Spatial variability in the structure of the Roberts Mountains allochthon, western Nevada

JOHN S. OLDOW *Department of Geology, Rice University, Houston, Texas 77251*

ABSTRACT

Structural variability in rocks of the upper plate of the Roberts Mountains thrust indicates a complex history of thrust emplacement during the mid-Paleozoic Antler orogeny. The Roberts Mountains allochthon consists predominantly of a highly deformed assemblage of structurally imbricated lower continental-slope and continental-rise sedimentary and volcanic rocks of early Paleozoic age. It has been interpreted variously as a back-arc thrust and as a grounded accretionary prism that overrode the upper Precambrian and lower Paleozoic passive margin of western North America. Current understanding of structural and stratigraphic relations supports the second interpretation.

The trace of the Roberts Mountains thrust trends south-southwesterly across Nevada from near the Idaho border to the vicinity of Tonopah (38°N lat.), where it is interpreted to swing westerly and extend to the Sierra Nevada. Subparallel to the thrust trace is the trend of the western boundary of the late Precambrian passive continental margin as deduced from lower Paleozoic facies patterns and the $^{87}Sr/^{86}Sr = 0.706$ line. The westerly deflection of these and younger trends has been attributed by some workers to crustal deformation of late Mesozoic and/or Cenozoic age, and by others to an original bend in the continental margin. Results presented here support the latter interpretation.

Structures in the northern and central segments of the Roberts Mountains thrust (characterized by south-southwest trace) consist of a single phase of folds and indicate easterly transport. The inferred southern segment of the thrust, with a westerly trend, exhibits two and locally three phases of folds interpreted as being genetically related to emplacement of the thrust. First-phase folds in the south are correlated with folds in the central and northern segments of the thrust and, after the effects of superimposed structures are geometrically removed, also yield an easterly transport direction. Cross folds in the southern part of the allochthon and their absence to the north indicate different structural histories for the regions.

Structures in the allochthon are interpreted as having developed during the formation of an accretionary prism. Differences in structural history are related to differential rates of slip on the allochthon's basal thrust during transport and emplacement. Development of cross folds in the south is thought to be due to a local reduction in the rate of displacement and corresponding internal shortening of the upper-plate rocks caused by resistance to subduction of a west-facing promontory of continental crust.

INTRODUCTION

Much of northern and central Nevada is underlain by the Roberts Mountains thrust, which trends north-northeast–south-southwest (Fig. 1) and juxtaposes two terranes of lower Paleozoic rocks: a western assemblage (allochthon) consisting dominantly of siliceous basinal rocks, and an eastern assemblage (autochthon) composed largely of continental-shelf carbonate and clastic rocks. Emplacement of the allochthon occurred during the Antler orogeny of Late Devonian and Early Mississippian age and is interpreted to have resulted in at least 100 km of displacement (Roberts and others, 1958; Smith and Ketner, 1968). Intermediate assemblage rocks are locally recognized in erosional windows through the upper plate of the Roberts Mountains thrust and in a few thrust slices within the allochthon. The trace of the thrust is best defined in central Nevada and is located by stratigraphic juxtaposition. Assignment of specific assemblages to the upper or the lower plate is not without controversy, but a general consensus exists, largely due to the lack of significant post-Antler deformation in much of the region (Speed, 1983a; Speed

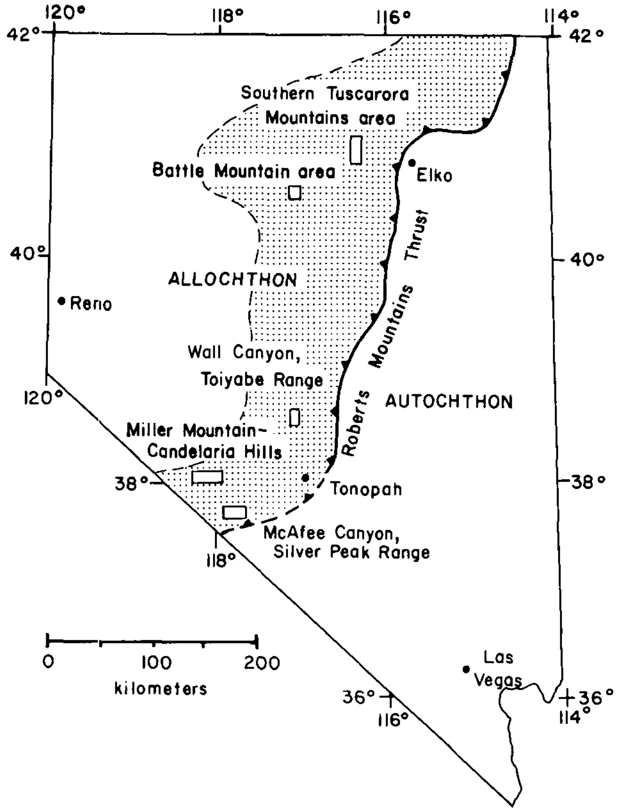

Figure 1. Index map of Nevada showing a generalized trace of the Roberts Mountains thrust, dashed where approximately located, and areas studied in this and previous (Evans and Theodore, 1978) investigations. The stippled pattern represents the approximate areal distribution of the Roberts Mountains allochthon.

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and Sleep, 1982). The southern extent of the thrust is generally considered to have a westerly trace and to extend to the Sierra Nevada (Burchfiel and Davis, 1972, 1975; Stewart and Pool, 1974; Poole and others, 1977; Rich, 1977; Stevens, 1977). This interpretation was recently questioned by Stewart (1980) who argued that no significant juxtaposition of facies is recognized in lower Paleozoic rocks of this area in west-central Nevada, possibly indicating the lack of Antler-age thrusting. Delineation of a southern extension of the thrust is further obfuscated by early and late Mesozoic deformation in this region (Speed, 1983a; Speed and Sleep, 1982; Oldow, 1981a, 1981b, and in press).

Early interpretations of the transport direction for the Roberts Mountains thrust in central Nevada were based on regional reconstructions of sedimentary-facies patterns that yield directions good only as a first approximation. Rocks of the western assemblage, consisting of interbedded chert, shale, quartzite, limestone, and greenstone, are interpreted as seaward facies deposited west of coeval continental-shelf carbonate rocks, calcareous shale, and quartzite (Roberts and others, 1958; Stewart and Poole, 1974). Thrusting reportedly transported the western assemblage eastward over the miogeoclinal rocks. Evans and Theodore (1978) studied mesoscopic structures within the allochthon and autochthon in north-central Nevada and concluded that transport was essentially west to east, corroborating earlier interpretations. They also concluded that deformation within the allochthon appeared to be relatively homogeneous over distances of at least 65 km.

The original setting and mode of emplacement of the Roberts Mountains allochthon have been the source of much interest over the last decade. They were proposed to be the product of marginal-basin collapse and back-arc thrusting (Burchfiel and Davis, 1972, 1975; Poole, 1974; Poole and Sandberg, 1977; Poole and others, 1977) and, alternatively, the result of accretionary-prism obduction during partial westward subduction of a passive continental margin beneath a volcanic arc (Moores, 1970; Dickinson, 1977; Speed, 1977, 1979; Speed and Sleep, 1982; Johnson and Pendergast, 1981). It is important to recognize, however, that a history corresponding to either model can result in kinematically and morphologically identical allochthons, particularly if the marginal basin of the active continental-margin model is relatively wide and a significant amount of oceanic lithosphere is consumed during closure. Constraints for model differentiation are based on the nature of sedimentary facies within the allochthon and on regional tectonic patterns. These relations currently are best explained by the accretionary-prism obduction model, but the hypotheses can be tested only by careful comparison of lower Paleozoic rocks in the Sierra Nevada and the Great Basin.

Formation of the Roberts Mountains allochthon by the accretionary process carries several important implications concerning structural development. Accretionary prisms exposed on Barbados (Speed, 1978, 1983b; Speed and Larue, 1982), Kodiak (Moore and Wheeler, 1978; Moore and Allwardt, 1980), and Nias (Moore and Karig, 1980) Islands all contain genetically related imbricate thrust faults and folds. Folds are generally tight to isoclinal, commonly with axial-plane cleavage, and in many instances are coaxially refolded or exhibit a girdle distribution of fold axes within planar-axial surfaces (sheath folds). Spatially, fold types either occur in discrete domains, commonly bounded by thrust faults, or change style gradationally, with sheath folds and/or coaxially refolded folds becoming more prevalent near bounding faults. In all cases, fold development is interpreted as occurring during thrust imbrication and, as a result, fold geometry is useful in determining thrust transport directions.

The present study attempts to delineate spatial variations in the style orientation and degree of deformation within Ordovician and Devonian rocks interpreted as parts of the Roberts Mountains allochthon. The objectives are to substantiate the existence of a westerly trending segment of the Roberts Mountains thrust in west-central Nevada, to deduce thrust transport directions in the allochthon, and to address the question of the origin of the nonlinearity of the thrust and younger structural and depositional trends in the region. Structures in three areas of west-central Nevada (Fig. 1) are compared with one another and with structures in north-central Nevada. Results of the investigation suggest that obduction of an accretionary prism, represented by the Roberts Mountains allochthon, occurred along an irregular continental margin and that a west-facing promontory of continental crust affected the kinematics of allochthon emplacement.

