; half arrows show direction of movement; A, motion away from viewer; T, motion toward viewer

Anticline

Syncline

Monocline

Boundary of Moapa Peak shear zone

Figure 21 (facing page). Contrasting interpretations for the major structures in the southern Mormon Mountains, Nevada. *A*, The model proposed by Axen and others (1990) depicts the three elements of the Moapa Peak shear zone: (1) the Horse Spring and Davidson Peak faults, (2) the clockwise-rotated Weiser syncline, and (3) a buried fault scarp in the Mormon Mesa basin interpreted from seismic-reflection data. *B*, The interpretation of this report (for a slightly larger area than diagram *A*) shows variable throw on segments of the Horse Spring and Davidson Peak fault systems as linked to variable displacements on normal and normal-sinistral faults that merge from the north. Diagram *B* also illustrates faults southwest of Moapa Peak and northeast of Candy Peak that offset overturned elements of the regional southeast-facing homocline, and a buried interbasin ridge that separates the Mormon Mesa basin south of the Mormon Mountains from a similar basin south of the Tule Springs Hills to the east (not shown). Heavy barbs in diagrams *A* and *B* show contrasting interpretations of plan-view shear sense. Large arrows in diagram *B* show main-phase extension direction. The northern limit of coherent seismic reflections in diagram *B* probably indicates a south-facing fault, the southern limit of steep tilting characteristic of areas to the north, or both.

than hanging walls, and these stratal tilt relations provide indirect evidence for convex-upward fault shape. These slip-sense and geometric characteristics differ greatly from the archetypal detachment fault shape (gently dipping, generally planar, predominantly dip slip) used in the structural reconstructions (Wernicke, Axen, and Snow, 1988). More important, we recognize a pattern of strong lateral variations in displacement magnitude on many major faults, directly associated with strong uplift and tilting of the footwall blocks. Faults that produce such localized deformation are commonly arranged en echelon in this region and, as a geometric consequence, the extensional strain represented by them is not cumulative in the direction of extensional kinematic axes. This discontinuous and inhomogeneous distribution of uplift and tilting resulted in scattered structural culminations that vary in size from about 20 to 2 km^2. Most of these uplifts are clearly too small and have flanks that are too steep to consider isostatic adjustments following tectonic denudation as a viable mechanism for their formation (Hamilton, 1987).

Because it is physically continuous with the adjacent stable Colorado Plateau, the main culmination in the Beaver Dam Mountains offers an excellent opportunity to evaluate how culminations form. We suggest that the formation of this culmination can be likened to resting one's right arm (Colorado Plateau) and fist (future Beaver Dam Mountains) on a table and flexing the fist upward. In the process, the knuckles and fingers (extension-parallel corrugations beneath the Castle Cliff detachment) move toward the arm as the proximal slope of the fingers decreases. The wrist produces a synclinal or homoclinal fold in which the skin is locally crumpled (Shivwitz syncline). At what stage the corrugations form is not known, but they could represent early ductile footwall shortening normal to the extension direction of the same deformation field represented by late strike-slip faults that displace the flexure axis. Rocks in the "hanging wall" above the knuckles are severely extended and attenuated, and record extreme extension across the culmination. The magnitude of attenuation and extension appears to have been about proportional to the magnitude of uplift and shortening. The deformation was highly localized and involved critical elements of in-place rotations around subhorizontal axes. This model of deformation is very different from some models that assume fault planarity, continuity, and interconnectedness that have been used in published estimates of extensional magnitude (Miller and others, 1983; Wernicke, Axen, and Snow, 1988). Conversely, this model is consistent with the observed complex fault shape and lack of interconnectedness reported for the Eldorado Mountains (Anderson, 1971) and Black Mountains (Anderson, 1978) 100 km to the southwest, and it is consistent as well with the complex pattern of extensional domains in the Nevada Test Site area 150 km to the west, which James Cole (oral commun., 1990) refers to as "mosaic extension."

In many ranges in the Basin and Range province where the structurally deepest exposures reveal significant block tilting, an inference was made that the tilting is related to displacement on an inferred, deeper detachment fault. Examples are by Bartley and Wernicke (1984) for the Egan and Schell Creek Ranges; by Davis and Lister (1988) for the Whipple Mountains; by Faulds and others (1990) for the southern Black Mountains and Eldorado Mountains, Arizona-Nevada; and by Wernicke and others (1985) for the Mormon Mountains. The tilting of footwall blocks beneath the Castle Cliff and Pahcoon Flat faults in the Beaver Dam Mountains cannot be associated with a buried detachment fault because no such fault emerges between those blocks and the western edge of the Colorado Plateau. Instead, the tilting must involve a major element of in-place rotation around subhorizontal axes, and we propose the upward-convex normal-fault geometry to explain such rotations. Wernicke and Axen (1988) interpreted the uplift and tilting as an isostatic response to tectonic unloading on a detachment fault, but King and Ellis (1990) modeled the deformation as associated with a steep fault. We prefer the steep-fault interpretation because it satisfactorily explains the shortening structures in the eastern part of the range and potential-field data directly west of the range. Rocks in the uplifted and tilted footwall block actually have a component of eastward motion relative to the adjacent unstrained margin of the Colorado Plateau (Wernicke and Axen, 1988). This compressional strain signature is somewhat similar to that modeled for footwall blocks by Buck (1988). We suspect that other strongly rotated and uplifted culminations in the area also involve major elements of approximately in-place horizontal-axis rotations rather than displacements on buried detachment faults. The convex-upward form interpreted by Anderson (1978) for the west-bounding fault of the northern Black

