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Metamorphic "klippen" in the Diamond Mountains, Nevada, and the Implications for Mesozoic Shortening and Cenozoic Extension[1]

PHYLLIS A. CAMILLERI[2]

1. Manuscript received February 2, 1999; Accepted October 14, 1999
2. Department of Geology and Geography, P.O. Box 4418, Austin Peay State University, Clarksville, Tennessee 37044; e-mail: camillerip@APSU.edu

ABSTRACT

The western flank of the Diamond Mountains in central Nevada exposes a small belt of metamorphosed strata previously inferred to be klippen belonging to the Roberts Mountains allochthon. The Roberts Mountains allochthon is an assemblage of deep marine, early Paleozoic strata that was thrust eastward over the continental shelf during the late Paleozoic Antler orogeny, and the klippen in the Diamond Mountains would represent the easternmost exposures of the allochthon at this latitude. The occurrence of fragments of the allochthon in the Diamond Mountains is enigmatic because cross cutting relationships indicate that the fault beneath the klippen postdates the Antler orogeny and, therefore, the fault can not be the Roberts Mountains thrust. This relation suggests complex telescoping of the Roberts Mountains allochthon post-dating the Antler orogeny. However, reevaluation of the metamorphic rocks indicates that 1) they are probably Permian in age and post-date the Antler orogeny and 2) they geometrically do not define klippen but rather form part of the hanging wall of the regionally extensive north-trending Phillipsburg fault. The Phillipsburg fault dips about 45° west and extends for at least 40 km along the west flank of the Diamond Mountains. Overall, hanging wall rocks dip steeply to the west, are probably overturned, and contain a partitioned high-angle west-dipping cleavage. Silurian to Permian strata are exposed in the footwall and define a north-trending overturned anticline-syncline pair that locally contains axial planar cleavage similar in orientation to cleavage in the hanging wall of the fault. The Phillipsburg fault has been inferred to be a contractional fault by some workers and an extensional feature by others. Retrodeformation of strata in the hanging wall suggest a normal sense of slip for the Phillipsburg fault and that hanging wall strata represent an offset segment of the steeply west-dipping limb of the overturned Mesozoic (?) anticline. The Phillipsburg fault appears to be partially responsible for exhumation and relative uplift of strata in the Diamond Mountains and consequently is probably a Cenozoic normal fault. In summary, the metamorphic strata previously interpreted as klippen belonging to the Roberts Mountains allochthon and the fault that bounds them do not bear any relation to the Antler orogeny. Moreover, the Roberts Mountains allochthon was not structurally translated into the Diamond Mountains.

INTRODUCTION

The purpose of this paper is to reexamine enigmatic metamorphic klippen in the Diamond Mountains, Nevada, in order to reconcile the origin of the klippen and to provide new insight into the poorly resolved polyphase Paleozoic to Cenozoic contractional and extensional history of this region. The Diamond Mountains occupy a position in the hinterland of the Jurassic to Tertiary Sevier thrust belt and lie east of, but adjacent to, the leading edge of the late Paleozoic Roberts Mountains thrust (Fig. 1). The Diamond Mountains region is unique in that it is one of the rare places in the Sevier hinterland where large-scale thrusts and folds crop out. Consequently, this area is an important laboratory for assessing the poorly understood geometry and style of contractional strain in the hinterland (e.g., Trexler and Cashman, 1991; Taylor et al., 1993; Carpenter et al., 1993 and 1994; Dobbs et al., 1993; Davies, 1997).

At least three major phases of deformation that involved large-scale faulting affected the Diamond Mountains and vicinity. The oldest is the Antler orogeny, which involved eastward thrusting of deep marine strata of the Vinini Formation (Roberts Mountains allochthon) over a coeval but little deformed autochthonous shelf sequence along the Roberts Mountains thrust during the late Devonian to Mississippian (Fig. 1b; Merriam and Anderson, 1942; Roberts, 1951; Roberts et al., 1958; Johnson and Pendergast,1981; Nilsen and Stewart, 1980, and many others). Emplacement of the Roberts Mountains allochthon also resulted in the formation of a foreland basin and deposition of a foredeep sequence (Poole, 1974; Poole and Claypool, 1984). Presently, Antler foreland basin strata are exposed in the Diamond Mountains and the Roberts Mountains allochthon is exposed extensively to the west in the Roberts and Sulphur Spring mountains (Fig. 1). Thus, the leading edge of the allochthon is concealed by Cenozoic sediment filling Diamond Valley. A second phase of contraction is manifest as folding and thrust faulting of Paleozoic to Mesozoic strata in the Diamond Mountains and in the Eureka district (Fig. 1a; Dott, 1955; Nolan, 1962; Larson and Riva, 1963; Nolan et al., 1971; Vandervoort and Schmitt, 1990; Taylor et al., 1993). Structures formed during this phase include the top-to-the-east Hoosac thrust and the top-to-west Milk Ranch thrust near Eureka, both of which project into the subsurface in Diamond Valley, and regionally extensive, north-trending folds in the Diamond Mountains (Fig. 1a; Dott, 1955; Nolan, 1962; Larson and Riva, 1963; Nolan et al., 1971; Taylor et al., 1993; Carpenter et al., 1993 and 1994; Dobbs et al., 1993). The youngest phase of deformation affecting this region is extensional and involves normal faulting responsible for the modern Basin and Range physiography.

This paper focuses on the origin of a small belt of klippen of cleaved metamorphosed strata that overlie unmetamorphosed strata along the western flank of the central part of the Diamond Mountains (Larson and Riva, 1963; Fig. 2a). The metamorphic rocks were tentatively correlated with the Vinini Formation of the Roberts Mountains allochthon (Larson and Riva, 1963; Roberts et al., 1967). Strata structurally beneath the klippen belong to the autochthonous shelf sequence that includes Antler foreland basin strata as well as overlying Pennsylvanian and Permian strata that post-date the Antler orogeny (Larson and Riva, 1963). This structural juxtaposition is intriguing, if not enigmatic, for several reasons. First, the fault beneath the klippen cuts an overturned anticline in its footwall and Permian rocks are involved in folding (see cross section in Fig. 2). This relationship implies that the fault bounding the klippen is younger than the Devonian-Mississippian Antler orogeny and, therefore, can not be the Roberts Mountains thrust. Secondly, the apparent juxtaposition of metamorphosed strata over unmetamorphosed strata could indicate that structurally deeper metamorphosed strata were thrust over structurally shallower unmetamorphosed strata. The foregoing observations suggest that complex and overprinting phases of faulting post-dating the Antler orogeny may be responsible for the juxtaposition of fragments of the Roberts Mountains allochthon over folded autochthonous shelf rocks. To assess the possibility of complex overprinting and telescoping of the Roberts Mountains allochthon subsequent to the Antler orogeny, the fault bounding the klippen and its footwall and hanging wall rocks were investigated.

In this paper new data are presented indicating that the metamorphic rocks are probably Permian in age and do not form klippen, but rather are part of a regional hanging wall of a high-angle down-to-the-west normal fault called the Phillipsburg fault. Furthermore, the fabric in the hanging wall of the fault appears to be an axial planar foliation related to the regional north-trending folds that post-date the Antler orogeny in the footwall. This implies that neither the rocks nor the deformation in strata previously assigned to the Roberts Mountains allochthon are related to the Antler orogeny. These data consequently preclude complex, post-Antler thrusting of the Roberts Mountains allochthon into the Diamond Mountains and provide new insight into the geometry of contractional structures in the region.