MILLER MOUNTAIN–CANDELARIA HILLS

Ordovician and Devonian rocks in the Miller Mountain–Candelaria Hills area (Fig. 2) make up a structurally complex assemblage with an aggregate tectonic thickness of approximately 1,500 m. The rocks originally were thought to represent a single stratigraphic succession and were assigned to the Ordovician Palmetto Formation by Ferguson and others (1954). Reevaluation of the assemblage (Stanley and others, 1977; Stewart, 1979) indicated structural imbrication of the constituent rocks and, accordingly, the succession is referred to here as the Palmetto complex. Ordovician units are composed of phyllitic shale, radiolarian chert, and minor amounts of calc-hornfels and quartzite. They are structurally interleaved with Devonian strata composed of siliceous calc-hornfels, chert, siliceous shale, calcareous quartz sandstone, sandy limestone, siliceous hornfels, and quartzite (Stanley and others, 1977). The depositional environment of both the Ordovician and Devonian rocks is interpreted as lower slope and continental rise (Stanley and others, 1977).

The Palmetto complex is overlain with pronounced angular unconformity by the Permian Diablo Formation (Ferguson and Muller, 1949; Ferguson and others, 1954; Page, 1959; Speed and others, 1977). In this area, the Diablo Formation (Speed and others, 1977) consists of chert-quartz sandstone, chert-pebble conglomerate, and sedimentary breccia all deposited in shallow-marine environments. The succession attains a maximum thickness of 25 m but is commonly 10 m or less thick, and locally it is absent. It is interpreted as Guadalupian in age (Silberling and Roberts, 1962) and is important as a firm upper age limit for the deformation in the underlying Palmetto complex.

In the eastern Candelaria Hills, the Diablo Formation is conformably overlain by the Candelaria Formation, which is as young as Early Triassic (R. C. Speed, 1982, personal commun.). Here, the Diablo and Candelaria Formations, undifferentiated upper Paleozoic and Mesozoic rocks, and the subjacent Palmetto complex are imbricated by thrust faults. Although some question exists concerning the minimum age of thrusting, the faults are probably related to early Mesozoic tectonism. One thrust slice contains Mississippian carbonate rocks that apparently overlie the Palmetto complex with angular unconformity (Fig. 2). Interpretation of the contact between the Mississippian carbonate rocks and the underlying Palmetto complex is equivocal but may indicate that major penetrative deformation of the underlying Palmetto occurred prior to Mississippian time.

Structure

Mesoscopic structures were studied in four areas of the Miller Mountain–Candelaria Hills exposures. Four phases of folds are recognized, and the general characteristics of each fold set, designated "D_1," "D_2," "D_3," and "D_4" in order of decreasing age, are summarized below. The first three phases occur only in rocks of the

Palmetto complex and predate deposition of the Diablo Formation and apparently the Mississippian carbonate rocks. The fourth phase is most easily recognized in the Diablo Formation but also deforms the overlying Candelaria Formation and undifferentiated late Paleozoic and Mesozoic assemblage (Fig. 2) as well. Fourth-generation structures deform the thrust imbricates exposed in the eastern Candelaria Hills and are probably the product of regionally extensive, late Mesozoic tectonism (Oldow, in press).

First-phase folds (D_1) consist of tight to isoclinal major and minor folds[1] with upright to overturned axial surfaces with variable strikes and shallowly to moderately plunging fold axes (Fig. 3). Axial-plane cleavage is well developed in shale and within thin shale interbeds in the folded chert units (Fig. 4A). Poorly developed cleavage occurs locally within hinge zones of folds in limestone beds. Folds are characterized by sharp hinges and very long homoclinal limbs. In several instances, first folds are rootless or have such long limbs that antiform-synform pairs cannot be identified. Thickening of competent layers is observed in fold hinges, yielding a class 1c to 2 fold morphology (Ramsay, 1967). First-phase folds are abundant but due to their isoclinal-to-tight habit are, in many areas, difficult to recognize.

D_1 fabric elements, consisting of fold axes and poles to axial surfaces and axial-plane cleavage, have a widespread, although systematic, distribution (Fig. 3) attributable to reorientation, predominantly during D_2 deformation. To varying degrees throughout the area, poles to first-generation axial surfaces and axial-plane cleavage define girdles about the concentrations of associated D_2 fold axes. In the western Candelaria Hills (areas A and B), two shallowly dipping, northerly striking girdles are developed about steeply plunging D_2 axes. In the eastern Candelaria Hills (area D), sparse data suggest a partial girdle, with a westerly strike and steep dip, about subhorizontal D_2 axes. First-phase fabric at Miller Mountain (area C) is similar in distribution to that of the Candelaria Hills, but it lies on the easterly trending southern limb of a major D_2 synclinorium. Here, two diffuse girdles are defined, one striking north-northeast, dipping shallowly west, and the other east-west, dipping shallowly south, and they have poles that correspond with the mode of moderate- to steep-plunging D_2 axes.

Second-generation folds (D_2) are close to tight major and minor folds with predominantly northeast-striking upright axial surfaces and fold axes with shallow to steep plunges (Fig. 3). Axial-plane cleavage is locally developed in the hinge zones of some folds that demonstrably fold axial surfaces and axial-plane cleavage of the D_1 folds (Fig. 4C). Only minor thickening of hinge zones is observed and folds generally lie within class 1c.

The orientational uniformity of second-phase fabric data throughout the area indicates the lack of significant reorientation by later fold events (D_3 and D_4). In the four study areas, mesoscopic data are consistent with orientations of map-scale D_2 fold patterns (Fig. 2). The major D_2 folds defined by form surfaces are upright, with no obvious preferred vergence, and they control the map-scale distribution of lithologic units and postdate the imbrication of thrust sheets.

Third-phase structures (D_3) are interpreted as a locally developed conjugate set of open to close folds with axial-surface orientations of approximately N70°E, 75°NW and N40°W, 30°SW. No axial-plane cleavage is associated with these folds, which consist only of minor folds; no major D_3 folds are observed. Preferential development of one or the other axial surface of the conjugate set is controlled by the map-scale orientation of bedding. In the western Candelaria Hills, characterized by northerly striking bedding, the N40°W, 30°SW conjugate is observed. In the Miller Mountain area, with west-northwesterly trending bedding, N70°E, 75°NW folds are prevalent. In only one domain, Miller Mountain, are folds of both orientations observed (Fig. 3).

Fourth-generation folds (D_4) consist of major open folds with half-wavelengths ranging from hundreds of metres to kilometres. The folds have upright, northwesterly striking axial surfaces and are most easily recognized where the laterally continuous Diablo Formation acts as a form surface. No mesoscopic D_4 folds were recognized.

McAFEE CANYON, SILVER PEAK RANGE

Stewart and others (1974) and Robinson and others (1976) correlated deformed and metamorphosed lower Paleozoic rocks in the Silver Peak Range (Fig. 1) with those exposed about 60 km north in the Miller Mountain–Candelaria Hills area. Rocks assigned to the Palmetto Formation in the Silver Peak Range are in thrust

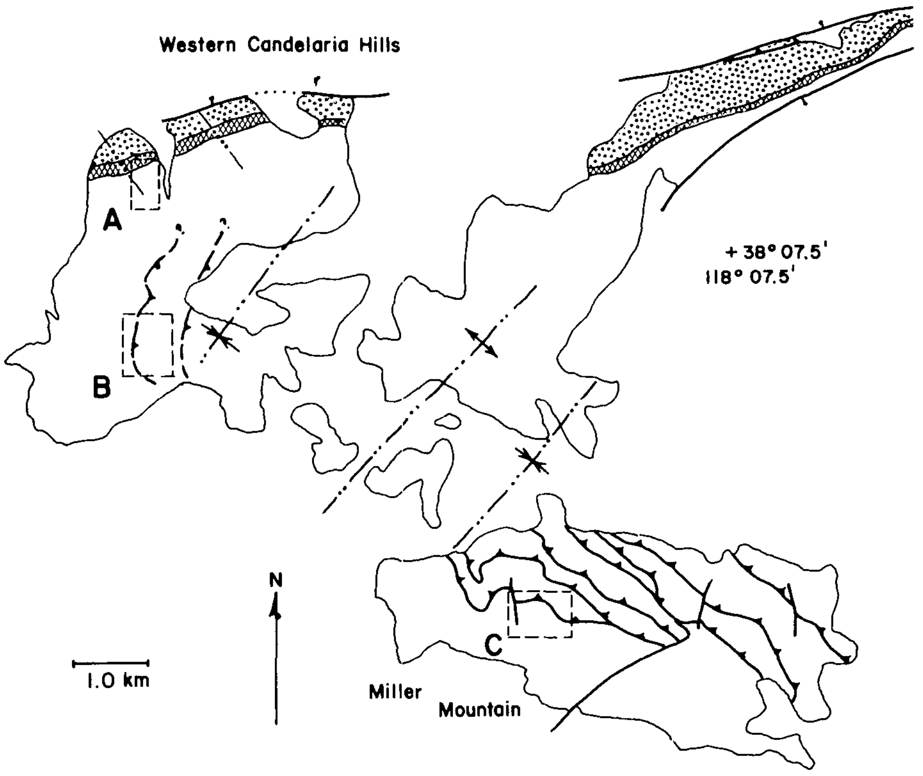

Figure 2. Generalized geologic map of the Miller Mountain—Candelaria Hills area; after Ferguson and others (1954), Page (1959), Speed and others (1977), and Stewart (1979). A, B, C, and D denote areas of detailed structural analysis.