Mountains south of Lake Mead suggests this type of rotation, as does a detailed study of fault geometry, magnitude, and kinematics at a major accommodation zone farther south in the Black Mountains (Faulds and others, 1990). The type of well-documented, in-place large-magnitude tilting associated with extension in the San Antonio Mountains, Nevada (Shaver and McWilliams, 1987) is probably more common in the Basin and Range province than heretofore recognized, although searches for its cause are generally unsuccessful.

In general, we find no geological or geophysical evidence for regionally extensive detachment faults in the Mesquite basin area. Extreme uplift of basement blocks such as those in the Beaver Dam and northeastern north Virgin Mountains and coeval subsidence of the adjacent 5-km-deep Mesquite basin (Carpenter and others, 1989; Grow and others, 1990) are primary features of the extensional strain signature and not a response to detachment faulting. These features, with a potential differential vertical relief of 12 km, formed simultaneously with displacement on range-bounding steep- to moderate-dipping normal and oblique-normal faults (King and Ellis, 1990).

There appears to be a genetic and kinematic association between oblique extension (components of strike-slip motion on major and minor north- to northeast-striking faults) and extension-normal constriction (foldlike map-scale uplifts and depressions that are generally oriented parallel to the extensional kinematic axis). Good examples of this association are in the southern part of the East Mormon Mountains, where large-amplitude folds are spatially associated with and in some places bounded by strike-slip faults. We interpret much of this type of vertical structural relief in the area as recording extension-normal constriction. Much of the well-known extension-parallel doming of detachment faults such as in the lower Colorado River region (Frost and Martin, 1982) probably has a similar origin. The view held by Hamilton (1987) that such doming cannot be due to compression because it forms together with extensional structures does not recognize that significant strains can be expected coaxial with the intermediate compressive stress direction, expecially if flexural rigidity was drastically reduced during the deformation (Spencer, 1987). We speculate that a significant part of the uplift and tilting that formed the homocline in the Moapa Peak area is Tertiary and that the uplift and tilting absorbs some of the southward translation of the Mormon Mountains on generally north striking sinistral faults located between the Mormon and East Mormon Mountains (fig. 22). Much of the internal folding in the Moapa Peak area resembles a down-to-the-mountain folding and faulting style seen at monoclinal margins of many ranges in the Basin and Range province (Longwell, 1945; Thompson and White, 1964; Anderson and Mehnert, 1979; Anderson, 1983; Anderson and Barnhard, 1987; Anderson and Christensen, 1989), as well as in the nearby Virgin Gorge area (Bohannon and others, 1983). This internal deformation could result from gravitational collapse and spreading as the uplifted and tilted rocks of the monocline lose lateral support at shallow or near-surface structural levels. The monocline, on the other hand, to the extent that it is Tertiary in age, probably reflects uplift produced by shortening normal to its overall trend or by a combination of sinistral shear and shortening. Dextral slip is seen only on sparse northwest-striking faults. The sinistral slip on north- and northeast-striking faults west of Candy Peak could be the eastern part of a large-displacement sinistral-slip shear zone coupled through the homocline to the East Mormon Mountains, as shown in figure 22. According to this speculation, the Tertiary component of tilting and folding on northeast and east trends results from structural crowding at a right step in a sinistral-slip shear system (fig. 22). Similar structural crowding is seen in analogous structural settings in Tertiary rocks in the central Sevier Valley area of Utah (Anderson and Barnhard, 1987), in the Cedar City–Parowan monocline northeast of Cedar City in southwestern Utah (Anderson and Christensen, 1989), and in the Echo Hills in southern Nevada (Campgna and Aydin, 1989).

