History and kinematics of Cenozoic extension in the northern Toiyabe Range, Lander County, Nevada

DAVID LEE SMITH* *Department of Geology, Stanford University, Stanford, California 94305*

ABSTRACT

Since earliest Oligocene time, ~15 km of extension has occurred along a major gently dipping normal fault system and a younger more steeply dipping system of normal faults in the northern Toiyabe Range in central Nevada. The Bernd Canyon fault is the structurally lowest of the gently dipping faults in this area. It dips 12°–28° west and is similar to well-known detachment faults. Paleozoic rocks in the hanging wall are cut by subsidiary gently dipping normal faults and are tilted 40° to more than 90° to the east. The early Oligocene intracaldera tuff of Hall Creek is the oldest Cenozoic unit present in the hanging wall and is tilted 28°–58° eastward. Successively younger units have systematically decreasing dips and record a history of progressive, possibly episodic, extension. Bedding in greenschist-grade lower Paleozoic rocks in the footwall of the Bernd Canyon fault intersects the fault at angles of 5° to 25° and is arched across the range. Unlike many other detachment faults, the Bernd Canyon fault contains early Oligocene and younger volcanic and sedimentary units in the footwall that may be correlated to units in the hanging wall, and they record a similar tilting history. Sequential untilting of successively older Tertiary units suggests that the Bernd Canyon fault was initiated at a dip of 50°–60° and was rotated to a dip of ~25°–30° during progressive extension before being cut and further rotated by younger faults. Restoration of Tertiary units also suggests that the doming of Paleozoic units across the range is a Tertiary feature and that associated low bedding-to-fault angles in the footwall of the Bernd Canyon fault are the result of penetrative inhomogeneous simple shear deformation of the footwall.

Including faults outside the area of detailed study, ~20 km of east-west extension occurred across a domain that is now ~45 km long (north-south) by ~35 km wide (east-west). Extension apparently began in earliest Oligocene time, before or perhaps synchronously with, the onset of volcanism, and it continued into the Pliocene epoch. Tilt directions of Oligocene volcanic rocks, calcite veining near the detachment, and elongate fossils in footwall units indicate that the extension direction on the detachment and related faults may have been nearly east-west to possibly east-northeast–west-southwest. Changing tilt directions in younger rocks suggest that the extension direction switched to west-northwest–east-southeast at some time. Palinspastic restoration of normal faults also suggests that Oligocene basins were initially bounded by high-angle faults and had topographically elevated footwalls. The restoration implies that the styles of Miocene to Recent "basin and range" faulting and pre-Miocene "pre–basin and range" faulting are closely similar.

INTRODUCTION

Large-magnitude extension has been recognized for some years within the Basin and Range province of the western United States but has been considered by many to be restricted to belts in eastern Nevada, western Utah, and southern Idaho (Armstrong, 1982; Gans and Miller, 1983; Axen, 1986; Wernicke and Axen, 1988) and in southeastern California, western Arizona, and southwestern Nevada (Proffett, 1977; Howard and John, 1987; Davis and Lister, 1988) (Fig. 1).

New data presented here indicate that 15 km of extension has occurred since earliest Oligocene time along a major, gently dipping, normal-fault system and a younger, more steeply dipping system of normal faults in the northern Toiyabe Range in central Nevada. The principal gently dipping fault is here called the "Bernd Canyon fault" after exposures along Bernd Canyon in the Mount Callaghan 7½ minute quadrangle. This fault was previously inferred to be part of the Early Mississippian Roberts Mountains thrust (Stewart and Palmer, 1967; Stewart and McKee, 1968a, 1968b, 1969), but it cuts Tertiary rocks and can be shown by palinspastic restoration to have originated as a high-angle normal fault which developed low-angle contact relationships in its footwall by progressive simple shear of the footwall during ongoing extension. This domain is one of a number of heterogeneously distributed areas in central and east-central Nevada where extension is greater than 100% (Smith and others, 1991). Although smaller than most detachment faults, the Bernd Canyon fault is similar in many ways, and relationships in this area may have important implications for the kinematic development of regional detachment systems, for the mechanisms that may have initiated extension, and for the style of extension through time in the Basin and Range.

GEOLOGICAL SETTING

Pre-Cenozoic Stratigraphy

Extensional faults in central Nevada have dismembered a structural stack of five tectonostratigraphic sequences, each arising from a separate pre-Cenozoic tectonic event (Fig. 2). From base to top, these sequences are (1) lower Paleozoic autochthonous strata deposited during initial rifting and subsequent thermal subsidence of the western North American continental

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*Present address: 3474 Victoria Ave., Santa Clara, California 95051.