GEOLOGIC FRAMEWORK OF THE DIAMOND MOUNTAINS

The Diamond Mountains are a north-trending horst bounded on the west and east by normal faults (Dott, 1955; Larson and Riva, 1963; Nolan et al., 1971; Figs. 1a and 3a). Structurally, rocks within the range appear to occupy a position in the hanging wall of the top-to-the-west Milk Ranch thrust (Fig. 1a). The Diamond Mountains expose Silurian to Permian strata that define an overturned anticline-syncline

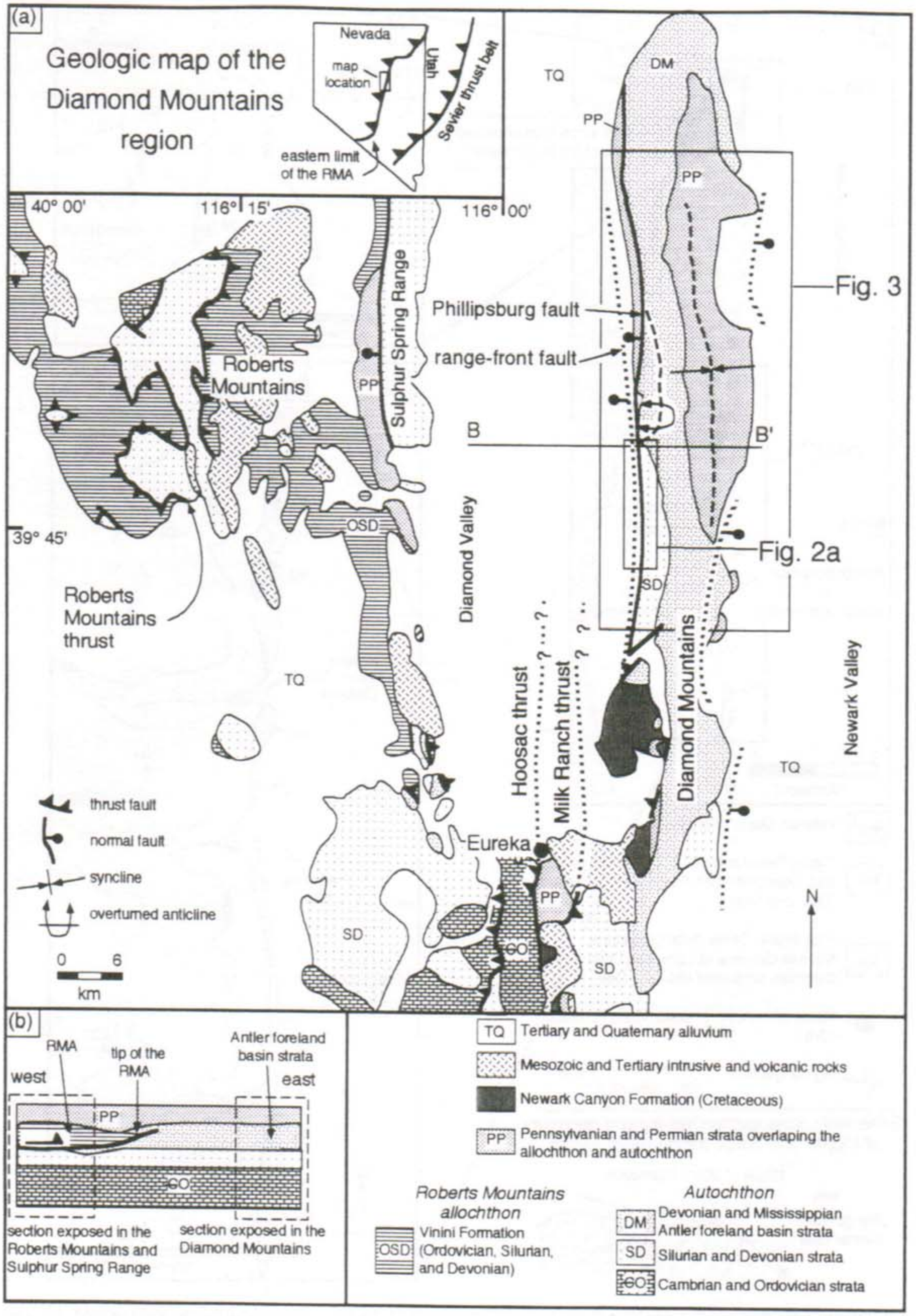

Figure 1. (a) Simplified geologic map of the Diamond Mountains and vicinity. Map is compiled from, and modified after, Roberts et al. (1967), Hose et al. (1976) and Taylor et al. (1993). (b) Schematic west-east cross section depicting tectonostratigraphic sections exposed in various ranges. RMA = Roberts Mountains allochthon.