The folding of the Tertiary rocks in the Candy Peak area (pl. 4) and the angular unconformity at the base of the Tertiary sedimentary rocks in that area are consistent with the speculation that much of the deformation results from along-strike absorption of Neogene displacements on strike-slip faults. Another example of generally north south shortening is north and northwest of the Beaver Dam Mountains where systems of large and small conjugate(?) dextral and sinistral faults cut Miocene strata (unit Tsv, pl. 1). Also, open folds in Cenozoic strata detected in a north-south reflection profile to the south of the Mormon Mountains (Grow and others, 1990) could be part of the same deformation. The severe uplift of the large northeast-trending pod-shaped, basement-cored masses in the northern Virgin Mountains is probably mostly of late Cenozoic age (R.G. Bohannon, oral commun., 1989). Northwest-southeast structural crowding or shortening across these features is suggested by steep to overturned strata and conjugate(?) sets of sinistral and dextral strike-slip faults. It is currently unclear to what extent formation of the northeast-trending Neogene Virgin River depression and its south-flanking basement uplifts with differential vertical structural relief of about 12 km (Carpenter and others, 1989; Grow and others, 1990) reflects northwest-southeast crustal constriction. It seems likely that such extreme abrupt upper crustal structural relief involves a component of midcrustal rock flowage from depressed areas to uplifted areas, as was suggested by Gans (1987).

The cumulative amount of north-south to northwest-southeast shortening recorded in these previously unreported varied Cenozoic fault-fold structures in the Mormon Mountains area is unknown. It is believed to be several kilometers and possibly more than 10 km. Whatever its