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[1] Major folds: folds with half-wavelengths greater than 30 m. Minor folds: folds with half-wavelengths less than or equal to 30 m.

contact with Lower Cambrian limestone, phyllite, quartzite, and marble of the Mule Spring Limestone and the Harkless, Poleta, and Campito Formations.

The best exposures of the Palmetto lie in the McAfee Canyon area (Fig. 5), studied by Buckley (1971). The Palmetto there consists of a succession of thinly interbedded carbonates, calcareous siltstone, argillite, and chert units alternating with thick carbonate units; the Palmetto has been divided into six informal map units by Buckley (1971). Two of the units contain Ordovician conodonts. The nature of contacts between several map units is equivocal, but Buckley interpreted them largely as normal or slightly sheared sedimentary contacts. In light of the structural and biostratigraphic complexities demonstrated in the similar assemblage of lower Paleozoic rocks in the Miller Mountain–Candelaria Hills area, however, it is likely that the Palmetto assemblage in the Silver Peak Range is also more structurally complex than originally noted. The existence of numerous thrusts and the imbrication of rocks of various ages are probable.

Structure

Mesoscopic structures analyzed near the head of McAfee Canyon (Fig. 5) add constraints that amplify the conclusions drawn by Buckley (1971) concerning the geometry of folding. Three phases of folds (D_1, D_2, and D_3) are recognized, but ages of the deformations are poorly constrained. A history similar to that of the Miller Mountain–Candelaria Hills area is inferred from the sequential development and orientation of structures.

First-phase folds (D_1) are tight-to-isoclinal minor folds with upright-to-recumbent axial surfaces and moderately to shallowly plunging fold axes (Fig. 6). No major folds are recognized. Axial-plane cleavage is poorly developed and exists only in the hinge regions of some folds (Fig. 4D). Folds characteristically have sharp hinges and long homoclinal limbs and approximate a class 1c to 2 morphology.

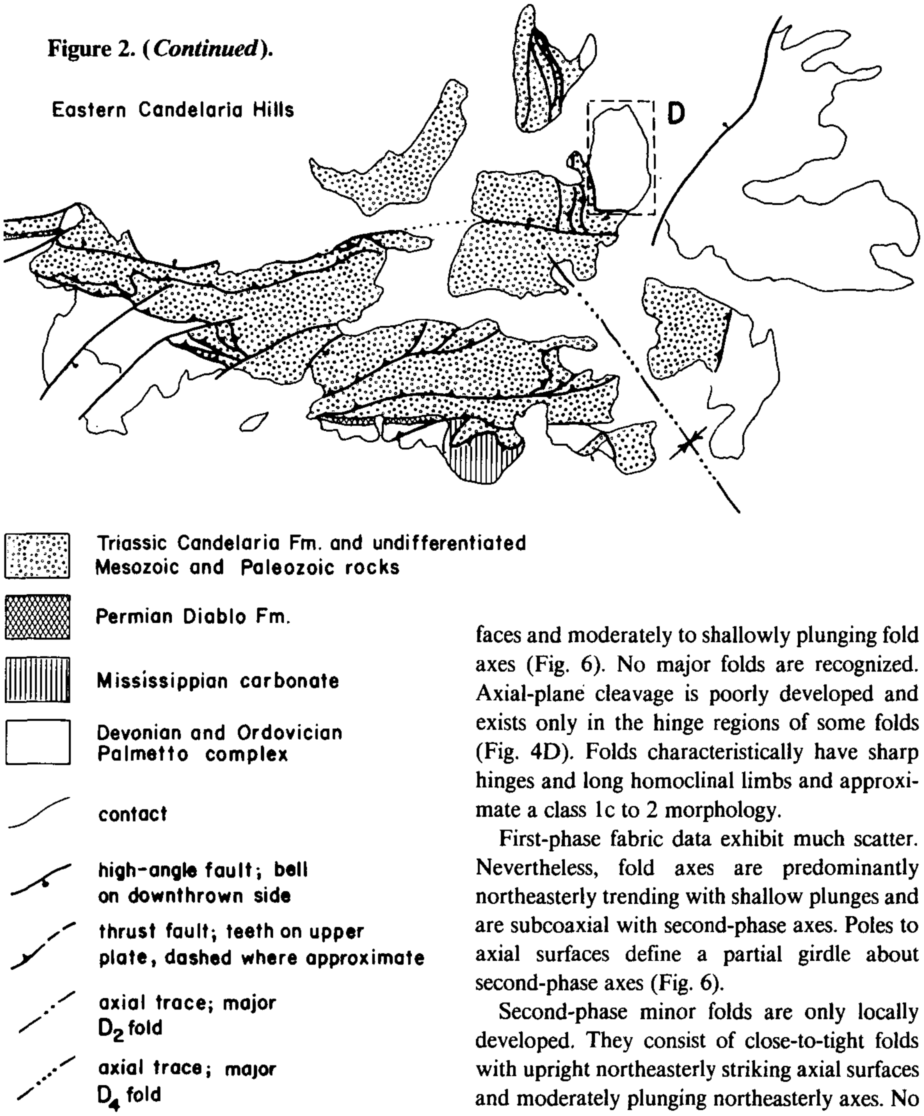


Figure 2. (***Continued***).

Eastern Candelaria Hills

First-phase fabric data exhibit much scatter. Nevertheless, fold axes are predominantly northeasterly trending with shallow plunges and are subcoaxial with second-phase axes. Poles to axial surfaces define a partial girdle about second-phase axes (Fig. 6).

Second-phase minor folds are only locally developed. They consist of close-to-tight folds with upright northeasterly striking axial surfaces and moderately plunging northeasterly axes. No appreciable thickening of second-fold hinges is noted, and they approximate a class 1b morphology. The few measured minor folds (Fig. 6) are consistent with major folds mapped farther west by Buckley (1971).

Third-phase folds are major open-to-close folds with upright to possibly slightly southerly vergent axial surfaces that strike northwesterly. The existence of D_3 folds is indicated by map-scale form surfaces, including lithologic units and axial traces of major D_2 folds. No minor folds are recognized.

WALL CANYON, TOIYABE RANGE

The lower Paleozoic strata exposed in Wall Canyon (Fig. 7), on the eastern flank of the Toiyabe Range, were assigned to the Palmetto and Gold Hill Formations by Ferguson and Cathcart (1954). A general vertical succession is recognized in rocks of the Palmetto Formation and consists of a lower unit composed of slate overlain by limestone and an upper unit composed of interbedded graptolitic shale, quartzite, limestone, and bedded chert. The shales contain graptolites typical of the Lower and Middle Ordovician (Ferguson and Cathcart, 1954; Ross, 1977). The Early Cambrian Gold Hill Formation (Ferguson and Cathcart, 1954) is composed of interbedded quartzite, mica schist and slate, dolomitic limestone, and oolitic limestone. The structural relations between and within the lithologic units are unclear but in all probability are similar to those of previously described units elsewhere. Whether the Wall Canyon assemblage resides in the upper or lower plate of the Roberts Mountains thrust is controversial. Ross (1977) argued that it is allochthonous; whereas Stewart (1980), on the basis of stratigraphic relations, proposed that it is autochthonous and that it represents a window in the Roberts Mountains thrust sheet.