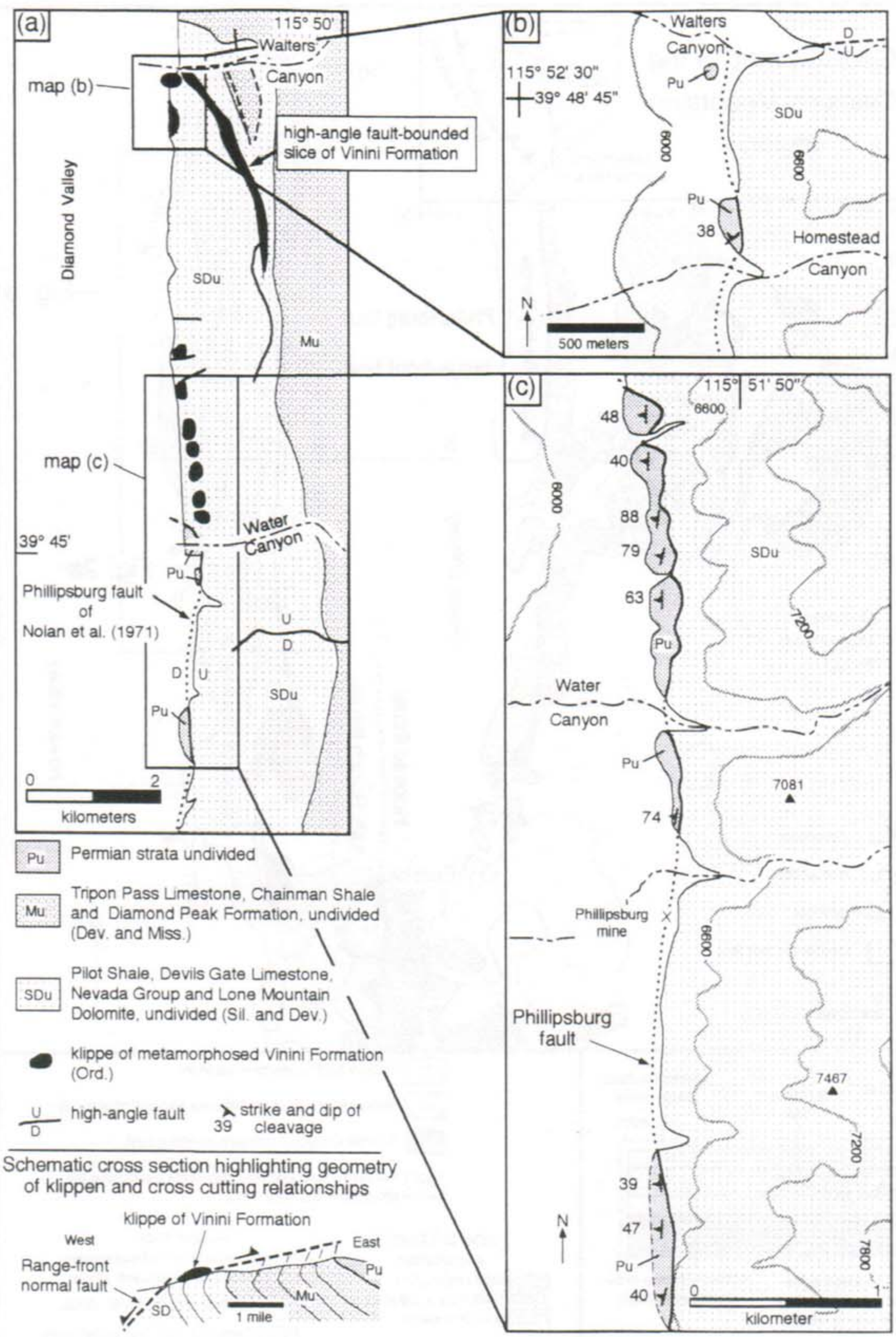

Figure 2. (a) Simplified geologic map of the western flank of the central part of the Diamond Mountains. Map depicts klippen of strata correlated with the Roberts Mountains allochthon. North of 39° 45′ latitude this map is modified after Larson and Riva (1963) and to the south it is modified after Nolan et al. (1971). (b) and (c) are simplified new geologic maps of local parts of the area shown in map (a). Contour interval is 600 feet.

pair with north-trending axial traces (Fig. 3a). In addition, a folded sequence of Cretaceous strata (Newark Canyon Formation) discordantly overlap Mississippian to Permian strata in the southernmost part of the range (Fig 1a; Nolan et al., 1971; Vandervoort and Schmitt, 1990; Taylor et al., 1993). Throughout most of its extent, the western margin of the Diamond Mountains contains a series of discontinuously exposed high-angle faults that contain Permian strata in their hanging walls (Fig. 3). The metamorphic klippen inferred to be fragments of the Roberts Mountains allochthon are exposed between Walters and Water canyons, and are situated in the middle of the discontinuous fault-bounded exposures of Permian strata (see map in Fig. 2a and location of this map in Fig. 3). The following sections focus first on the metamorphic klippen and subsequently on the faults containing Permian strata in their hanging walls.

NATURE OF THE METAMORPHIC ROCKS AND UNDERLYING FAULT

Larson and Riva (1963) and Roberts et al. (1967) mapped two geometrically distinct bodies of rock that they correlated with the Vinini Formation. One constitutes the klippen between Walters and Water canyons and the other is a high-angle-fault-bounded slice within Devonian rocks just south of Walters Canyon (Fig. 2a). Strata in the fault bounded slice are structurally and lithologically distinct from strata in the klippen and, therefore, are discussed separately.

This study, in part, involved remapping of the metamorphic "klippen" assigned to the Vinini Formation. The mapping indicates that the metamorphic rocks are not bounded by a low-angle fault defining the base of a series of klippen but rather they constitute discontinuous exposures of the hanging wall of a high-angle west dipping fault (Fig. 2b, c). Although the fault plane is not exposed, contouring of the fault trace from map data indicates a dip of ~45°. Much of the metamorphic rock adjacent to the fault is silicified, hence fault-related fabric is not apparent; however, in a few places silicified breccia was observed adjacent to the fault suggesting brittle deformation. Metamorphic rocks in the hanging wall of the fault are cleaved and lithologically diverse but are very distinct from strata in the footwall. Rocks immediately structurally below the metamorphosed strata consist of overturned Silurian and Devonian dolomitic strata that lack cleavage and apparent metamorphism. In contrast, much of the hanging wall section has been hydrothermally altered. Sparse unaltered exposures consist of interbedded phyllite, quartzite, conglomerate, sandy (quartz) meta-limestone and dark- to light-gray, very fine grained calcite marble and pebbly marble. Pebbles in conglomerate and metacarbonate consist predominantly of recrystallized limestone and black and red chert. The only relict macroscopic fossils observed within the metamorphic rocks are sparse, stretched fragments of crinoid columnals in fine-grained marble. The metamorphic rocks contain a moderate to strong cleavage that is predominantly a product of pressure solution. The presence of chlorite and sericite and the lack of biotite within cleavage in phyllite, suggests that the rocks sustained very low grade chlorite-zone metamorphism. Overall, cleavage strikes north to north-northeast and dips steeply to the west (Figs. 2b, c, and 3c). The foliation, coupled with intense alteration, obscures bedding in most places and hence the orientation of bedding is uncertain.

Strata in the high-angle, fault-bounded slice lie structurally within the core of the overturned anticline wherein rocks are intensely deformed (Figs. 2a and 3a; Larson and Riva, 1963). In this area, Larson and Riva (1963) recognized and mapped numerous faults that presumably accommodated, in part, shortening in the core of the fold. Rocks assigned to the Vinini Formation within in this area, albeit fault-bounded, are unlike strata in the klippen because they are unmetamorphosed and lack a ductile deformational fabric. Furthermore, they bear no stratigraphic resemblance to the metamorphic rocks but rather are lithologically indistinct from surrounding Devonian dolomite, sandstone, and sandy dolomite and consequently do not appear to be allochthonous. Thus, these strata are best correlated with adjacent Devonian strata.

In summary, the metamorphic and altered rocks are restricted to, and comprise the hanging wall of, a major west-dipping fault. Cleavage dips steeply west and the orientation of bedding is uncertain.

Structural and Stratigraphic Correlation of the Metamorphic Rocks

On the basis of lithologic and structural arguments, the metamorphosed rocks can be correlated with fault-bounded Permian strata exposed due north and south of the metamorphic rocks. Furthermore, the faults that bound the metamorphic and Permian rocks appear to be discontinuous exposures of the same fault.

Permian strata to the north of the metamorphic rocks (north of Threemile Canyon) consist of a heterogeneous sequence of steeply west dipping siliciclastic strata and limestone in the hanging wall of a high-angle west dipping fault (Figs. 3a and 4; Dott, 1955; Larson and Riva, 1963). Dott (1955) and Larson and Riva (1963) indicate that the Permian strata are at least Lower Permian in age on the basis of the presence of sparse Leonardian fusulinids. Moreover, Dobbs (1994) correlated the Permian strata with lowermost Permian strata overlying the Pennsylvanian Ely Limestone exposed to the east in the footwall of the fault. These fault-bounded Permian rocks, in terms of protoliths, are lithologically very similar to the metamorphosed strata described herein. The only significant difference between