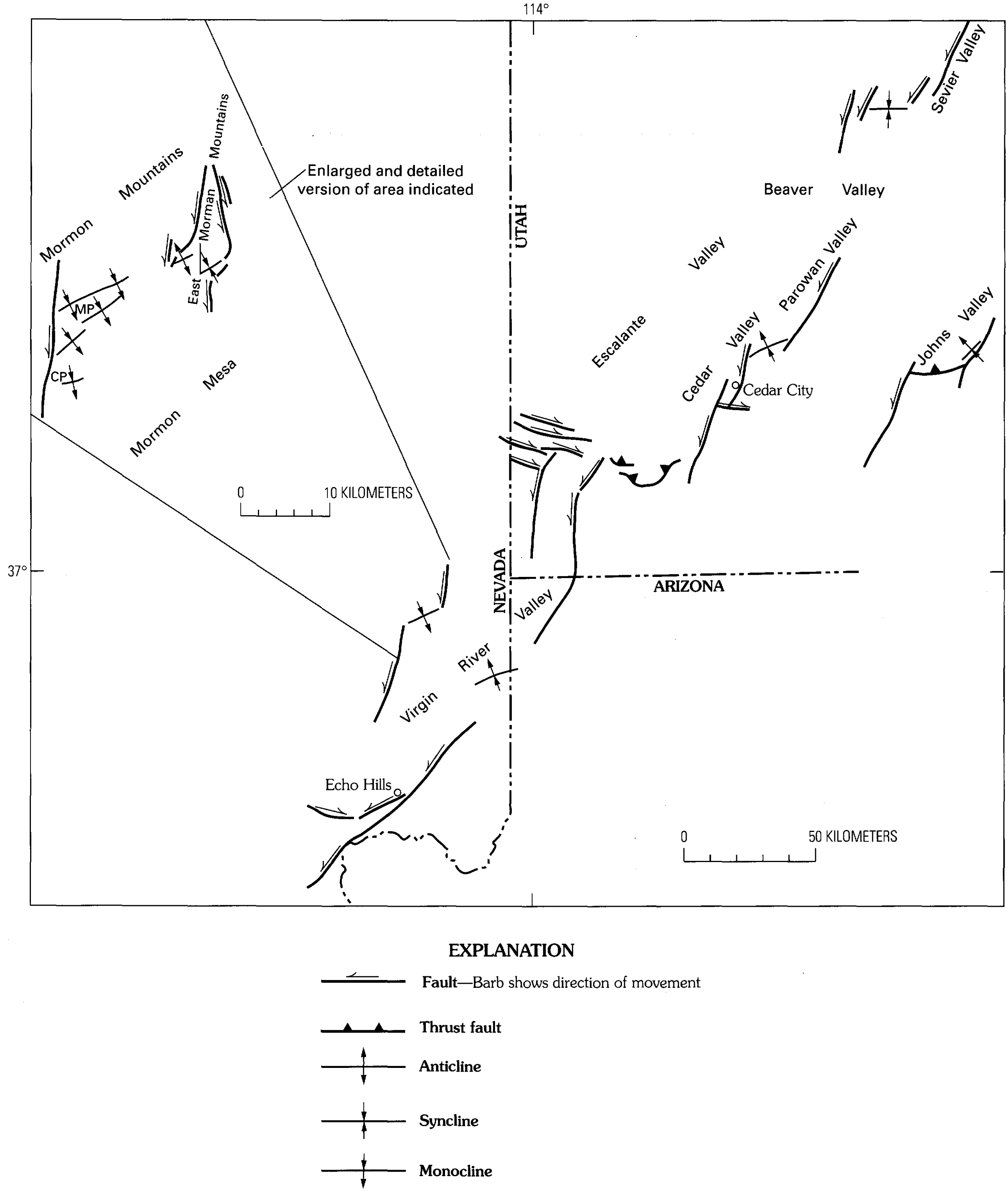


Figure 22. Map of the southeastern Great Basin, Utah-Nevada-Arizona, showing traces of selected faults with known or suspected components of strike slip, traces of associated thrust faults, and folds. Structural crowding associated with right steps in northeast-striking sinistral systems is in the area between Sevier Valley and Beaver Valley and between Parowan Valley and Cedar Valley. We apply an analogous interpretation to folds and thrust faults in the Johns Valley area, as well as to the folding in the East Mormon Mountains, Moapa Peak, and Candy Peak areas. In our model, the Mormon Mountains have been translated southward relative to the East Mormon Mountains, both of which have been similarly translated relative to pre-Tertiary rocks beneath Mormon Mesa.

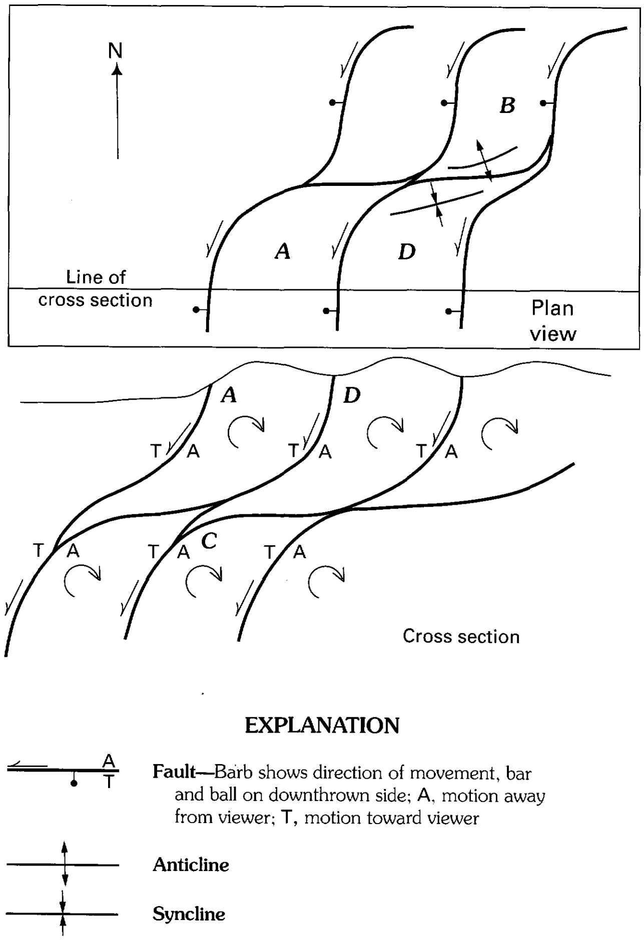


Figure 23. Schematic plan view and cross section of relationships between oblique-slip faults interconnected through transverse and subhorizontal zones of structural accommodation. The plan-view sigmoidal fault pattern is the predominant regional pattern in the southeastern Great Basin, Utah-Nevada-Arizona, as shown in figure 22. The sigmoidal fault traces in the cross section resemble those depicted by Bohannon (1989) for the early-stage rifting of the Red Sea-Gulf of Aden areas. Here it is assumed that initial development of the interconnected subhorizontal zones of the sigmoids are controlled by mechanically weak rocks or preexisting fault-damaged rock and that the zones separate stacked blocks with separate tilt axes. At high strain levels, the zones accommodate large-magnitude differential rotations (curved arrows). The southward translation of block *B* could be absorbed by folding, as sketched. Alternatively, through complex interchanges and very high strain, block *B* could be translocated to the position of block *A*, as block *C*, through severe uplift and tilting, moves to the position of block *D*, which is eroded away. As block *C* is uplifted and tilted, block *A* is attenuated and structurally translocated out of the system.

magnitude, it represents a strain component that must be added to the north-south shortening deduced from displacements on major regional strike-slip fault systems (Wernicke, Axen, and Snow, 1988; Anderson, 1990). Footwall rocks of the central Mojave metamorphic core complex near Barstow, Calif., show internal constriction of probable large magnitude coeval with and normal to the extensional elongation (Fletcher and Bartley, 1990). Constrictional strains of this orientation are predictable and are probably very common in the Basin and Range province. Strain analysis of extensional mylonites (Glazner and Bartley, 1991) shows that constrictional strains predominate over the plane-strain flattening that would be expected if simple shear were the prime mode of extensional deformation. These recent research results, together with the results reported here, indicate a critical need for additional research focused on constrictional strains in extended terranes.