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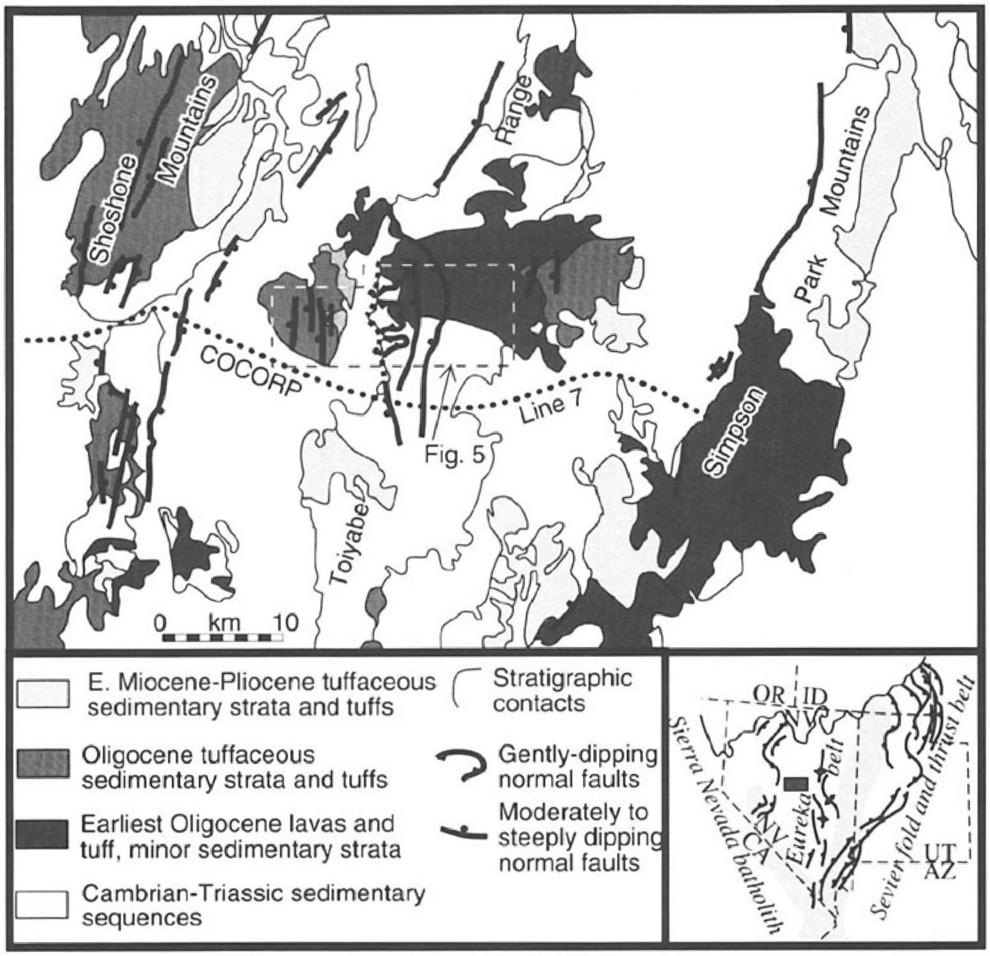


Figure 1. Index map of Tertiary rocks and major ranges in central Nevada. Early Miocene and younger rocks include the Bates Mountain Tuff and all overlying units (Fig. 3); Oligocene rocks include all units from the top of the tuff of Hall Creek to the base of the Bates Mountain Tuff; early Oligocene rocks include the tuff of Hall Creek and all underlying units. Inset locates study area. Shaded areas on inset map represent well-known areas of large-magnitude Cenozoic extension.

margin (Stewart, 1972; Stewart and Poole, 1974), (2) deformed deep-water sequences of the Roberts Mountains allochthon emplaced in mid-Paleozoic time (Merriam and Anderson, 1942; Roberts and others, 1958), (3) a clastic and carbonate overlap assemblage deposited unconformably on the allochthon during late Paleozoic extensional faulting (Ketner, 1977; Speed and others, 1977; Smith and Miller, 1990), (4) deformed deep-water rocks of the Golconda allochthon emplaced in Permian time (Silberling and Roberts, 1962; Speed, 1977; Tomlinson, 1988), and (5) a Triassic overlap assemblage deposited unconformably on the Golconda allochthon (Stewart and others, 1977; Harris, 1988). Of the five sequences, the upper three were all apparently removed by pre-Oligocene erosion within the area of detailed study (see below).

The lower Paleozoic sequences underwent metamorphism and ductile deformation during Middle Jurassic and Late Cretaceous time (Speed, 1983; Speed and others, 1988; Smith, 1989), but a sedimentary record of any post-Triassic, pre-Oligocene events is not preserved in this area. The maximum structural thickness of pre-Oligocene strata exposed in the Toiyable Range is ~10–11 km (Fig. 2).

Cenozoic Stratigraphy

All five of the sequences described above are overlapped by widespread Oligocene to Quaternary volcanic and sedimentary rocks (Fig. 3). In contrast to the laterally continuous Paleozoic sequences, the Tertiary section varies greatly over short distances. The discussion below and the columns in Figure 3 apply only to the immediate vicinity of the study area in the northern Toiyabe Range.