Ferguson and Cathcart (1954) reported that the lower Paleozoic rocks are overlain with angular unconformity by the Permian Diablo Formation, which consists predominantly of conglomerate containing pebbles of slate, chert, and limestone derived from the underlying units. Extensive re-examination of the Diablo Formation in the Toiyabe Range (Speed and others, 1977) indicates that the rocks constitute eight spatially and/or structurally discrete units. Of the eight units, which consist of diverse lithologies, only two are autochthonous and unconformably overlie the Palmetto. One authochthonous Diablo unit, located in Pablo and Jett Canyons (Fig. 7), contains fossils (Ferguson and Cathcart, 1954) characteristic of the Phosphoria Formation and accordingly is of Leonardian or

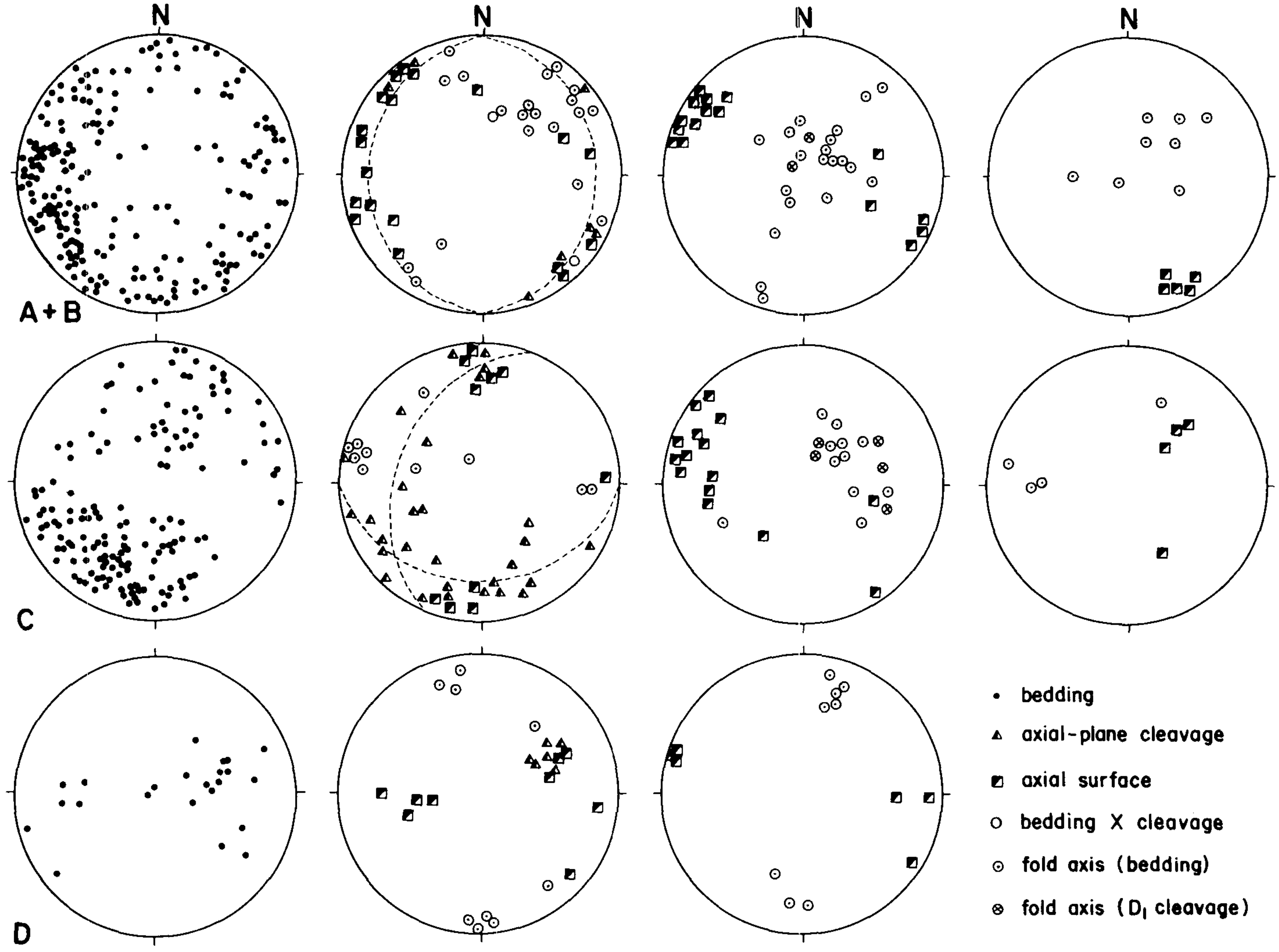


Figure 3. Lower-hemisphere, equal-area projections of mesoscopic fabric data for the Miller Mountain–Candelaria Hills area; discussion in text. Rows A + B, C, and D correspond to areas identified in Figure 2. Columns, from left to right, depict poles to bedding and structural fabric data for D_1, D_2, and D_3.

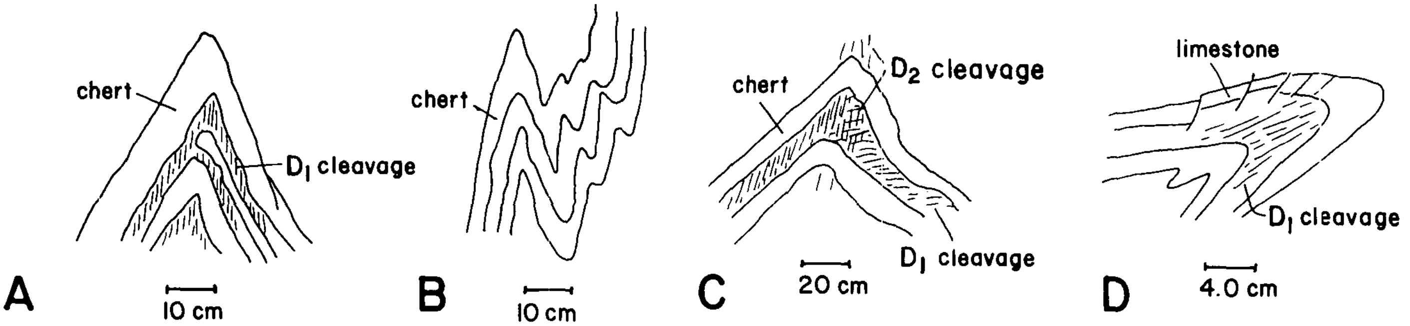
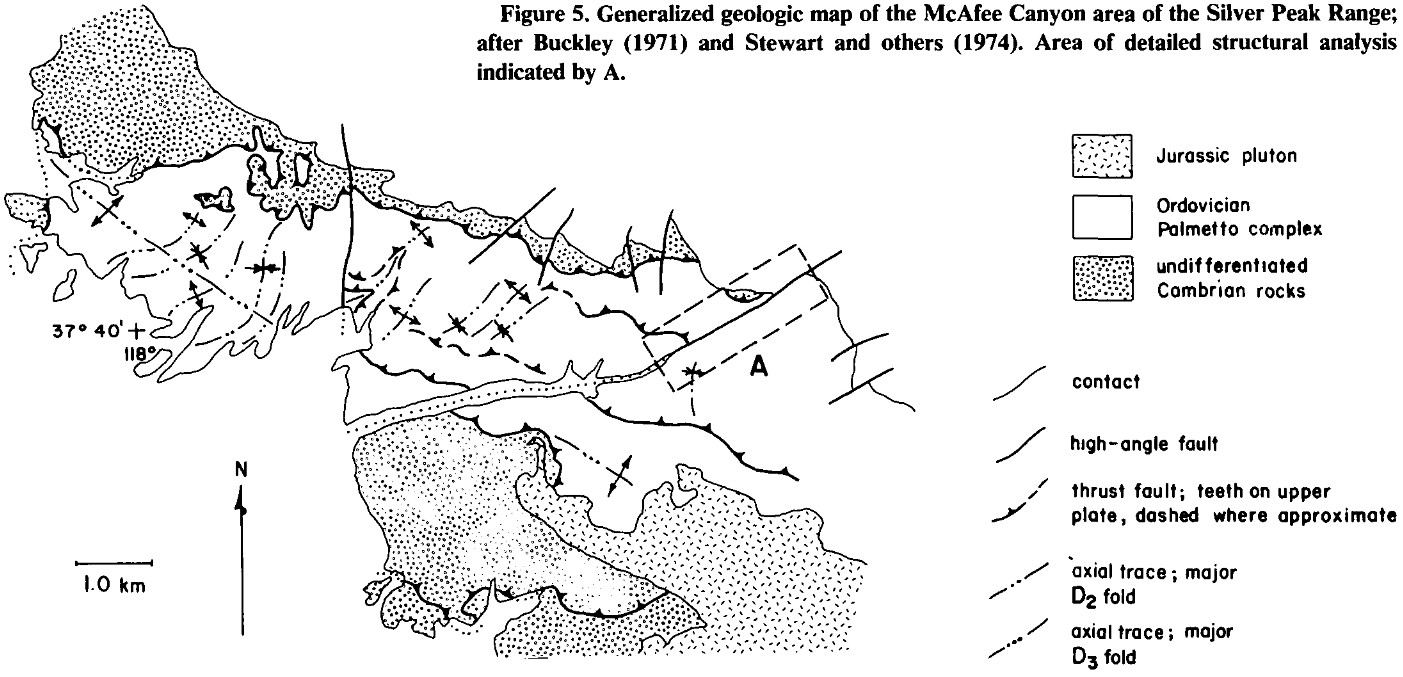


Figure 4. Sketches of minor folds. A, B, and C from Miller Mountain—Candelaria Hills; D from McAfee Mountain, Silver Peak Range. A. Tight D_1 fold of interbedded chert and argillite. B. Tight-to-isoclinal D_1 folds of bedded chert. C. Close D_2 fold of interbedded chert and argillite; D_1 axial-plane cleavage folded, D_2 axial-plane cleavage developed in hinge zone. D. Tight-to-isoclinal D_1 fold of interbedded limestone and calcareous mudstone; poorly developed axial-plane cleavage in calcareous mudstone.