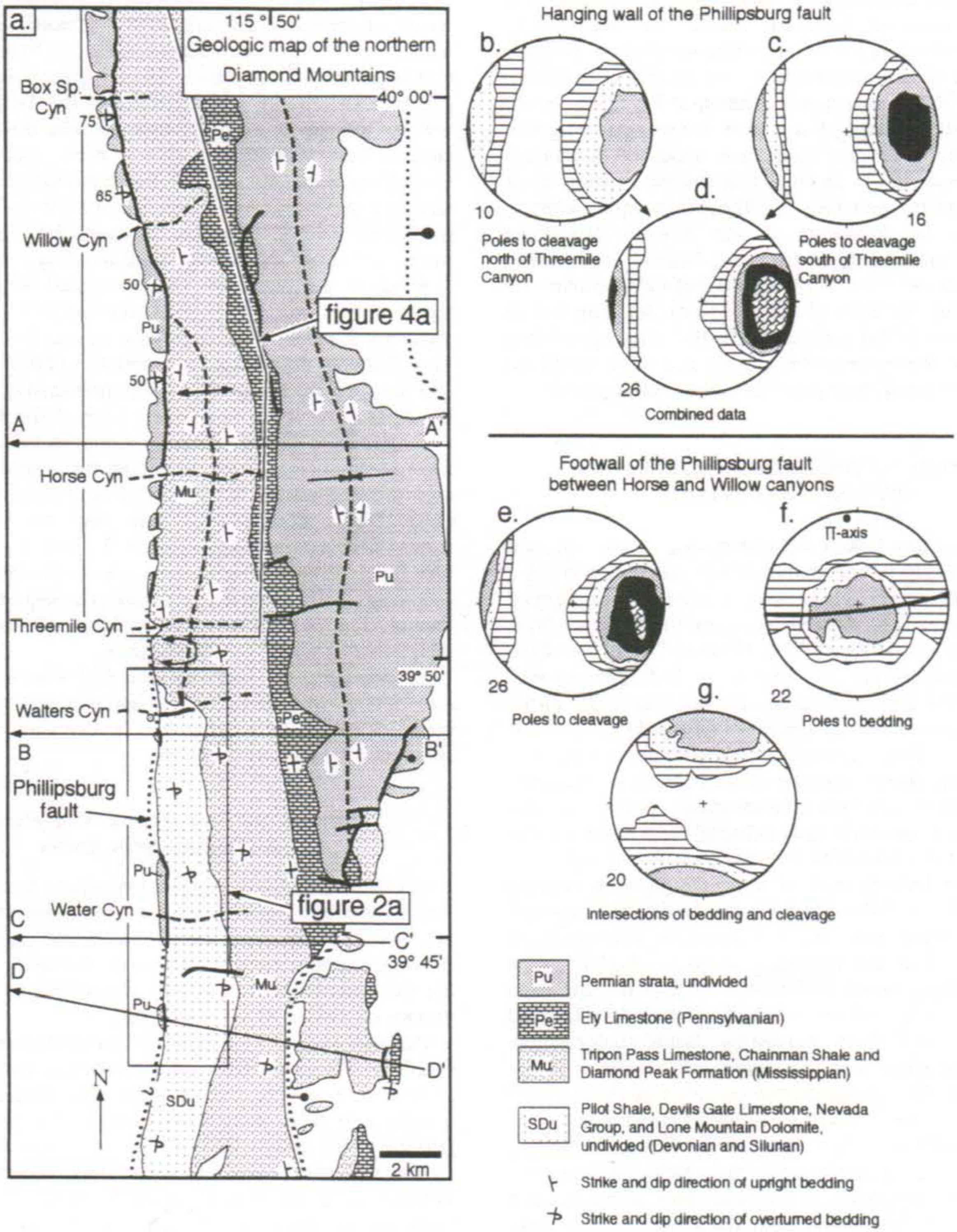

Figure 3. Simplified geologic map of the central Diamond Mountains and stereograms illustrating the attitudes of bedding and cleavage in the hanging wall and footwall of the Phillipsburg fault. Attitude data shown on the stereograms were obtained during this study. These data are contoured by the Kamb (1959) method with a two sigma contour interval. Number of data are indicated in the lower left or right corner of each stereogram. The geologic map is modified from Larson and Riva (1963) and Nolan et al. (1971) and incorporates map data from this study. For simplicity the range-front fault is not shown. This map shows the locations of cross sections in Figures 5 and 6. The section lines are shown with an arrow on their western ends to indicate that the line extends slightly beyond the maps border.

the metamorphosed rocks and Permian strata to the north appears to be the degree and character of metamorphism and deformation. The metamorphosed strata overtly display chlorite-zone metamorphism and contain a strong cleavage. In contrast, Dott (1955) and Larson and Riva (1963) considered the Permian strata overall as unmetamorphosed, but noted locally the presence of stretched fusulinids and chert pebbles. Microstructural and field inspection of the Permian strata during this study revealed that, although they do not appear to be overtly thermally metamorphosed, in places they contain a weak partitioned solution cleavage that is similar in attitude to that in the metamorphosed strata (c.f. Fig. 3b, c, d). In addition, flattening of the chert pebbles and fusulinids is a byproduct of cleavage development. The cleavage is most prominent between Threemile and Willow canyons (Fig. 4) but dies out north of Willow Canyon. Thus, on the basis of lithologic similarities and the presence of cleavage of similar attitudes, the metamorphosed rocks are correlated with Permian strata north of Threemile Canyon. Furthermore, the fault that bounds cleaved Permian rocks north of Threemile Canyon is on strike with the fault that bounds the metamorphosed strata (Fig. 3), and both of these faults dip ~45° west (dip derived from contouring the fault trace), suggesting that they are exposures of the same fault.

Larson and Riva (1963) correlated the Permian strata north of Threemile Canyon with lithologically similar rocks exposed in the hanging wall of a high-angle west-dipping fault at Water Canyon (Fig. 2a). Subsequently, Nolan et al. (1971) suggested that the Permian rocks at Water Canyon were correlative with similar rocks exposed in the hanging wall of a high-angle, west-dipping fault due south of and along strike with the rocks at Water Canyon. Nolan et al. (1971) named the fault extending from the Water Canyon area southward the "Phillipsburg fault" (Fig. 2a). Inspection of the hanging wall of the Phillipsburg fault indicated that it is composed predominantly of altered, low-grade metamorphic, very fine grained calcite or impure marble that in places has a cleavage that obscures bedding. The cleavage dips steeply to the west like that in metamorphosed strata north of Water Canyon (Fig. 2b, c). Thus, metamorphosed strata in the hanging wall of the Phillipsburg fault appear to be correlative with metamorphosed strata north of Water Canyon. Furthermore, the Phillipsburg fault is along strike with the fault that bounds the metamorphic rocks north of Water Canyon, suggesting that they are the same fault. Accordingly, all west-dipping fault segments that contain cleaved and uncleaved Permian strata in their hanging walls along the western flank of the Diamond Mountains are interpreted to be the same fault, the Phillipsburg fault. In summary, lithologic and structural data suggest that the metamorphosed strata, originally mapped as klippen of strata belonging to the Roberts Mountains allochthon, are actually Permian in age. Moreover, the metamorphosed strata form part of a belt of metamorphosed to unmetamorphosed strata that constitute the hanging wall of the west-dipping Phillipsburg fault.

Summary of Structural Characteristics of the Hanging Wall of the Phillipsburg Fault

The Phillipsburg fault is a regional structure dipping ~45° west and extending for at least 40 km along the west flank of the central and northern Diamond Mountains (Figs. 1 and 3). The hanging wall appears to expose exclusively Permian strata with overall steeply west-dipping bedding and cleavage. The degree of metamorphism and pervasiveness of cleavage development within the hanging wall appears to decrease northward. Rocks south of Walters Canyon tend to be altered and have a moderate to well-developed cleavage that obscures bedding and consequently the orientation of cleavage relative to bedding is uncertain in this area. North of Walters Canyon, bedding is discernible and strata contain a weaker, but sparse, partitioned cleavage that appears to die out north of Willow Canyon. Bedding within this region appears to be predominantly nearly parallel to cleavage, but in a few places bedding was observed to be dipping at a slightly higher angle than cleavage.