This stratigraphy was originally mapped and named by Stewart and McKee (1968b, 1969). It can be divided into two sequences along the upper contact of the tuff of Hall Creek (Fig. 3). The lower sequence is predominantly volcanic and is composed of a unit of andesite to quartz-latite flows and domes overlain by thin and discontinuous lenses of siltstone and conglomerate and then by the tuff of Hall Creek. This tuff is an intra-caldera, ash-flow tuff (Stewart and others, 1977; Smith, 1989) that contains abundant megabreccia and mesobreccia inferred to be the products of caldera collapse (Lipman, 1976). Both of these units are areally restricted and were erupted from vents in the immediate vicinity of the study area. Neither of these units has yet been well dated, but the flows may correlate with similar rocks in the Simpson Park Mountains (~25 km to the southeast, Fig. 1; Stewart and others, 1977, p. 35) that are ~35 m.y. old (Stewart and McKee, 1968b; McKee 1968; note that K-Ar ages in this paper have been recalculated with IUGS constants given in Steiger and Jäger, 1977). In any case, both units in the study area are older than the overlying 34.3 ± 1.3 Ma tuff of Cowboy Rest (Stewart and McKee, 1969; McKee and Silberman, 1970) and are probably younger than 40–38 Ma, which is the maximum age of volcanism detected anywhere in the Basin and Range province at this latitude (McKee and others, 1976; Gans and others, 1989). Smith (1984) reported a K-Ar date of 28.5 Ma on sanidine from the tuff of Hall Creek, which conflicts with the date from the tuff of Cowboy Rest. Pervasive hydrothermal alteration of the tuff of Hall Creek may have resulted in partial resetting of this age. Redating of these units is in progress.

The upper sequence in the study area consists largely of sedimentary strata with interbedded ash-flow tuffs derived from remote sources, including the tuff of Cowboy Rest (34.3 Ma, see above), a possibly correlative tuff, here informally called "the tuff of China Spring," and the Bates Mountain Tuff (~24 Ma; Stewart and

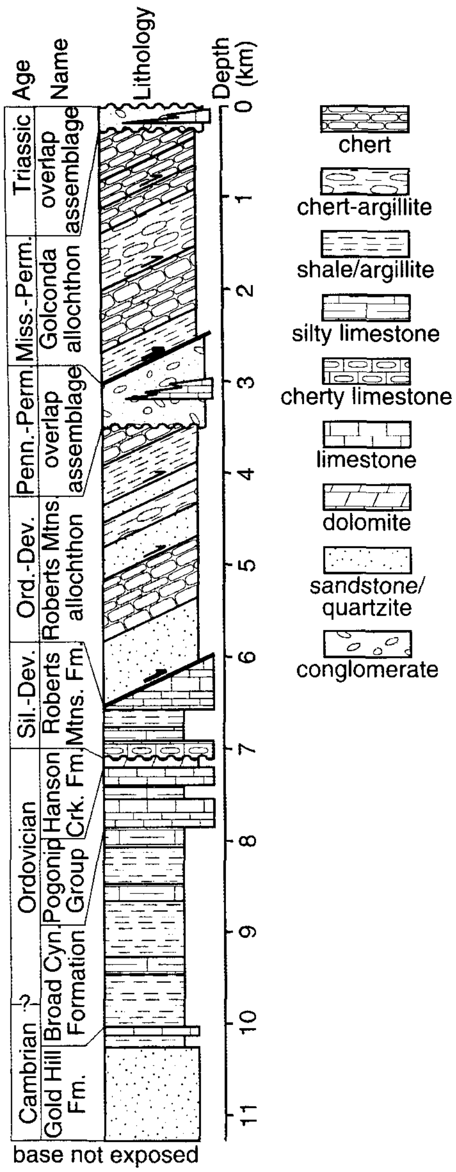


Figure 2. Composite stratigraphic column of pre-Cenozoic units in the Mount Callaghan area.

others, 1977 and references therein) (Fig. 3). Although the tuffs of Cowboy Rest and China Spring have not been analyzed in detail and are not positively correlated, they contain the same type and relative abundance of phenocrysts, and they occupy similar stratigraphic positions beneath the Bates Mountain Tuff (Fig. 3), indicating that they may be the same tuff. The only locally erupted volcanic rocks within the upper sequence are thin and discontinuous undated andesitic- to rhyolitic-lava flows which are present at several stratigraphic levels (Stewart and McKee, 1969; Fig. 3).