Figure 5. Generalized geologic map of the McAfee Canyon area of the Silver Peak Range; after Buckley (1971) and Stewart and others (1974). Area of detailed structural analysis indicated by A.



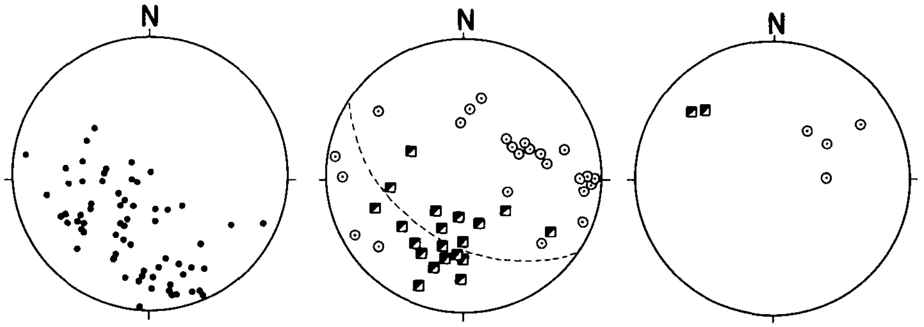


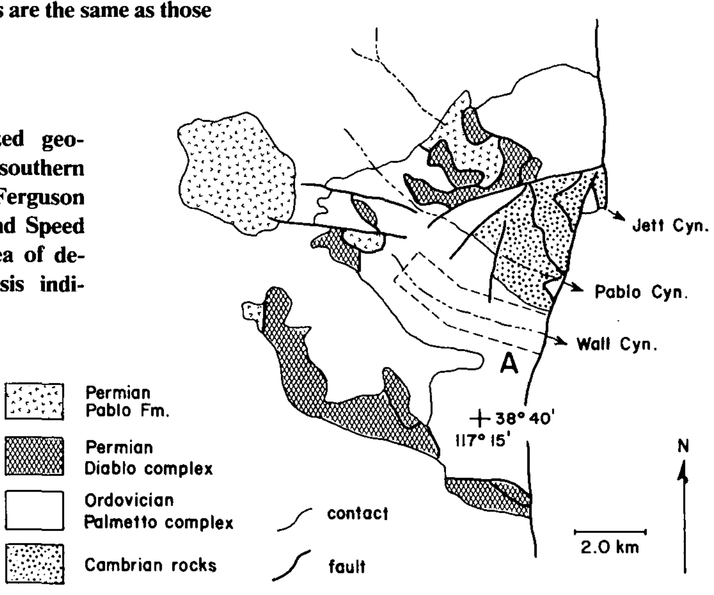
Figure 6. Lower-hemisphere, equal-area projections of mesoscopic fabric data (area A in Fig. 5) for McAfee Canyon, Silver Peak Range; discussion in text. Columns, from left to right, depict poles to bedding and structural fabric data for D_1 and D_2. Symbols are the same as those in Figure 3.

Guadalupian age (Speed and others, 1977). The autochthonous Diablo is deformed in polyphase, open-to-isoclinal folds together with the underlying lower Paleozoic strata. The deformation within the Diablo is attributed to emplacement of the Golconda thrust during the Permo-Triassic and to later deformation of Mesozoic age (Speed and others, 1977). Folds involving both Diablo and lower Paleozoic rocks, however, are restricted to the vicinity of the Diablo allochthons and do not penetrate more than a few tens of metres into the para-autochthonous lower Paleozoic rocks (autochthonous with respect to post-Devonian events) (R. C. Speed, 1979, personal commun.). Although relationships are structurally complicated, an upper age limit for the major penetrative deformation of lower Paleozoic rocks of the Wall Canyon area predates the Diablo Formation and is pre-Leonardian and/or pre-Guadalupian.

Structure

Isoclinal folds in the lower Paleozoic rocks have been recognized for some time (Ferguson and Cathcart, 1954; Ross, 1977), and Ferguson and Cathcart (1954) suggested that the entire assemblage is significantly thickened structurally. Ross (1977) stated that slate and limestone of the lower unit of the Palmetto assemblage

Figure 7. Generalized geologic map of part of the southern Toiyabe Range after Ferguson and Cathcart (1954) and Speed and others (1977). Area of detailed structural analysis indicated by A.



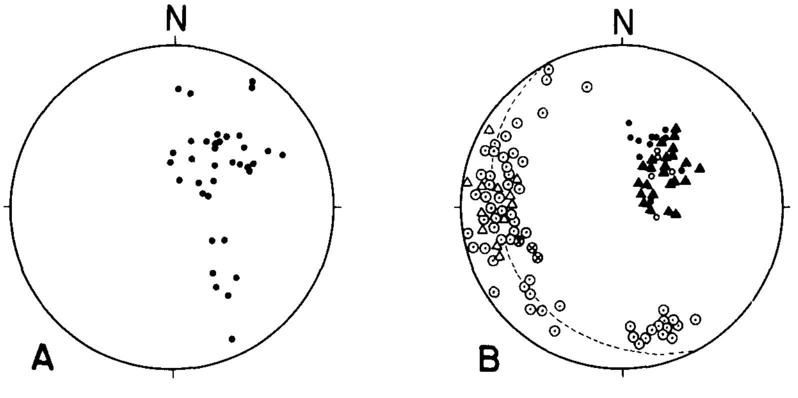


Figure 8. Lower-hemisphere, equal-area projections of mesoscopic fabric data for Wall Canyon (area A in Fig. 7), southern Toiyabe Range; discussion in text.

have undergone much greater deformation than has the overlying graptolitic shale of the upper unit. He suggested, on the basis of apparent difference in structural complexity, that folding of the lower unit may have occurred as early as late Arenigian (Ordovician), predating deposition of the shale. Differences in structural style within the two units, however, are due in part to differences in rheologic behavior of the units and to some degree are only apparent, because of the existence of well-defined markers in the limestone of the lower unit and absence of markers in the shale of the upper unit.

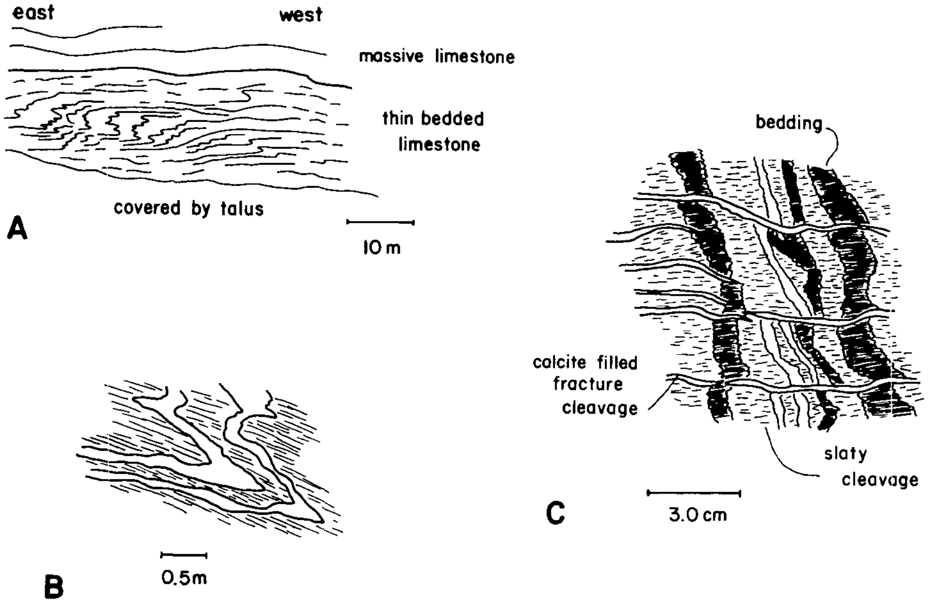


Figure 9. Sketches of structures in Wall Canyon, southern Toiyabe Range. A. Minor folds of thinly bedded limestone on south side of Wall Canyon illustrating west-over-east sense of shear. B. Minor fold of thinly bedded limestone illustrating class 2 morphology. C. Relation between bedding, slaty cleavage, and fracture cleavage.

A single phase of folds is observed in the assemblage of Wall Canyon and consists of tight-to-isoclinal major and minor sheath folds with half-wavelengths ranging from a few millimetres to at least several tens of metres. Axial planes uniformly strike north-northwesterly and have shallow westerly dips (Fig. 8). Arcuate hinges are common for minor folds with planar axial surfaces, and the relation presumably holds for major folds, although inadequate exposures did not allow direct observation. A penetrative slaty cleavage is developed parallel to axial planes and causes apparent displacements on the order of a few millimetres across bedding surfaces (Fig. 9C). Subparallel (within 10°) and crosscutting the slaty cleavage, there is a fracture cleavage with a spacing of 5 cm or greater. The fracture cleavage is characteristically filled with secondary calcite. Greater apparent displacement of bedding surfaces occurs across the fracture cleavage than observed for the slaty cleavage; it commonly is as great as 1 cm (Fig. 9C). The apparent displacement of bedding across both slaty cleavage and fracture cleavage may be due largely to dissolution, because no direct evidence currently exists to indicate slip during shear. The asymmetry of major folds, however, suggests the existence of a shear couple with a west-over-east rotation (Fig. 9A). Pronounced thickening of bedding occurs in hinges of folds, and they approximate a class 2 morphology (Fig. 9B).