No clear evidence of whether the steeply west dipping Permian are upright or overturned was found in the hanging wall the Phillipsburg fault to the south of Rock Canyon (Fig. 4). However, Larson and Riva (1963) postulated that hanging wall strata are overturned and they based their inference on reconnaissance observation of rocks just north of Box Springs Canyon (Fig. 4a) but did not cite the evidence for their inference. Observation of strata in the hanging wall just north of Box Springs Canyon revealed kink folds with limbs dipping steeply west to steeply east (Fig. 4b). Although the hanging wall rocks in this area are mostly hydrothermally altered, in a few places faint trough cross bedding defined by chert pebbles in altered limestone suggests that west-dipping strata are overturned and east-dipping are upright. This suggests, as Larson and Riva (1963) inferred, that steeply west dipping strata are likely overturned. In summary, bedding and cleavage in the hanging wall of the Phillipsburg fault dip steeply to the west and where bedding is discernible, cleavage appears to be nearly parallel or dipping at a slightly lower angle than bedding.

Structural Characteristics of the Footwall of the Phillipsburg Fault

In order to assess the origin and sense of slip of the Phillipsburg fault, rocks in its footwall were investigated to determine whether or not they contained a fabric and deformational history similar to that observed in the hanging wall. Footwall rocks, overall, define an overturned anticline-syncline pair (Figs. 1a and 3a; Larson and Riva, 1963).

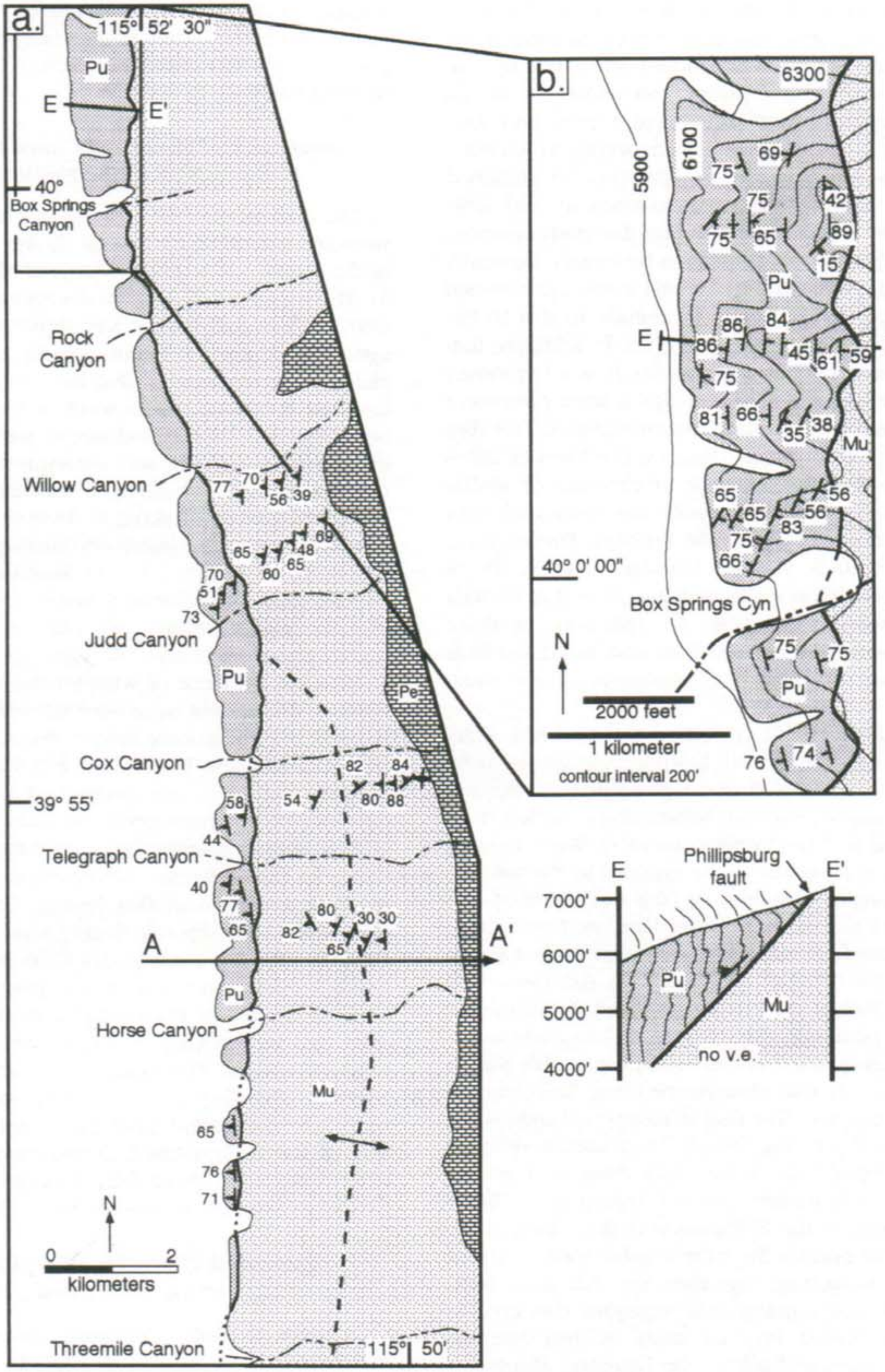

Figure 4. (a) Geologic map of the western flank of the northern Diamond Mountains north of Threemile Canyon. Geologic base map is simplified from Larson and Riva (1963) and modified to show attitudes of cleavage in the hanging wall and footwall of the Phillipsburg fault. Map shows location of cross section A-A' depicted in Figure 5. (b) Geologic map and cross section of the Phillipsburg fault and its hanging wall north of Box Springs Canyon. Map data is from this study. Units shown in (a) and (b) are the same as in Figure 3.

Inspection of footwall strata revealed, in places, the presence of a weak steeply west-dipping partitioned cleavage that is similar in orientation to that in the hanging wall of the Phillipsburg fault (Figs. 3e and 4a). Although cleavage in the footwall generally dips at a high-angle, locally there are variations in dip angle of as much as 35° (Fig. 4a). This variation can be attributed to cleavage refraction across layers of varying competency, which can be observed in outcrop.

Cleavage in the footwall is most apparent in Mississippian clastics exposed in the core of the anticline north of Threemile Canyon and it appears to die out north of Willow Canyon, as it does in hanging wall rocks (Fig. 4a). Cleavage is lacking in stratigraphically overlying Pennsylvanian and younger carbonate rocks east of the Mississippian strata. In contrast, cleavage is rare on the overturned limb in the footwall south of Threemile Canyon, where rocks in the hanging wall have the strongest cleavage.

Several observations suggest that the cleavage in the footwall of the Phillipsburg fault is related to development of the large-scale overturned folds. A *pi* diagram of poles to bedding for Mississippian and Pennsylvanian strata defining the large-scale anticline between Horse and Willow Canyons yields a hinge line that plunges gently to the north-northeast (Fig. 3f). Moreover, a plot of bedding-cleavage intersections from this same area indicates gently north and south plunging intersections (Fig. 3g). Collectively, these data suggest that cleavage is broadly axial planar to the large-scale folds. In summary, folds in the footwall of the Phillipsburg fault have an associated axial planar cleavage locally concentrated in Mississippian clastics, and this cleavage is very similar in orientation to cleavage in Permian strata in the hanging wall.