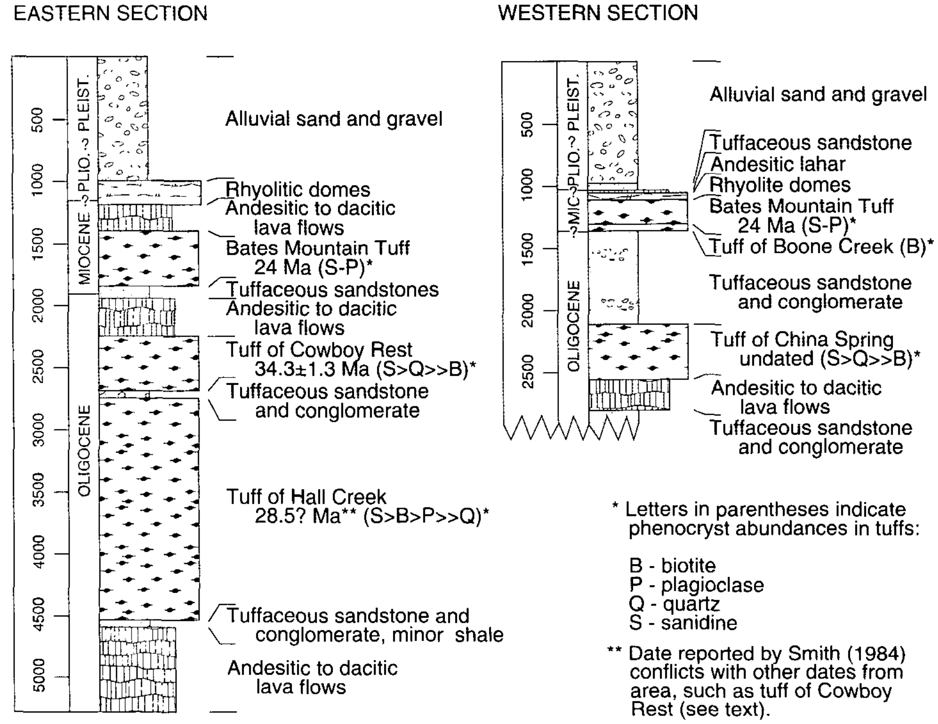
Sedimentary strata in this sequence occur largely on the flanks of the range and record the progressive unroofing of underlying units in adjacent areas. Early Oligocene sandstones deposited above the tuff of Hall Creek contains clasts derived almost exclusively from the tuff of Hall Creek and the Paleozoic allochthons. Middle to late Oligocene sandstone deposited above the tuff of China Spring and below the Bates Mountain Tuff contains scarce clasts of phyllite, quartzite, and chert breccia and abundant clasts of miogeoclinal limestone, chert from the Paleozoic allochthons and the tuff of Hall Creek. Pliocene-Pleistocene gravels contain abundant miogeoclinal quartzite in addition to all of the other rock types.

Pre-Early Oligocene Paleogeography

As Armstrong (1972) demonstrated, contact relations at the base of the Tertiary section and clast compositions of basal Tertiary units help to limit the amount of pre-Cenozoic deformation present in an area. In the vicinity of the study area, the lava flows at the base of the lower Tertiary sequence lie only on the Roberts Mountains allochthon or overlying units (Fig. 4). These units and flow rocks are also the only rocks present as clasts in sedimentary strata deposited between the lava flows and the tuff of Hall Creek. As the oldest flows and sedimentary strata are scarce in this area, the paleogeography inferred from these relationships is poorly constrained. The contacts of the tuff of Hall Creek in the area of Figure 5 cannot be used in this analysis as they reflect the structural relief generated during caldera collapse, not relief due to pre-Oligocene structures. Outside of this area, outflow sheets of the tuff of Hall Creek rest on the Roberts Mountains allochthon (Stewart and McKee, 1968b, 1969; D. L. Smith, unpub. mapping). In addition, clasts from Paleozoic allochthons make up much of the debris in breccia sheets within the caldera, suggesting that the allochthon may still have been present over much of the area of the caldera at the time of eruption. Although some amount of Mesozoic folding or faulting in the study area is likely, such disruption appears to have produced less than 4 km of structural relief. This is in keeping with regional observations indicating that this area was an area of limited supracrustal shortening located between two major fold-and-thrust belts in Mesozoic time (Speed, 1983).

EXTENSIONAL FAULTING

Two principal sets of faults are recognized in the study area: gently west-dipping, younger-on-older faults that cut both Paleozoic and Cenozoic rocks and a younger set of moderately dipping faults that cut and offset the older faults (Fig. 5). These younger faults generally strike north-northeast and dip 40°–50° westward, al-



* Letters in parentheses indicate phenocryst abundances in tuffs:

B - biotite
P - plagioclase
Q - quartz
S - sanidine

** Date reported by Smith (1984) conflicts with other dates from area, such as tuff of Cowboy Rest (see text).

Figure 3. Composite stratigraphic columns of Tertiary volcanic and sedimentary units in the area north of Mount Callaghan. See text for further descriptions of units.

though antithetic faults are present locally. A few of these faults, including the modern range-front fault, have large dip-slip separations, but most have separations of less than 100 to 200 m.

Ignoring offsets on these younger faults, the study area is divided into two principal structural domains by the Bernd Canyon fault, which is the structurally lowest of the low-angle faults (Fig. 5). The Bernd Canyon fault is exposed as a 50-cm- to 5-m-thick zone of variably silicified calcite-matrix limestone breccia. Where discrete fault surfaces within this zone are exposed, they anastamose around lenses of breccia and dip 11°–25° to the west. The sense of stratigraphic separation on the fault is hanging wall down to the west. Slickensides were not found in any exposures.