Poles to beds give a diffuse north-striking girdle consistent with the dominant orientation of fold axes (Fig. 8). Poles to axial planes and slaty and fracture cleavages plot as a point maximum with fold axes and lineations forming a girdle consistent with the orientation of D_1 axial foliations. The girdle contains a maximum of axes in the downdip orientation of the associated axial foliations.

The variation in fold-axis orientation is a primary feature and the result of noncylindricism of the folds. Variably oriented fold axes are contained in single axial planes with changes of axis orientation of as much as 130° measured in individual folds. Furthermore, bedding-cleavage lineations (both slaty cleavage and fracture cleavage) plot on a common great circle coincident with axial planes (Fig. 8). These relations cannot readily be attributed to refolding of axes that were colinear at the end of an earlier deformation.

Boudins also have long-axis orientations parallel to the maximum of fold axes and to lineations lying downdip in the axial planes. In the limbs of folds, boudins lie in bedding planes that closely approximate the orientation of cleavage. The correspondence of linear fabric elements to the downdip position in axial planes of folds suggests significant rotation of the fabric elements into the direction of the **X** strain-axis (**X** $\geq$ **Y** > **Z**) during progressive deformation.

INTERPRETATIONS

The difference in deformation of the upper and lower plates of the Roberts Mountains thrust is large. Rocks of the allochthon are generally highly deformed (Gilluly and Gates, 1965; Smith and Ketner, 1977; Evans and Theodore, 1978), whereas those of the autochthon are markedly less deformed (Merriam, 1963; Gilluly and Gates, 1965; Nolan and others, 1974; McKee, 1976; Smith and Ketner, 1977). Intense deformation of Antler age appears only locally in the autochthon, in a narrow zone lying immediately below the basal thrust (Means, 1962; Evans and Theodore, 1978). Strong development of structures in lower Paleozoic rocks in the three study areas supports the contention that they reside in the upper plate of the Roberts Mountains thrust. In the Miller Mountain–Candelaria Hills area and Wall Canyon of the Toiyabe Range, deformation of lower Paleozoic rocks prior to deposition of the Permian overlap succession is well constrained. In the Miller Mountain–Candelaria Hills overlap, deposition probably occurred as early as the Mississippian, but relations are equivocal. As discussed below, most structures in the Silver Peak Range are probably Antler age as well.

Direct evidence for the synchronous development of D_1 folds and thrust faults was not obtained in this study. However, given the degree of shortening by thrusting during emplacement of the Roberts Mountains allochthon and the thin-bedded character of sedimentary rocks composing imbricate thrust sheets, it is reasonable to presume a related origin. Available age constraints support this interpretation but are not sufficiently fine for its demonstration. Assuming a relationship between D_1 folds and thrusting, fold geometry is used to estimate transport direction for the Roberts Mountains thrust in each study area.

Wall Canyon, Toiyabe Range

The geometry of folds within the lower Paleozoic strata of Wall Canyon is best explained by models involving folding and simple shear. Similar fabrics are described for rocks in the southern Appalachians and British and Norwegian Caledonides (Bryant and Reed, 1969), the Apennines (Carmignani and others, 1978), the western Italian Alps (Minnigh, 1980), and Kodiak Island in Alaska (Moore and Wheeler, 1978; Moore and Allwardt, 1980) and are attributed to simple-shear rotation of fold axes during progressive deformation. In all cases, large strain is evident within the rocks, which, according to theoretical studies (Hudleston, 1972; Sanderson, 1973; Escher and Watterson, 1974; Cobbold and Quinguis, 1980), is a requirement for significant strain rotation of fold axes toward the simple-shear slip line. The class 2 morphology of folds, large limb appression, strongly arcuate hinges associated with planar axial surfaces, and two subparallel axial-plane cleavages are indicative of significant strain. These relations, coupled with the strong west-over-east asymmetry of folds, are supportive of the simple-shear rotation interpretation.

The origin of the girdle distribution of fold axes, with the majority oriented downdip in axial planes, is attributable to one of two or a combination of two deformation scenarios. In the first, fold axes are formed with moderately variable orientations with coplanar axial planes and undergo rotation toward the slip line during superposition of a simple-shear strain. Fold axes that had an original orientation closer to that of the slip line will lie nearer the slip line after simple shear than will axes that originally were at a higher angle. (Note: fold axes lying perpendicular to the slip line will not reorient themselves during homogeneous simple shear; Sanderson, 1973.) The second mechanism calls for simultaneous simple shear and fold formation, during which earlier formed folds will undergo rotation to an orientation more closely approximating the slip line than will younger folds. A combination of both mechanisms is probably responsible for the structural fabric of the Wall Canyon exposures, but the relative dominance of one or the other is not established.

In either case, the girdle maximum of fold axes should indicate the major principal extensile strain-axis (**X**). Inasmuch as only Antler-age folds exist, the **X** strain-axis most likely relates to the transport direction of the Roberts Mountains thrust sheet. Using this criterion and the west-over-east asymmetry of major folds, the deduced transport direction of the Roberts Mountains thrust in this area is S85°W to N85°E. The high strain indicated by the rocks suggests that the assemblage is very close to the base of a thrust sheet (Milton and Williams, 1981). The possibility exists that the inferred thrust is not actually the Roberts Mountains thrust itself but rather an imbricate thrust associated with the regionally extensive detachment surface. The transport direction inferred for this portion of the Roberts Mountains allochthon is reasonable even in light of this contingency, because, for most cases, thrust imbricates undergo only minor differential motion, as indicated by the subparallel orientation of structural fabrics developed during thrusting within imbricate thrust sheets elsewhere (see Oldow, 1981a, 1981b, and in press).

Miller Mountain–Candelaria Hills

The relative age of thrust imbrication and folding is important in understanding the tectonic history of the Palmetto complex in the Miller Mountain–Candelaria Hills. Field relations of folds and thrust faults indicate that thrusting predated formation of D_2 folds, particularly the large second-phase folds that control the outcrop pattern in the area as a whole (Fig. 2). The relation of D_1 folds and thrusts is less clear, but they probably formed together during imbrication of the Palmetto complex.

The orientation of folds is used to determine the direction of thrust transport in this area. The horizontal component of shortening within thrust sheets that have not undergone significant internal strain rotations is subparallel to the transport direction of the thrust. If first folds are related to thrusting, then the horizontal component of the normal to their axial planes is a reasonable estimation of the thrust transport direction. This obviously assumes that the axial planes of the folds correspond to the **XY** plane of the thrust sheet and that the **X**-axis is downdip. Although this is not a necessary configuration for the **X**-axis, it is common for fold-thrust belts (Seidensticker and others, 1982; Bouchez and Pecher, 1981; Avé Lallemant, 1979; Balk, 1952), and without data to the contrary, it is a good approximation.

To deduce the original orientation of first folds, the effects of the major second folds are geometrically removed by symmetrically unfolding D_1 axial surfaces about the mean D_2 fold axis (Fig. 10). The orientations of D_1 axial surfaces used in the rotations are those that parallel the regional trends of the limb of the map-scale D_2 folds in the Miller Mountain and western Candelaria Hills areas (Figs. 2 and 3). The equal development of D_2 minor structures in both limbs of the D_2 major folds (areas A, B, and C in Fig. 2) suggests that both limbs rotated during deformation (Ramsay, 1958). The slight asymmetry of the D_2 major folds affecting first-generation axial surfaces (Fig. 10), however, causes some uncertainty in determining the total rotation of each limb and in estimating the original orientation of D_1 folds. The degree of asymmetry of the D_2 major folds, however, is not great and does not introduce significant error in this first-approximation restoration of D_1 fold orientations. Restoration yields first folds with subhorizontal fold axes contained in an upright axial plane striking north-northwesterly. The effects of third-phase folds are not removed; they apparently are not important, as they occur sporadically and only as minor folds. Effects of fourth-phase folds also are not removed, because the northwesterly trending open folds do not significantly reorient the earlier structures, as indicated by the fabric distributions for the western and eastern Candelaria Hills (Fig. 3). The approximate transport vector deduced from the restored D_1 axial surfaces is west-southwest to east-northeast, with the sense of slip constrained by regional facies relations. This vector is similar

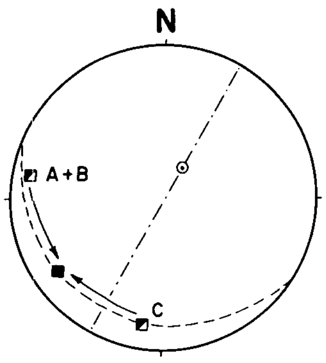


Figure 10. Lower-hemisphere, equal-area projection illustrating the geometric removal of the effects of D_2 deformation on the orientation of D_1 axial surfaces. The circle-dot represents the mean D_2 fold axis for structural domains A, B, and C (Figs. 2 and 3) and lies in the upright N35°E-trending D_2 axial plane (great-circle trace: dash-dot line). Squares are poles to D_1 axial surfaces. Half-filled squares are the mean orientation of domains A + B and C. The filled square is the orientation of D_1 axial planes after a symmetric rotation of 45° for each domainal pole about the D_2 fold axis. The domainal poles (A + B and C) migrate along the great-circle trace normal to the D_2 axis.

to the transport direction inferred in the Toiyabe Range.