RESOLVING SENSE OF SLIP ALONG THE PHILLIPSBURG FAULT

The Phillipsburg fault south of Water Canyon has been inferred to be a normal fault (Nolan et al., 1971) and to the north a reverse fault (Dott 1955; Larson and Riva, 1963), albeit no attempt has been made to reconcile these inferences or to retrodeform the steeply west-dipping Permian strata in the hanging wall of the fault. The viability of both normal and reverse fault options are explored here by schematically retrodeforming strata in the hanging wall of the Phillipsburg fault. In either case, it is assumed that the oppositely verging Hoosac and Milk Ranch thrusts extend northward in the subsurface of Diamond Valley, and that strata in the Diamond Mountains occupy a position in the hanging wall of the Milk Ranch thrust. The normal fault interpretation requires that west dipping strata in the hanging wall of the Phillipsburg fault are overturned and the reverse fault interpretation that strata are upright. Four simplified, west-east trending cross sections, A-A' through D-D', transecting the hanging wall and footwall of the Phillipsburg fault are restored (Figs. 5, 6). Figure 5 illustrates present-day and restored cross sections assuming a normal sense of slip. Only one of these cross sections, B-B', extends into Diamond Valley and illustrates the projected Hoosac and Milk Ranch thrusts. Figure 6 also shows cross section B-B' but assumes a reverse sense of slip. The locations of cross sections in Figures 5 and 6 correspond to locations of published cross sections by Nolan et al. (1971) and Larson and Riva (1963). The cross sections presented here, however, differ with respect to subsurface structure, which is based collectively on mapping and data obtained during this study and the geometry of footwall rocks as depicted on the published maps of Nolan et al. (1971) and Larson and Riva (1963).

The simplest interpretation of the Phillipsburg fault is that it is a normal fault. In this interpretation hanging-wall strata are overturned and simply represent an offset segment of the cleaved folds exposed in the footwall of the fault (Fig. 5). The cross sections depicted on the left in Figure 5 represent present-day sections. In each of these sections the western flank of the Diamond Mountains is shown bounded by two normal faults that dip at a moderate to high angle. The easternmost normal fault is the Phillipsburg fault whereas the other represents the modern range-front fault. This geometry is based on seismic reflection data that suggest the modern range-front fault that juxtaposes Tertiary valley fill with Paleozoic bedrock dips at a high or moderate angle (Effimoff and Pinezich, 1981; Anderson et al., 1983) and is situated west of exposures of the trace of the Phillipsburg fault. Although all cross sections in Figure 5 depict the range-front fault as merging with, and hence related to, the Phillipsburg fault, it is equally likely that the range-front fault cuts the Phillipsburg fault. The cross sections on the right side of Figure 5 are restored. Each of the restored cross sections depicts the inferred locations and traces of axial planar cleavage, which is based on the distribution and geometry of cleavage observed in the field (for simplicity cleavage traces are not shown in the present-day sections). Cleavage development appears to have been localized on the crestal parts of the folds toward the western flank of the range.

Assuming the Phillipsburg fault is a reverse fault requires a geometrically complex thrusting history. Figure 6 shows cross section B-B' wherein the Phillipsburg fault is retrodeformed as a reverse fault rather than a normal fault. In this scenario, the Phillipsburg fault transected the Milk Ranch thrust and juxtaposed upright, steeply west-dipping Permian strata from a syncline in the footwall of the Milk Ranch thrust against older strata in its hanging wall (Fig. 6). Figure 6c shows a restored cross section of the Milk Ranch thrust and the trace of cleavage in its hanging wall and footwall prior to formation of the Phillipsburg fault. In this cross section, cleavage in the hanging wall of the Milk

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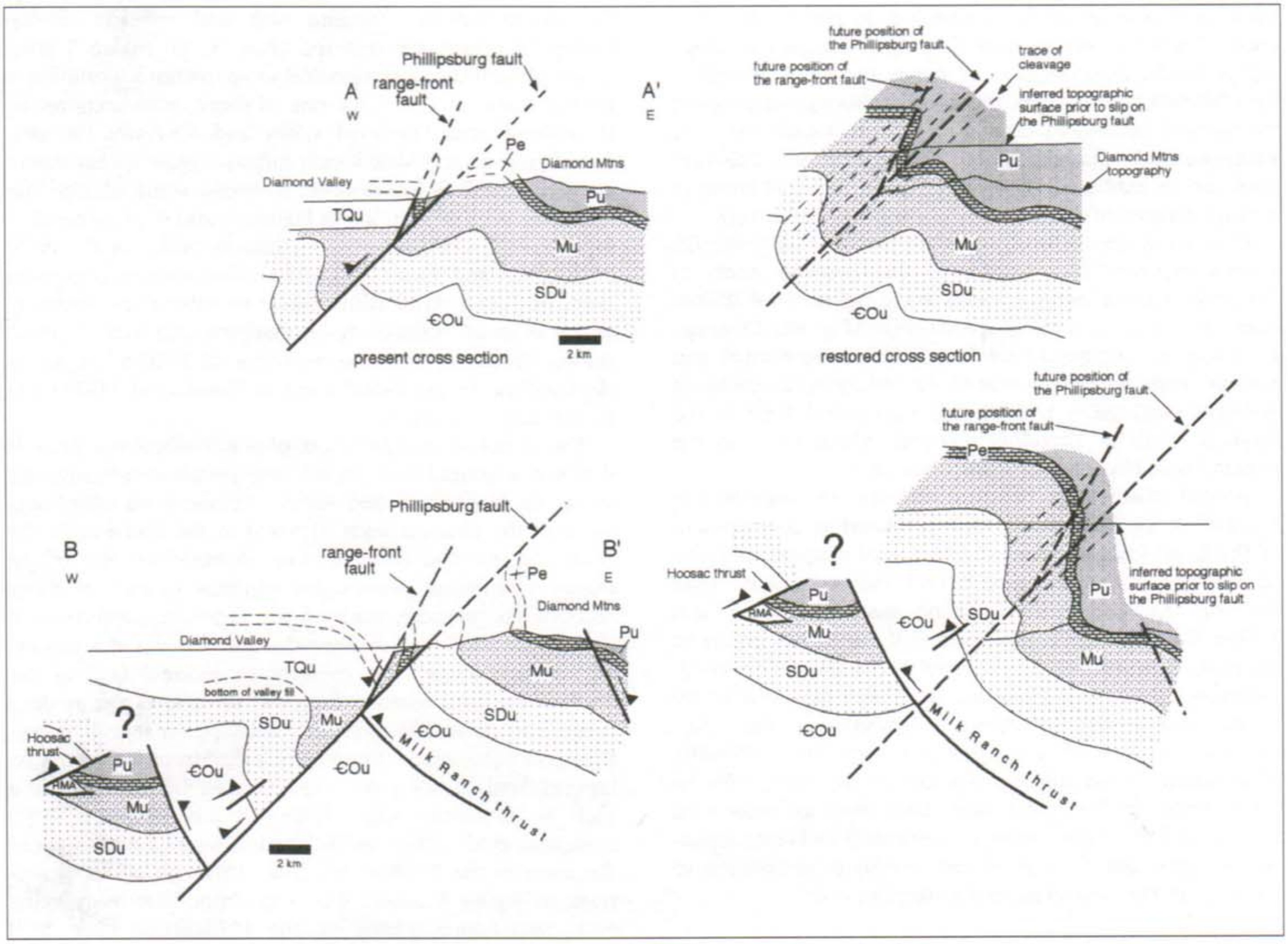