Hanging-Wall Domain

Above the Bernd Canyon fault, rocks ranging from the Lower Cambrian limestone unit of the Gold Hill Formation through the tuff of Hall Creek are steeply tilted and cut by several gently dipping faults that merge downward into the Bernd Canyon fault (location 2, Fig. 5). These subsidiary faults dip 20°–25° to the west, and all place structurally higher rocks over structurally deeper rocks (Fig. 5). The amount and direction of tilting of Paleozoic rocks varies from 10° to greater than 90° and from north through east to southeast (Fig. 6a). This scatter in the orientation of bedding is probably the result of a combination of pre-existing structures and variable amounts of drag on Cenozoic faults. The hanging-wall domain also contains several small exposures of the tuff of Hall Creek in which compaction foliation now dips 28°–58° to the east (Figs. 5 and 6). It is possible that these exposures are from sections near a caldera wall where compaction foliation was not initially horizontal; however, the relative thinness and scarcity of breccia sheets in these exposures suggest that this is not the case (Smith, 1989). Most of the observed variability is probably the result of drag along Cenozoic faults.

A thick section of the upper sediment-dominated Tertiary sequence is exposed 4 km west within the hanging wall, away from exposures of the Bernd Canyon fault. Dips decrease upsection from ~30° eastward in the Oligocene tuff of China Spring to ~5° eastward in Miocene to Pliocene sedimentary strata. In particular, dips decrease smoothly upsection in Oligocene sedimentary rocks (Ts3, location 1, Fig. 5) which form eastward-thickening wedges that are bounded on their east sides by a set of faults which now dip 25° to 35° (3-point solutions) to the west (Fig. 5). Some of the decrease in dips, especially on the east end of the wedges, was probably produced by normal drag along these faults, but much of it was probably the result of deposition during active faulting. Other Cenozoic strata are not as well exposed, and significant hiatuses and angular unconformities may separate many of those units.

Line 7 of the COCORP 40°N deep seismic reflection transect of Nevada (Fig. 1) (Potter and others, 1986) imaged a continuous, 5-km-long, gently west-dipping reflector along a line 2 to 5 km south of the exposures of Tertiary and Quarternary strata in the western half of the area shown in Figure 5 (reflection D, Fig. 2 of Potter and others, 1986). In Figure 7a, this reflection has been projected northward beneath tilted and faulted sections of Oligocene strata and is inferred to represent the downdip continuation of the Bernd Canyon fault, downdropped along the range-front fault system. Aside from the range front fault, only one other fault in section A–A′ (Figs. 5 and 7a) dips steeply enough to intersect this reflection. The reflection does not appear to offset by the possible southward continuation of this fault, but the displacement on this fault is small and might not be resolved in the COCORP data. Potter and others (1986) also identified reflection D as a continuation of low-angle faults exposed around Mount Callaghan, but they identifed this fault as a segment of the Roberts Mountains thrust based on previous mapping (Stewart and Palmer, 1967; Stewart and McKee, 1968b; Stewart and others, 1977).

Footwall Domain

The subsidiary low-angle faults described above in the hanging wall of the Bernd Canyon fault are absent in its footwall. Bedding in the greenschist-grade marble, phyllite, and quartzite

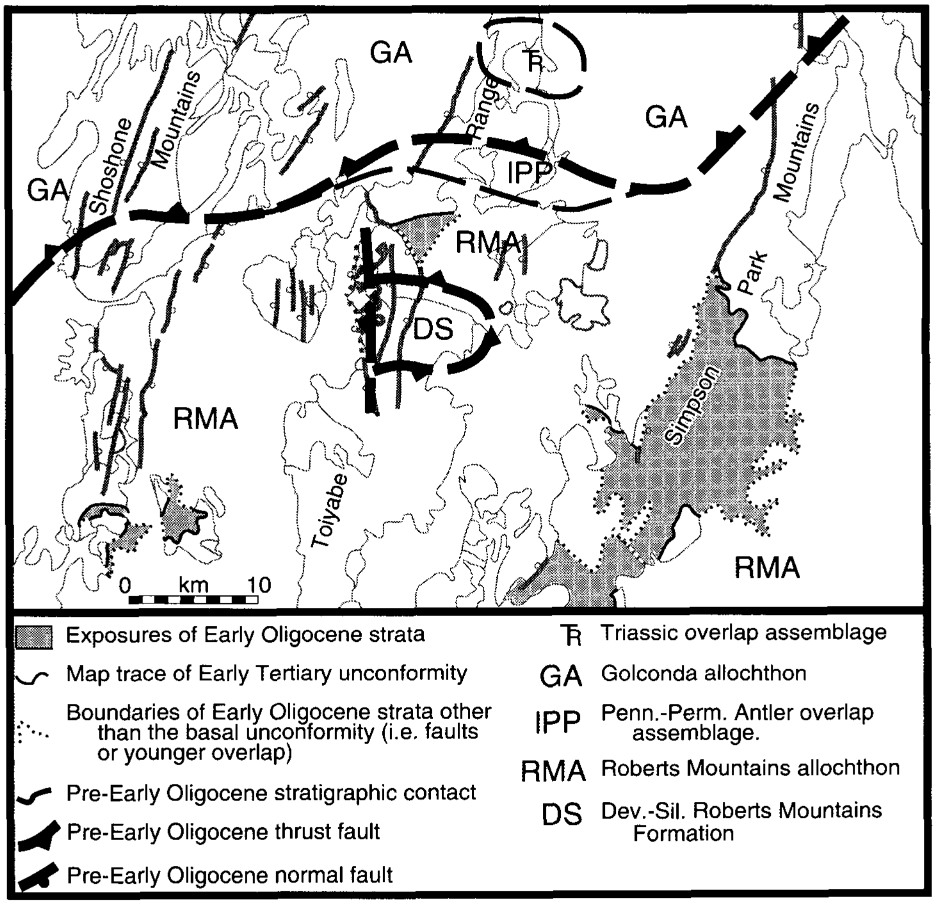


Figure 4. Outcrop map of oldest Tertiary volcanic rocks and the distribution of older units on the pre-volcanic unconformity surface in part of the northern Toiyabe Range. Where old volcanic rocks are absent, the pattern of units on the unconformity surface is based on the youngest unit exposed in the area. Normal fault in center of map is speculative and is based on reconstruction described in text.