Collectively, the several newly recognized attributes of Neogene structural geology have a high potential for significantly reducing the magnitude of estimated extensional strain by introducing important components of noncumulative and nontranslational tilting as well as important components of horizontal contraction oriented normal to the extensional kinematic axis. A suggested scheme for the plan-view and cross-sectional traces of faults associated with this complex mixture of tilting, rotation, faulting, and folding is shown in figure 23. Clearly, this scheme is neither rigorously developed nor unique. It does depict sigmoidal fault patterns and complex structural interactions similar to those seen in this part of the Basin and Range province. It also shows map patterns that are strikingly similar to patterns in cross section, and we recognize this similarity as another attribute characteristic of the structure of this region. In order to be valid, any scheme that is developed to explain the extraordinarily complex and heterogeneous elements of the Neogene strain field in this region must integrate the three-dimensional aspects of the deformation. Vertical and horizontal contractions combine to form constrictional strains whose magnitudes seem to match those of the extensional components. The concentration of strike-slip faults, map-scale and smaller folds, and localized extreme uplifts and depressions in the southeastern part of the northern Basin and Range province may be a province-boundary feature not likely to be found in more central parts of the province.

REFERENCES

Anderson, R.E., 1971, Thin skin distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, no. 1, p. 43–58.

———1978, Geologic map of the Black Canyon 15-minute quadrangle, Mohave County, Arizona, and Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ–1394, scale 1:62,500.

———1981, Structural ties between the Great Basin and Sonoran Desert sections of the Basin and Range Province, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mojave Sonoran Desert, California and Arizona: U.S. Geological Survey Open-File Report 81–503, p. 4–6.

———1983, Cenozoic structural history of selected areas in the eastern Great Basin, Nevada-Utah: U.S. Geological Survey Open-File Report 83–504, 47 p.

———1990, West-directed tectonic escape between the northern and southern sectors of the Basin and Range Province: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 2.

Anderson, R.E., and Barnhard, T.P., 1986, Genetic relationship between faults and folds and determination of Laramide and neotectonic paleostress, western Colorado Plateau-transition zone, central Utah: Tectonics, v. 5, no. 2, p. 335–357.

———1987, Neotectonic framework of the central Sevier Valley area, Utah, and its relationship to seismicity: U.S. Geological Survey Open-File Report 87–585, p. F1–F134.

Anderson, R.E., and Christensen, G.E., 1989, Map showing Quaternary faults, folds, and selected volcanic features in the Cedar City 1°×2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89–6, 29 p., scale 1:250,000.

Anderson, R.E., and Hintze, L.F., in press, Geologic map of the Dodge Spring quadrangle, Washington County, Utah, and Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map 1721.

Anderson, R.E., and Mehnert, H., 1979, Reinterpretation of the history of the Hurricane fault in Utah: Rocky Mountain Association of Geologists, Utah Geological Association, 1979 Basin and Range Symposium, guidebook, p. 145–173.

Angelier, Jacques, Colletta, Bernard, and Anderson, R.E., 1985, Neogene paleostress changes in the Basin and Range—A case study at Hoover Dam, Nevada-Arizona: Geological Society of America Bulletin, v. 96, p. 347–361.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Asmerom, Yemane, Snow, J.K., Holm, D.K., Jacobsen, S.B., Wernicke, B.P., and Lux, D.R., 1990, Rapid uplift and crustal growth in extensional environments—An isotopic study from the Death Valley region, California: Geology, v. 18, no. 3, p. 223–226.

Axen, G.J., and Wernicke, Brian, 1987, Magnitude and style of Miocene Society of America Abstracts with Programs, v. 19, no. 7, p. 576.

———1989, On the role of isostasy in the evolution of normal fault systems—Reply: Geology, v. 17, no. 8, p. 775–776.

Axen, G.J., Wernicke, B.P., Skelly, M.F., and Taylor, W.J., 1990, Mesozoic and Cenozoic tectonics in the Sevier thrust belt of the Virgin River Valley area, southern Nevada, *in* Wernicke, Brian, ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 123–153.

Bartley, J.M., and Wernicke, B.P., 1984, The Snake Range décollment interpreted as a major extensional shear zone: Tectonics, v. 3, p. 647–659.

Blank, H.R., Jr., and Kucks, R.P. 1989, Preliminary aeromagnetic, gravity, and generalized geologic maps of the USGS Basin and Range—Colorado Plateau transition zone study area in southwestern Utah, southeastern Nevada, and northwestern Arizona (the BARCO project): U.S. Geological Survey Open-File Report 89–432, 16 p., 3 plates, scale 1:250,000.

Bohannon, R.G., 1983a [1984], Geologic map, tectonic map, and structure sections of the Muddy and northern Black Mountains, Clark County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I–1406, scale 1:62,500, 2 sheets.

———1983b, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada, *in* Miller, D.M., and others, eds., Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 125–148.

———1989, Style of extensional tectonism during rifting, Red Sea and Gulf of Aden: Journal of African Earth Sciences, v. 8, p. 589–602.