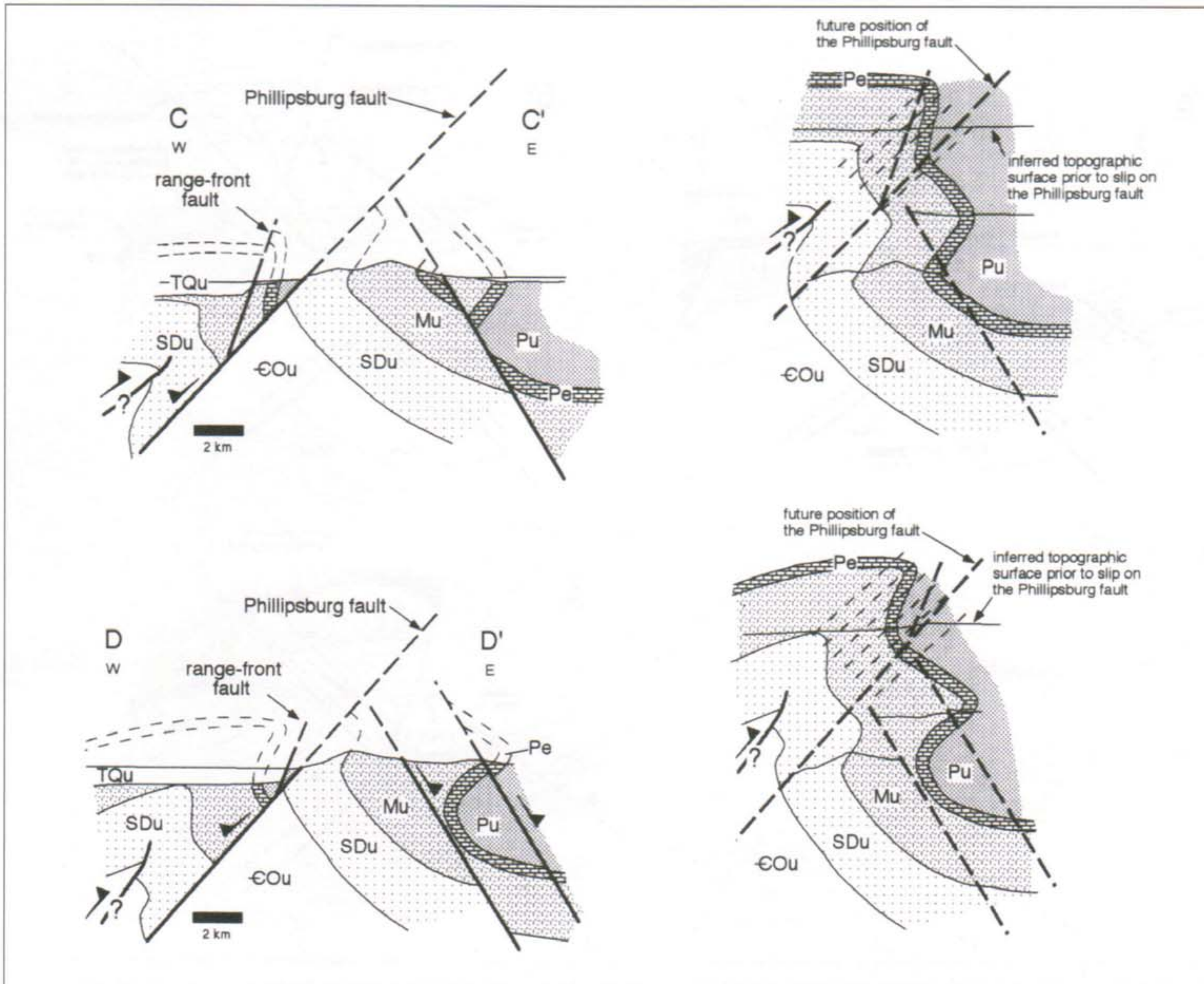
Figure 5. Present and restored west-east cross sections through the Diamond Mountains. Present-day cross sections are on the left and have no vertical exaggeration. The restored cross sections are on the right. Cross sections assume the Phillipsburg fault is a normal fault. For simplicity only the restored cross sections illustrate the trace of cleavage. Locations of section lines are shown in Figure 3a. Cross sections A-A' and B-B' are located along the same line as Larson and Riva's (1963) cross sections B-B' and F-F', respectively. Cross sections C-C' and D-D' are located along the same line as Nolan et al. (1971) cross sections A-A' and B-B', respectively. Units are the same as in Figure 3 with the exception of "COu" and "TQu". COu = Cambrian and Ordovician strata undivided. TQu = Tertiary and Quaternary basin fill undivided.

Ranch thrust is axial planar to folds, and can be interpreted as related to fold development, but cleavage in the footwall is depicted as having no genetic relation to folds. It is equally plausible, however, that the inferred syncline in the footwall of the Milk Ranch thrust has an overturned western limb and consequently the cleavage could be axial planar, and hence related to, development of the footwall syncline. The range-front fault in the reverse fault interpretation is also inferred to sole into the Phillipsburg fault. Although this interpretation suggests reactivation of the Phillipsburg fault as a normal fault, it is equally likely that the Phillipsburg fault was not reactivated but instead is transected by the range-front fault.

Discussion and Regional Perspective

The reverse and normal fault interpretations of the Phillipsburg fault are two geometrically plausible end-member options, however, the normal fault interpretation is preferred here. It is the simplest explanation that is compatible with the observation that west-dipping strata in the hanging wall are probably overturned. Thus, strata in the hanging wall of the Phillipsburg fault are interpreted to simply represent a transected part of an overturned limb of an anticline.

The ages of the Phillipsburg fault and map-scale overturned folds in the Diamond Mountains are not precisely constrained, but inferences can be made on their relative ages



note: restoration of cross sections C-C′ and D-D′ required that the east dipping normal faults on the eastern flank of the Diamond Mountains are younger than the Phillipsburg fault

Figure 5. (continued)

based on regional relationships. On the basis of cross cutting relationships, the Phillipsburg fault is constrained to be Permian or younger in age. However, a normal sense of slip for the Phillipsburg fault implies that it is responsible for partial relative uplift of the Diamond Mountains (Fig. 5) and therefore it is reasonable to infer that it is a Cenozoic normal fault related to Basin and Range extension. The cleaved map-scale folds predate the Phillipsburg fault and are only constrained to be Permian or younger in age. A more tightly constrained age bracket for these folds can be surmised by considering their possible relations to the Milk Ranch thrust. Taylor et al. (1993) note that near Eureka Lower Cretaceous strata (Newark Canyon Formation) depositionally overlap the Milk Ranch thrust and that the thrust cuts strata as young as Permian and, therefore, the age of the thrust is bracketed between Permian and Early Cretaceous. The folds in the Diamond Mountains appear to occupy a position in the hanging wall of the Milk Ranch thrust and two end-member possibilities exist for the origin of these folds (Fig. 7). One explanation is that the folds constitute