of the Gold Hill Formation is arched across the range from dips of 30°–50° eastward on the east side of the range, to dips of 10°–15° westward in exposures immediately beneath the Bernd Canyon fault. A marked westward thinning of the Lower Cambrian units occurs on the west flank of the arch (Fig. 5). These units, especially the Cambrian limestone unit, are nearly constant in regional thickness (Stewart and others, 1977). The observed thinning is associated with east-west elongation of *Girvanella* in the limestone unit and boudinage of quartzite beds interbedded with schist in the Gold Hill Formation 40 m beneath the Bernd Canyon fault, suggesting that the thinning is tectonic (location 3, Figs. 5 and 8). The north-south–trending axes of the boudins and the east-west stretching of the *Girvanella* are both consistent with east-west ductile stretching of these units. This deformation is concentrated in rocks immediately to the south of (and by projection, immediately beneath) the Bernd Canyon fault.

Much of the footwall in the study area consists of intra-caldera sections of the tuff of Hall Creek. Pumice foliation in the tuff generally dips 40°–70° eastward. These sections are far enough removed from the Bernd Canyon fault that they have not been affected by the high-strain deformation described above, but there may be some drag folding of the foliation. Although tilting during caldera collapse cannot be ruled out, the observed moderate to steep dips suggest that the footwall of the Bernd Canyon fault has been tilted approximately the same amount as the hanging wall. The amount of tilting decreases upward through overlying volcanic and sedimentary units outside the area of Figure 5 which have been mapped in reconnaissance. Correlative units throughout the section have similar tilts in both the footwall and hanging wall.

Other Faults

Near the center of the area shown in Figure 5, the footwall is cut by a major fault that juxtaposes the tuff of Hall Creek with several hundred meters of the quartzite unit of the Lower Cambrian Gold Hill Formation along the north side of Mount Callaghan. This fault currently strikes east–west and dips 50°–70° north. The age of this fault with respect to the Bernd Canyon fault cannot be directly determined, but the most likely explanation is that this fault is part of the structural wall of the caldera which did not cave in during caldera subsidence. In the north-central part of the area in Figure 5, several east-west-trending faults juxtapose the Roberts Mountains allochthon with miogeoclinal strata and are overlapped by the tuff of Hall Creek. The origin of the faults is unclear, but they may have been small faults formed in the floor of the caldera during collapse.

DISCUSSION

Restoration of Extension

The presence of three distinct ash-flow tuffs in both the footwall and hanging wall of the Bernd Canyon fault provides a unique opportunity to study the development of an extensional fault system (Fig. 7). Upon eruption, these tuffs formed a nearly flat surface of uniform elevation. Realigning and untilting offset sections of correlative tuffs provides paleogeographic "snapshots" of the geometry of the fault system at the time the tuffs were erupted.

Younger Faults. The first step in the restoration is to remove the effects of the moderately dipping faults that cut and offset the Bernd Canyon fault (Fig. 7a). The range-front fault, which is inferred to be one of these younger faults, bounds an eastward-thickening wedge of sedimentary strata younger than the Bates Mountain Tuff (Figs. 5 and 7a). This suggests that these younger faults became active after the earliest Miocene Bates Mountain Tuff was deposited. Accordingly, the young faults were restored by aligning the basal contact of the Bates Mountain Tuff across the section. The tuff is not present in the eastern half of the study area, but its basal contact is projected from its nearest mapped position 6 km east of the study area, assuming that the mapped lack of intervening young faults is correct (Stewart and McKee, 1969; this study). Within the range, all offsets of the Bernd Canyon fault and other older faults were also restored in this step, and the 15°–20° eastward tilt of the Bates Mountain Tuff across the area was removed (Fig. 7b).