———1991, Geologic map of the Jacobs Well and southern part of Elbow Canyon quadrangles, Mojave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–2167, scale 1:24,000.

Bohannon, R.G., Antweiler, J.C., Lucchitta, Ivo, Anderson, R.E., Beard, L.S., Hovorka, D.S., and Briggs, J.P., 1983, Geology and mineral resource potential of The Narrows (AZ–010–135), Lime Hills (AZ–010–134), and Sand Cove (AZ–010–128) wilderness study areas, Mohave County, Arizona: U.S. Geological Survey Open-File Report 83–887, 10 p.

Bohannon, R.G., and Lucchitta, Ivo, 1991, Geologic map of the Mount Bangs quadrangle, Mojave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–2166, scale 1:24,000.

Bosworth, William, Lambiase, Joseph, and Keisler, Ron, 1986, A new look at Gregory's rift—The structural style of continental rifting: EOS [Transactions of the American Geophysical Union], v. 67, p. 577–583.

Boyer, S.E., and Mitra, Gautam, 1988, Relations between deformation of crystalline basement and sedimentary cover at the basement/cover transition zone of the Appalachian Blue Ridge province, *in* Mitra, Gautam, and Wojtal, Steven, eds., Geometries and mechanisms of thrusting, with special reference to the Appalachians: Geological Society of America Special Paper 222, p. 119–136.

Buck, Roger, 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959–973.

Cameron, T.E., and Frost, E.G., 1981, Regional development of major antiforms and synforms coincident with detachment faulting in California, Arizona, Nevada, and Sonora: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 421–422.

Campagna, David, and Aydin, Atilla, 1989, The Echo Hills, Nevada—Compressional feature in the Basin and Range: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A68.

Carpenter, D.G., Carpenter, J.A., Bradley, M.D., Franz, U.A., and Reber, S.J., 1989, Comment and reply on "On the role of isostasy in the evolution of normal fault systems": Geology, v. 17, p. 774–775.

Chapin, C.E., 1978, Evolution of the Rio Grande rift—Comparisons between segments and the role of transverse structures [abs.], *in* Proceedings, International Symposium on the Rio Grande rift, Santa Fe, New Mexico: Los Alamos Scientific Laboratory Conference Proceedings LA–7487–C, p. 24–27.

———1989, Volcanism along the Socorro accomodation zone, Rio Grande rift, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 46–57.

Cook, E.F., 1957, Geology of the Pine Valley Mountains, Utah: Utah Geological and Mineralogical Survey Bulletin 58, 114 p.

———1960, Geologic atlas of Utah—Washington County: Utah Geological and Mineralogical Survey Bulletin 70, 124 p.

Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, 490 p.

Davis, G.H., and Krantz, R.W., 1986, Post-"Laramide" thrust faults in the Claron Formation, Bryce Canyon National Park, Utah: Geological Society of America Abstracts with Programs, v. 18, no. 2, p. 98.

Davis, G.A., and Lister, G.S., 1988, Detachment of faulting in continental extension—Perspectives from the southwestern U.S. Cordillera, *in* Clark, S.P., Jr., Burchfiel, B.C., and Suppe, John, eds., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 133–160.

Dutton, E.E., 1880, Report on the geology of the high plateaus of Utah: U.S. Geographical and Geological Survey, Rocky Mountain Region, 307 p., with atlas.

Ekren, E.B., Orkild, P.P., Sargent, K.A., and Dixon, G.L., 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I–1041, scale 1:250,000.

Faulds, J.E., 1989, Structural development of a major extensional accommodation zone in the Basin and Range Province, northwestern Arizona and southern Nevada–Implications for kinematic models of continental extension: Albuquerque, University of New Mexico Ph.D. dissertation, 263 p.

Faulds, J.E., Geissman, J.W., and Mawer, C.K., 1990, Structural development of a major extensional accommodation zone in the Basin and Range province, northwestern Arizona and southern Nevada—Implications for kinematic models of continental extension, *in* Wernicke, Brian, ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 37–76.

Fletcher, J.M., and Bartley, J.M., 1990, Constrictional strain in the footwall of the central Mojave metamorphic core complex, California: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 23.

Frost, E.G., and Martin, D.L., eds., 1982a, Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, 608 p.

———1982b, Comparison of Mesozoic compressional tectonics and mid-Tertiary detachment faulting in the Colorado River area, California, Arizona and Nevada, *in* Cooper, J.D., compiler, Geologic excursions in the California desert: Geological Society of America, Cordilleran Section, 78th Annual Meeting, Anaheim, Calif., April, 1982, p. 113–159.

Gans, P. B., 1987, An open-system, two-layer crustal stretching model for the eastern Great Basin: Tectonics, v. 6, no. 1, p. 1–12.

Gardner, L.S., 1941, The Hurricane fault in southwestern Utah and northwestern Arizona: American Journal of Science, v. 239, p. 241–260.