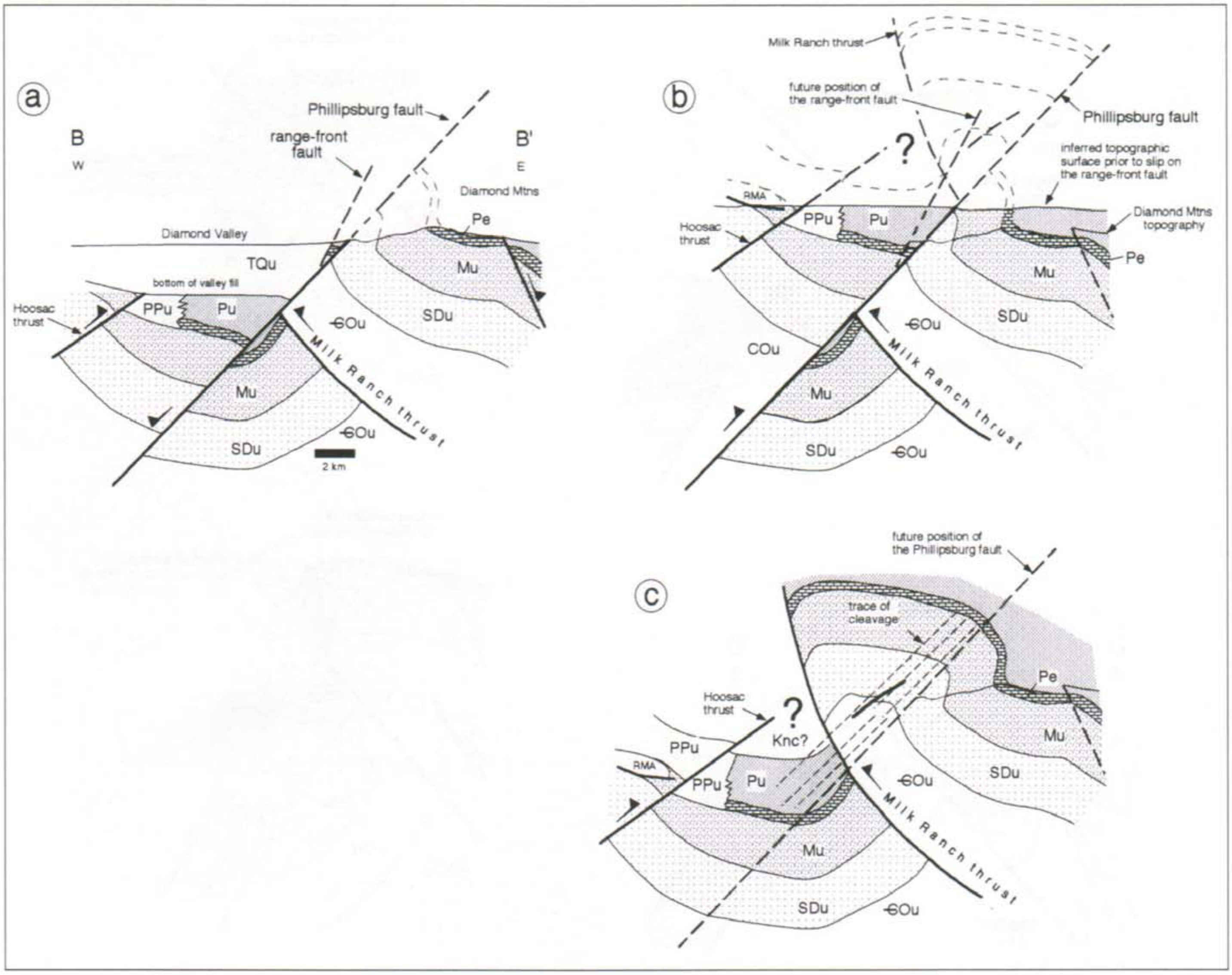


Figure 6. Cross section B-B' illustrating the Phillipsburg fault as a reverse fault. Units are the same as in Figure 5 with the exception of "Knc" and "PPu". Knc = Cretaceous Newark Canyon Formation. PPu = Pennsylvanian and Permian strata undivided.

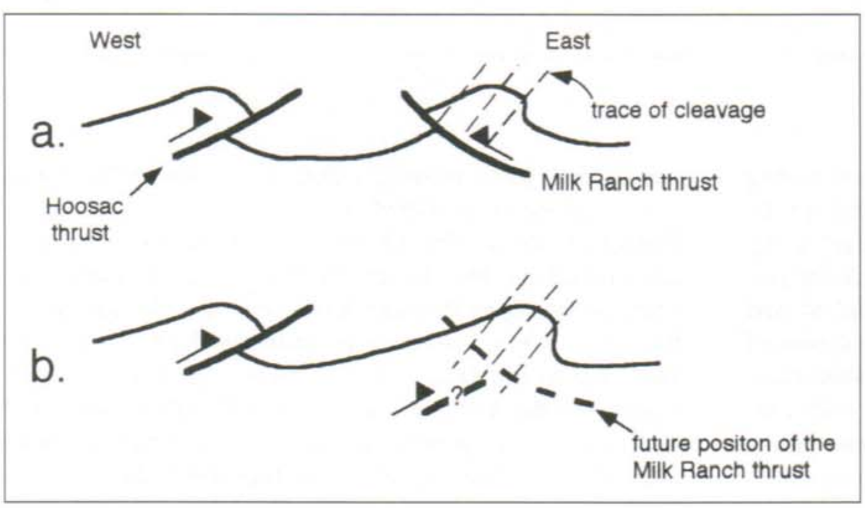


Figure 7. Diagram illustrating two possible origins of cleaved folds in the Diamond Mountains.

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back folds in the hanging wall of the Milk Ranch thrust. In this scenario, folding and cleavage development would most likely post-date the formation and inception of slip along the thrust (Fig. 7a). This would imply that the folds could either share the same age constraints as the thrust or conversely they may be post-Early Cretaceous. For example, it is possible that back folding of the hanging wall in the central and northern Diamond Mountains may have largely taken place after cessation of slip on the Milk Ranch thrust near Eureka. Moreover, Cretaceous strata in the southernmost part of the Diamond Mountains have been deformed by contractional structures implying that at least some contractional deformation took place during and/or after deposition of Lower Cretaceous strata (Nolan et al., 1971; Vandervoort and Schmitt, 1990; Taylor et al., 1993). Consequently, the folds (and cleavage) could be as young as Late Cretaceous. The other possibility is that the folds predate the Milk Ranch thrust and represent a cleaved east-vergent, possibly fault-propagation, fold subsequently cut by the Milk Ranch thrust (Fig. 7b). In this case the folds share the same age constraint as the Milk Ranch thrust. Unfortunately, there is not enough data to distinguish which option is the most geometrically viable.

CONCLUSIONS

1. Fault bounded metamorphosed strata on the western flank of the Diamond Mountains that were previously interpreted as klippen of Ordovician strata belonging to the Roberts Mountains allochthon appear to be Permian in age and form part of the hanging wall of the regionally extensive high-angle, west-dipping Phillipsburg fault. Consequently, fault-bounded metamorphosed strata on the western margin of the Diamond Mountains bear no relation to the Antler orogeny.

2. The Phillipsburg fault is interpreted as a normal fault of probable Cenozoic age that is partially responsible for relative uplift and exhumation of strata in the Diamond Mountains.

3. The Phillipsburg fault transected the overturned limb of an east-vergent anticline that locally has a steeply west-dipping axial planar cleavage. Steeply west-dipping, cleaved strata in the hanging wall of the Phillipsburg fault are inferred to represent part of the overturned limb of the anticline.

4. The anticline in the Diamond Mountains probably constitutes either a back fold in the hanging wall of the top-to-the-west Milk Ranch thrust or is a result of top-to-the-east fault propagation folding that is unrelated to, and preceded development of, the Milk Ranch thrust. Folding and cleavage development can only be constrained as Permian or younger in age and may be as young as Late Cretaceous.

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