Older Faults. As discussed above, Oligocene sedimentary strata of unit Ts3 were probably deposited synchronously with movement on faults which are slightly steeper than the Bernd Canyon fault and which are assumed to merge with the down-dip continuation of that fault. This period of faulting was restored by aligning offset sections of the tuff of China Spring that underlies Ts3. To restore the slip on the Bernd Canyon fault itself and subsidiary older faults, the tuff of China Springs was aligned with the tuff of Cowboy Rest projected from outcrops present 3 km to the east of the study area (Stewart and McKee, 1969). Both tuffs were restored to horizontal by removing 20° of tilting from section 7b. Although these two tuffs are not positively correlated, it is probable that they are the same unit (see above). If not, then the geometry of Figure 7c is incorrect, but other steps in the reconstruction are unaffected because they are based on restoration of different units. In this step, the splays of the Bernd Canyon fault are restored for simplicity (Fig. 7c). There is no direct evidence for the timing of the splays, but they must have formed before the younger faults and after the eruption of the tuff of Hall Creek. Clast contents in Ts3 (see above) indicate that the siltstone unit of the Gold Hill Formation (Ꞓs) was exposed shortly after deposition of the tuff of China Spring. Nevertheless, the presence of remnants of the tuff of Hall Creek along line A–A′ requires that Ꞓs was still buried as shown in Figure 7b when the tuff of China Springs erupted. The caldera margin is oblique to the line of section (Fig. 5), and it is likely that a source for the observed clasts was exposed to the south of line A–A′.

The next step in the restoration is to connect the contacts of the tuff of Hall Creek. Because this is a caldera fill section, its contacts do not represent paleohorizontal and cannot be used to untilt the section. Instead, the attitude of pumice foliation away from the margins of the caldera was untilted to horizontal to complete the restoration. Crosscutting versus paraconformable relations between the tuff and underlying units in different areas were used to reconstruct the caldera geometry in Figure 7d. This section lies 0.5 km south of the fault that is inferred to be the southern structural wall of the caldera (see above), and known faults along which subsidence occurred are not present in this section. The slope of the caldera wall cannot be determined from field relationships and is shown schematically.

The most important result of this step in the restoration is that the untilting of the tuff of Hall Creek probably requires that the gently dipping Bernd Canyon fault originated at a dip of no less than 55°. This result is independent of earlier steps in the process and depends only on the assumptions that the tuff foliation was originally horizontal, the footwall block of the Bernd Canyon fault is relatively rigid, and the upward projection of the Bernd Canyon fault is planar. The orientation of eroded parts of the fault is not known, but only an unlikely concave-down fault geometry would produce significantly shallower initial dips. If the footwall was not rigid, a shallower initial fault dip would only be possible if the footwall had tilted more than the fault. This requires upward and eastward flow of rocks immediately beneath the fault plane relative to rocks farther into the footwall. Because the fault dips east, such an upward and eastward sense of relative motion would produce reverse-sense simple shear of the footwall, which seems