The significance of second- and third-phase folds in their relationship to the kinematics of the Roberts Mountains allochthon is dependent upon the upper age bound for their formation. As previously stated, the Permian Diablo Formation (Fig. 2) overlies the Palmetto complex with profound angular unconformity and truncates the trace of major second-phase axial surfaces, and no evidence exists to suggest that it is involved in third-phase folds. Second and third folds thus predate deposition of the Diablo and, although relations are less clear, probably predate Mississippian carbonate rocks. Available data support the interpretation that D_2 and D_3 folds are genetically related to emplacement of the Roberts Mountains allochthon. The origin of D_2 and D_3 folds is addressed below.

McAfee Canyon, Silver Peak Range

Although absolute age relations are not currently available for structures in the Silver Peak Range, sufficient evidence exists to warrant comparison with the Miller Mountain–Candelaria Hills exposures. Relations among fold sets and thrusts locally are unclear because many thrusts are inadequately mapped. Some thrusts are demonstrably pre-D_2, whereas others postdate D_2 folding. As in the Miller Mountain–Candelaria Hills, thrusts and D_1 folds probably developed together. All thrust faults are deformed by D_3 folds, and thrust traces are truncated by a Jurassic pluton. The pluton is dated by K-Ar on biotite as 147.0 ± 5 m.y. B.P. and on hornblende as 150.3 ± 5 m.y. B.P. (E. H. McKee, 1970, written commun., *in* Stewart and others, 1974). The timing of pluton emplacement relative to the development of D_3 folds is still not known, but the pluton definitely postdates development of D_1 and D_2 structures. On the basis of these relations and the orientation and sequential development of structures, the history in the Silver Peak Range is related to that of the Miller Mountain–Candelaria Hills, as follows below. D_1 and D_2 structures of both areas are probably correlative. No folds of D_3 of the Miller Mountain–Candelaria Hills area are observed in the Silver Peak Range, which is not surprising, considering their limited development in the more northerly area. D_3 structures of the Silver Peak Range are tentatively correlated with D_4 folds of the Miller Mountain–Candelaria Hills.

Following the reasoning employed in interpreting the structures in the Miller Mountain–Candelaria Hills area, the original orientation of D_1 structures is estimated by geometrically removing the effects of D_2 folds. The deduced original orientation of D_1 folds is northwesterly trending, upright to slightly west vergent. Considering the geometric manipulations and the limited data base, the fold vergence determined here is probably not significant in deducing thrust transport directions. Using the strike of axial surfaces and regional facies relations, a southwest-to-northeast transport is proposed for the Roberts Mountains thrust in the Silver Peak Range.

IMPLICATIONS

The trace of the Roberts Mountains thrust crosses Nevada with a south-southwesterly trend from 42°N lat. to about 38°N lat. (Fig. 11), where it is inferred to swing westerly and extend to the Sierra Nevada. The change in the orientation of the fault trace corresponds with a bend in the sialic margin preserved in the western Great Basin and has been construed by many to be the product of late Mesozoic and/or early Cenozoic deformation. Deformational models involve either right-lateral shear of Jurassic or younger age, development of oroclinal bending (Albers, 1967; Stewart and Poole, 1974), or regional crustal flexure during Jurassic tectonism (Wetterauer, 1977; Speed, 1978, 1979). Alternatively, the nonlinearity of the passive margin

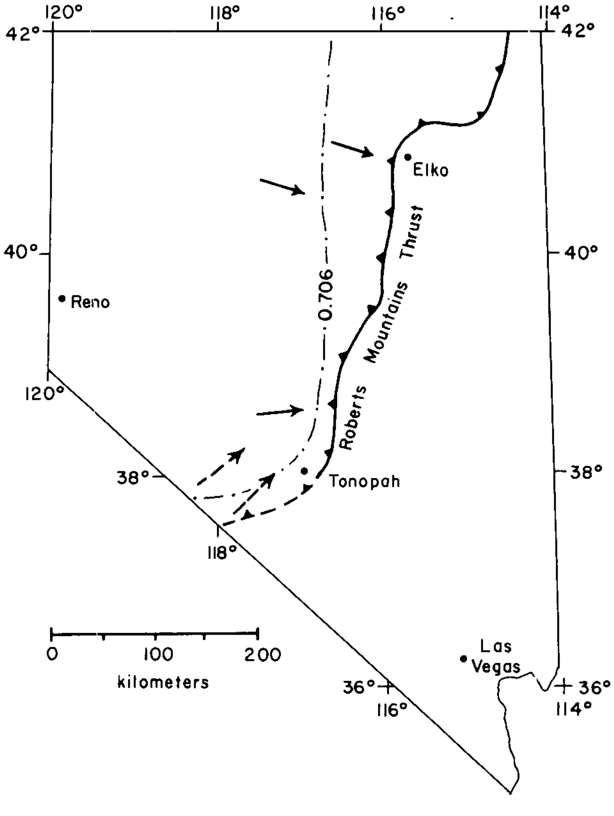


Figure 11. Map of Nevada illustrating generalized trace of the Roberts Mountains thrust and the contour of initial strontium isotopic composition of post-Paleozoic igneous rocks ($^{87}Sr/^{86}Sr$ = 0.706). Arrows represent transport direction deduced from mesoscopic structures. North-central Nevada directions from Evans and Theodore (1978). West-central Nevada directions determined in this study; dashed arrow represents direction deduced after geometric removal of effects of later folds.

has been proposed to be an original feature (Muller and Ferguson, 1939; Ferguson and Muller, 1949; Kistler and Peterman, 1978; Kistler, 1978) unrelated to later deformation. Results of this study support the second interpretation.

Recent studies in north-central Nevada (Wrucke and Theodore, 1970; Evans and Theodore, 1978) corroborate the easterly transport direction deduced for the Roberts Mountains allochthon from regional stratigraphic relationships (Roberts and others, 1958; Smith and Ketner, 1968). Structural analysis of mesoscopic folds (Evans and Theodore, 1978) indicates thrust transport of N70° to 75°W to S70° to 75°E (Fig. 11), and similarities in structures in exposures separated by 65 km suggest homogeneous deformation within the allochthon over large areas. The folds reported by Evans and Theodore (1978) are generally upright with northerly striking axial surfaces and have shallowly plunging northerly trending fold axes. The distribution of poles to axial surfaces in some areas, however, suggests that folds may be coaxially refolded and thus of a more complex geometry than reported. Nevertheless, it is apparent that no major cross folds formed during allochthon emplacement in the areas studied. Thus, in regard to inferred transport and the lack of contemporaneous cross folds, rocks of the allochthon in north-central Nevada and those in Wall Canyon of the southern Toiyabe Range, separated by more than 200 km, support the proposal that deformation within the allochthon was relatively homogeneous (Fig. 11).

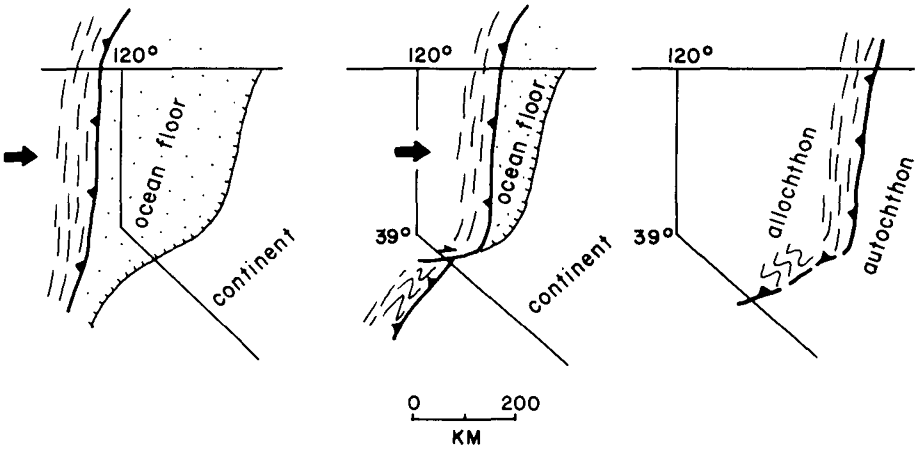
This interpretation is further supported by relations in the central Toiyabe Range (60 km north of Wall Canyon), where Means (1962) inferred the existence of a major north-trending syncline with a shallow, westerly dipping axial surface in rocks beneath the Roberts Mountains thrust. The structure is obscured by later superimposed folds thought to postdate emplacement of the Roberts Mountains allochthon and possibly to be as young as Jurassic. Apparently, no minor structures are associated with the earlier syncline, and no transport direction was deduced. The orientation of the fold is, nevertheless, consistent with those in north-central Nevada and Wall Canyon.