Glazner, A.F., and Bartley, J.M., 1991, Volume loss, fluid flow and state of strain in extensional mylonites from the central Mojave Desert, California: Journal of Structural Geology, v. 13, no. 5, p. 587–594.

Grow, J.A., Bohannon, R.G., Miller, J.J., and Anderson, R.E., 1990, A seismic reflection study of Miocene listric faulting north of Lake Mead, Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 67.

Guth, P.L., 1981, Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada: Geological Society of America Bulletin, v. 92, p. 763–771.

Hamblin, W.K., Damon, P.E., and Bull, W.B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau: Geology, v. 9, p. 293–298.

Hamilton, W., 1987, Crustal extension in the Basin and Range province, southwestern United States, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L. eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p.155–176.

———1988, Detachment faulting in the Death Valley region, California and Nevada, *in* Carr, M.D., and Yount, J.C., eds., Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada: U.S. Geological Survey Bulletin 1790, p. 51–85.

Hintze, L.F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 1–36.

Howard, K.A., Stone, Paul, Pernokas, M.A., and Marin, R.F., 1982, Geologic and geochronologic reconnaissance of the Turtle Mountains area, California—West border of the Whipple Mountains detachment terrane, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, p. 341–355.

John, B.E., 1987, Geometry and evolution of a mid-crustal extensional fault system—Chemehuevi Mountains, southeastern California, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 313–336.

King, G.C.P., and Ellis, M.A., 1990, The origin of large local uplift and flank volcanism in extensional regions: Nature, v. 348, p. 689–693.

Laubach, S.E., 1989, Normal fault geometry—Examples from above the Buckskin detachment fault, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A202.

Laubach, S.E., Vendeville, B.C., and Reynolds, S.J., in press, Patterns in the development of extensional fault-block shapes from comparison of outcrop-scale faults and experimental physical models: Norwegian Petroleum Society.

Longwell, C.R., 1945, Low-angle normal faults in the Basin and Range Province: American Geophysical Union Transactions, v. 26, p. 107–118.

———1949, Structure of the Northern Muddy Mountains area, Nevada: Geological Society of America Bulletin, v. 60, p. 923–968.

Lucchitta, Ivo, 1972, Early history of the Colorado River in the Basin and Range Province: Geological Society of America Bulletin, v. 83, p. 1933–1947.

Means, W.D., 1989, Stretching faults: Geology, v. 17, p. 893–896.

Michel-Noel, Gerard, 1988, Mecanismes et evolution de l'extension intracontinentale des Basins and Range, and developpement tectonique des bassins sedimentaires: Paris, France, Academie de Paris, Universite Pierre et Marie Curie, Memoires des Sciences de la Terre, thesis, 205 p.

Michel-Noel, Gerard, Anderson, R.E., and Angelier, Jacques, 1990, Fault kinematics and estimates of strain partitioning of a Neogene extensional fault system in southeastern Nevada, *in* Wernicke, Brian, ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 155–180.

Miller, E.L., Gans, P.B., and Garing, John, 1983, The Snake Range décollement—An exhumed mid-Tertiary ductile-brittle transition: Tectonics, v. 2, p. 239–264.

Miller, J.J., Grow, J.A., Bohannon, R.G., and Anderson, R.E., 1990, Seismic images of Miocene listric faulting North of Lake Mead, Nevada [abs.]: Geological Society of America Abstracts with Progams, v. 22, no. 3, p. 68.

Morley, C.K., Nelson, R.A., Patton, T.L., and Munn, S.G., 1990, Transfer zones in the east Africa rift system and their relevance to hydrocarbon exploration in rifts: American Association of Petroleum Geologists Bulletin, v. 74, no. 8, p. 1234–1253.

Morton, W.H., and Black, R., 1975, Crustal attenuation in Afar, *in* Pilger, Andreas, and Rosler, Artur, eds., Afar depression of Ethiopia, Inter-Union Commission on Geodynamics: International Symposium on the Afar region and related rift problems, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, Proceedings, Scientific Report 14, p. 55–65.

Olmore, S.D., 1971, Style and evolution of thrusts in the region of the Mormon Mountains, Nevada: Salt Lake City, University of Utah Ph.D. thesis, 213 p.

Olsen, P.E., and Schlische, R.W., 1990, Transtensional arm of the early Mesozoic Fundy rift basin—Penecontemporaneous faulting and sedimentation: Geology, v.18, p. 695–698.

Reynolds, S.J., and Lister, G.S., 1990, Folding of mylonitic zones in Cordilleran metamorphic core complexes—Evidence from near the mylonitic front: Geology, v. 18, p. 216–219.

Root, K.G., 1990, Extensional duplex in the Purcell Mountains of southeastern British Columbia: Geology, v. 18, p. 419–421.

Rosendahl, B.R., 1987, Architecture of continental rifts with special reference to East Africa: Earth and Planetary Science Letters, Annual Reviews, v. 15, p. 445–503.

Shaver, S.A., and McWilliams, Michael, 1987, Cenozoic extension and tilting recorded in Upper Cretaceous and Tertiary rock at the Hall molybdenum deposit, northern San Antonio Mountains, Nevada: Geological Society of America Bulletin, v. 99, p. 341–353.

Shawe, D.R., Blank, H.R., Jr., Wernicke, B.P., Axen, G.J., Barton, H.N., Day, G.W., and Rains, R.L., 1988, Mineral resources of the Mormon Mountains Wilderness Study Area, Lincoln County, Nevada: U.S. Geological Survey Bulletin 1729–B, 22 p.

Skelly, M.F., 1987, The geology of the Moapa Peak area, southern Mormon Mountains, Clark and Lincoln Counties, Nevada: Flagstaff, Northern Arizona University M.S. thesis, 150 p.

Smith, E.I., Anderson, R.E., Bohannon, R.G., and Axen, G.J., 1987, Miocene extension, volcanism, and sedimentation in the eastern Basin and Range Province, southern Nevada, *in* Davis, G.H., and VanderDolder, E.M., eds., Geologic diversity of Arizona and its margins—

Excursions to choice areas: Arizona Bureau of Geology and Mineral Technology, Geological Branch, Special Paper 5, p. 383–397.

Spencer, J.E., 1982, Origin of folds of Tertiary low-angle fault surfaces, southeastern California and western Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers (Anderson-Hamilton volume), p. 123–134.

———1984, Role of tectonic denudation in warping and uplift of low-angle normal faults: Geology, v. 12, p. 95–98.

———1987, Reduction of crustal flexural rigidity during folding of crystalline rocks in the Harcuvar and Whipple metamorphic core complexes, west-central Arizona and southeastern California [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 853.

Stewart, J.H., Moore, W.J., and Zietz, Isidore, 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geological Society of America Bulletin, v. 88, p. 67–77.

Stewart, J.H., and Suczek, C.A., 1977, Cambrian and latest Precambrian paleogeography and tectonics in the western United States, *in* Stewart, J.H., Stevens, C.H., and Fritche, A.E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 1–17.

Teel, D.B., and Frost, E.G., 1982, Synorogenic evolution of the Copper Basin formation in the eastern Whipple Mountains, San Bernardino County, California, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, p. 275–285.

Thompson, G.A., and White, D.E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U.S. Geological Survey Professional Paper 458–A, 52 p.

Tschanz, C.M., and Pampeyan, E.H., 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology Bulletin 73, 187 p.

Wernicke, Brian, 1981, Low-angle normal faults in the Basin and Range Province—Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648.

———1982, Processes of extensional tectonics: Cambridge, Mass., Massachusetts Institute of Technology Ph.D. thesis, 170 p.

———1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108–125.

———1990, The fluid crustal layer and its implications for continental dynamics, *in* Salisbury, M.H., and Fountain, D.M., eds., Exposed cross sections of the continental crust: Netherlands, Kluwer Academic Publishers, p. 509–544.

Wernicke, Brian, and Axen, G.J., 1988, On the role of isostasy in the evolution of normal fault systems: Geology, v. 16, p. 848–851.

Wernicke, Brian, Axen, G.J., and Snow, J.K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757.

Wernicke, Brian, Guth, P.L., and Axen, G.J., 1984, Tertiary extension in the Sevier orogenic belt, southern Nevada, *in* Lintz, J.P., ed., Western geological excursions: Reno, Nev., MacKay School of Mines, v. 4, p. 473–510.

Wernicke, Brian, Snow, J.K., Axen, G.J., Burchfiel, B.C., Hodges, K.V., Walker, J.D., and Guth, P.L., 1989, Extensional tectonics in the Basin and Range Province between the southern Sierra Nevada and the Colorado Plateau: International Geological Congress, 28th, Field Trip Guidebook T138, 80 p.

Wernicke, Brian, Snow, J.K., and Walker, J.D., 1988, Correlation of early Mesozoic thrusts in the southern Great Basin and their possible indication of 250–300 km Neogene crustal extension, *in* Weide, D.L., and Faber, M.L., eds., This extended land—Geological journeys in the southern Basin and Range: Geological Society of America, Cordilleran Section, Field Trip Guide, p. 255–268.

Wernicke, Brian, Walker, J.D., and Beaufait, M.S., 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, p. 213–246.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication October 22, 1991
Edited by Barbara Hillier
Graphics by Norma J. Maes and Alice A. Springfield and Joseph T. Springfield
Color design by Virginia D. Scott
Type composed by Marie Melone

☆ U.S. GOVERNMENT PRINTING OFFICE: 1993—774-3049/66,036 REGION NO. 8