In sharp contrast, the difference in structure between the southern Toiyabe Range and the Miller Mountain–Candelaria Hills and Silver Peak Range occurs within a distance of less than 100 km. The change in structural style corresponds spatially with the change in regional trend of the Roberts Mountains thrust. The age relation for major cross folds established in the Miller Mountain–Candelaria Hills area and its extrapolation to the Silver Peak Range suggest that cross folds formed during allochthon emplacement and are not the product of a later deformation. A significant difference in the kinematics of thrusting, therefore, occurred along strike.

The explanation preferred here calls for local impediment of thrusting and increased internal shortening within the thrust sheet where displacement on the basal thrust was reduced relative to adjacent areas. The best candidate for the impediment or buttress that retarded thrust displacement is a westwardly extending promontory of continental crust. If the nonlinearity of the continental margin and the trace of the Roberts Mountains thrust were the product of later rotational deformation, then transport directions for the westerly trending segment of the thrust would predictably lie at about 90° to those of the northerly trending segment. This difference is not observed; rather, all transport directions indicate a strong easterly component of displacement. The postemplacement models, including models invoking right lateral faults, also fail to explain the existence of regionally developed cross folds in the area of the proposed crustal promontory. The implication is that the promontory, which apparently formed during the late Precambrian breakup of western North America (Stewart, 1972), profoundly affected later deformation and has been responsible for and has controlled structural and stratigraphic trends in the area from its inception to the present.

In light of the preferred tectonic model for the emplacement of the Roberts Mountains allochthon, the development of cross folds in the southern reaches of the thrust sheet is best explained by partial subduction of the continental promontory and an ensuing reduction in displacement rate relative to the region to the north where oceanic crust was being consumed. In the model (Fig. 12), the ocean-continent boundary is only approximately located but is represented by a single line. Its location is inferred from facies reconstructions (Stewart and Suczek, 1977; Poole and others, 1977; Matti and McKee, 1977) and the trace of the $^{87}Sr/^{86}Sr = 0.706$ line through western Nevada (Speed, 1983a; Leeman, 1982; Kistler, 1978). The nonlinearity of the trend is thought to mirror a continental-margin irregularity similar to that of promontories reported for the Atlantic margin (Rankin, 1975, 1976; Thomas, 1977) during opening of the Iapetus Ocean.

Figure 12A illustrates encroachment of the arc terrane on the western margin of the North American plate. First-phase structures throughout the Roberts Mountains allochthon are interpreted as having formed during the sediment-accretion processes in an outer-arc or accretionary prism. Thrusts and folds with geometries similar to those observed in the allochthon are observed in present-day analogs: the Aleutian, Nias, and Barbados outer arcs. A common assumption of this type of model is that the orientation of folds and transport of associated thrusts



A. Middle Devonian B. Late Devonian C. Early Mississippian

Figure 12. Tectonic scenario depicting arc collision and emplacement of the Roberts Mountains allochthon. Large arrows indicate possible direction of motion of outboard plate relative to a fixed continental plate (see text for discussion); teeth on upper plate of convergent boundary; ruled lines represent axial traces of folds within Roberts Mountains accretionary-prism; solid hachured line represents approximate boundary between oceanic (stippled) and continental crust.

within an accretionary-prism assemblage will yield the relative convergence direction of the two plates involved. This was interpreted from work on Barbados (Speed, 1978; Speed and Larue, 1982) and Kodiak (Moore and Wheeler, 1978) Islands. However, other studies (Walcott, 1978; Moore and Karig, 1980) indicate that deformation in the accretionary prism is principally sensitive to the component of convergence normal to the trend of the trench and that, if a significant strike-slip component exists, it is manifest in strike-slip faults within and/or behind the volcanic arc. The component of left- or right-lateral motion during convergence of the Roberts Mountains allochthon thus may not be recorded in the structures. The development of cross folds in the allochthon overlying the northern flank of the westerly trending promontory, however, may suggest that the accretionary prism had a southerly component of motion not recorded in the D_1 structures. It is possible, therefore, that subduction was characterized by left-oblique rather than normal convergence.

In the model, as the subduction complex impinges upon the continental margin, the promontory begins to be subducted (Fig. 12B). Unlike the oceanic terrane to the north, the continental promontory resists subduction due to buoyancy forces. This results in reduced displacement on that part of the basal thrust of the accretionary prism that overlies the promontory. The accretionary prism suprajacent to the promontory undergoes internal shortening to accommodate differential slip on the basal detachment, developing cross folds with axial traces subparallel to the local trend of the continental margin. The orientation of axial surfaces of the cross folds is determined by the effect of the promontory on the stress distribution in the upper plate. This is illustrated in Figure 13, which depicts the effect of a wedge-shaped indentor on the internal stress field of an elastic body (Jaeger and Cook, 1976). The simplistic tectonic model (Fig. 12B) depicts a single transform fault between zones of high and low thrust displacement, whereas the boundary may actually consist of numerous faults or a zone of homogeneous strain.

Figure 12C is representative of the final configuration following cessation of subduction. Cross folds are not formed during partial subduction of continental lithosphere north of the promontory, because the consuming plate boundary and the continental-oceanic join are subparallel and, predictably, additional shortening would be coaxial with earlier structures. When sufficient continental crust is underthrust beneath the arc, the active site of subduction jumps westward to some undetermined location.

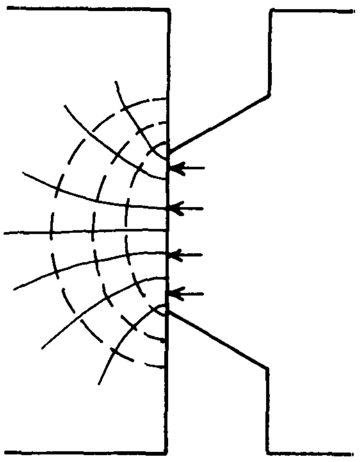


Figure 13. Effect of an indentor (with arrows) on an elastic plate (Jaeger and Cook, 1976); solid lines on elastic plate represent maximum compressive-stress trajectories, and dashed lines correspond to the axial-plane orientations of associated folds. The indentor corresponds to the crustal promontory in the tectonic model; the elastic plate corresponds to the Roberts Mountains allochthon.

CONCLUSIONS

The areal distribution of intense deformation of known or inferred Antler age in west-central Nevada supports the proposed existence of a westerly trending segment of the Roberts Mountains thrust system. The precise location of the thrust in this area is unclear largely because the facies of several units of the upper plate are common to the lower plate as well. Further definition of the thrust trace will require additional detailed structural study. The existence of later Mesozoic deformation must be considered during future work, but, in all likelihood, major Mesozoic penetrative deformation is not as prevalent in this area as in regions to the north and west (Oldow, in press).

The curvilinear trace of the Roberts Mountains thrust and the subparallel distribution of the western edge of sialic North America is concluded to be primary in origin. The lack of reorientation of thrust transport directions around the bend and the spatial correspondence of cross folds and the bend are not easily reconciled with late Mesozoic and/or Cenozoic oroclinal bending, crustal flexure, or strike-slip faulting. The westerly deflection of the Roberts Mountains thrust was formed during partial subduction of an irregularly shaped passive continental margin that probably formed during late Precambrian rifting of western North America.

The existence of a west-facing promontory of sialic crust during the early Paleozoic helps to explain the lack of significant facies juxtaposition by the west-trending part of the Roberts Mountains thrust. Facies patterns during miogeoclinal deposition probably reflect the depth of water and the distance from the stable platform on the east. These parameters are probably largely controlled by the position of the depositional site on the rifted sialic crust of the western borderland. As such, it is reasonable to propose that facies trends would mimic the paleobathymetry of an irregularly shaped continental margin and trend westerly on the northern flank of the west-facing promontory. During collision of an east-facing arc and formation of an accretionary prism, the earliest sediments incorporated would be oceanic basin, rise, and slope assemblages. As the sialic promontory was overthrust, however, it is reasonable to expect incorporation of shelf accumulations into the lower parts of the overriding prism. After subsequent erosion, then, preserved remnants of the accretionary prism could contain seaward facies and, also, shelf successions similar to those of the underlying autochthon. Farther north, in areas characterized by a north-trending margin, it is probable that shelf assemblages would be much less involved in the accretionary prism before subduction of the passive margin ceased. The wide tract of the Roberts Mountains thrust characterized by dramatic facies juxtaposition of upper and lower plates may owe its preservation in part to the lack of significant post-Antler deformation in the region.

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