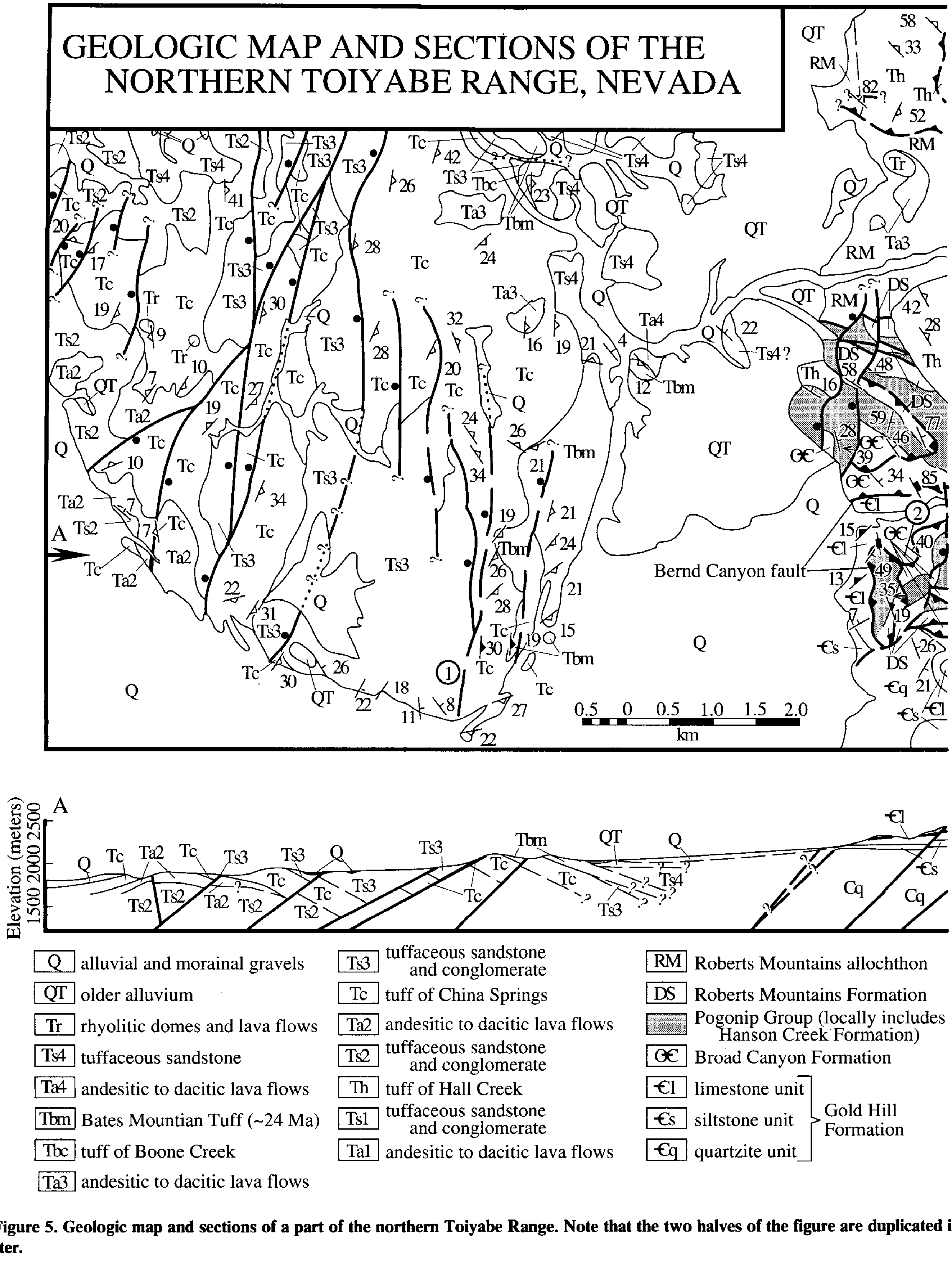


Figure 5. Geologic map and sections of a part of the northern Toiyabe Range. Note that the two halves of the figure are duplicated in the center.

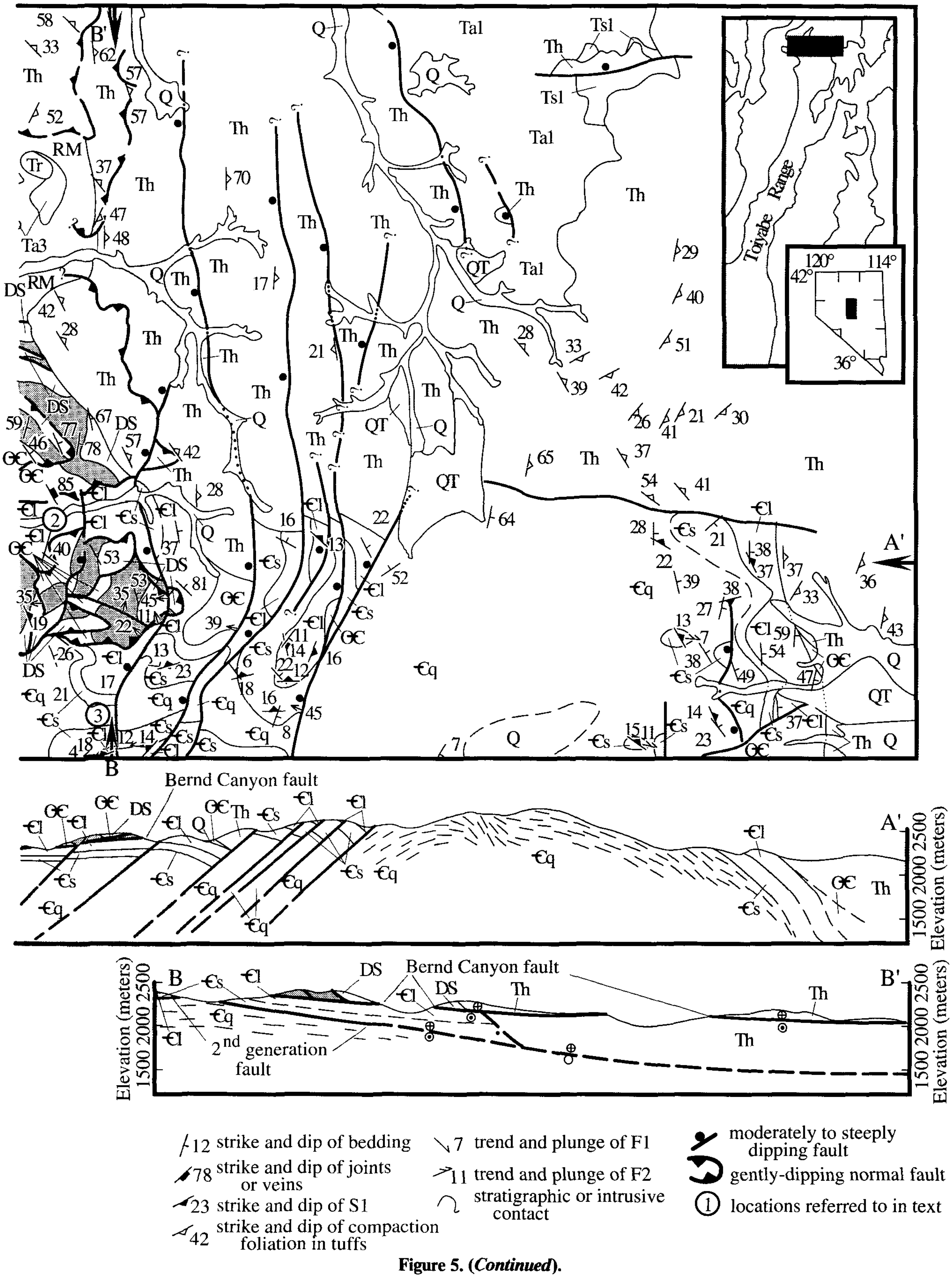


Figure 5. (*Continued*).

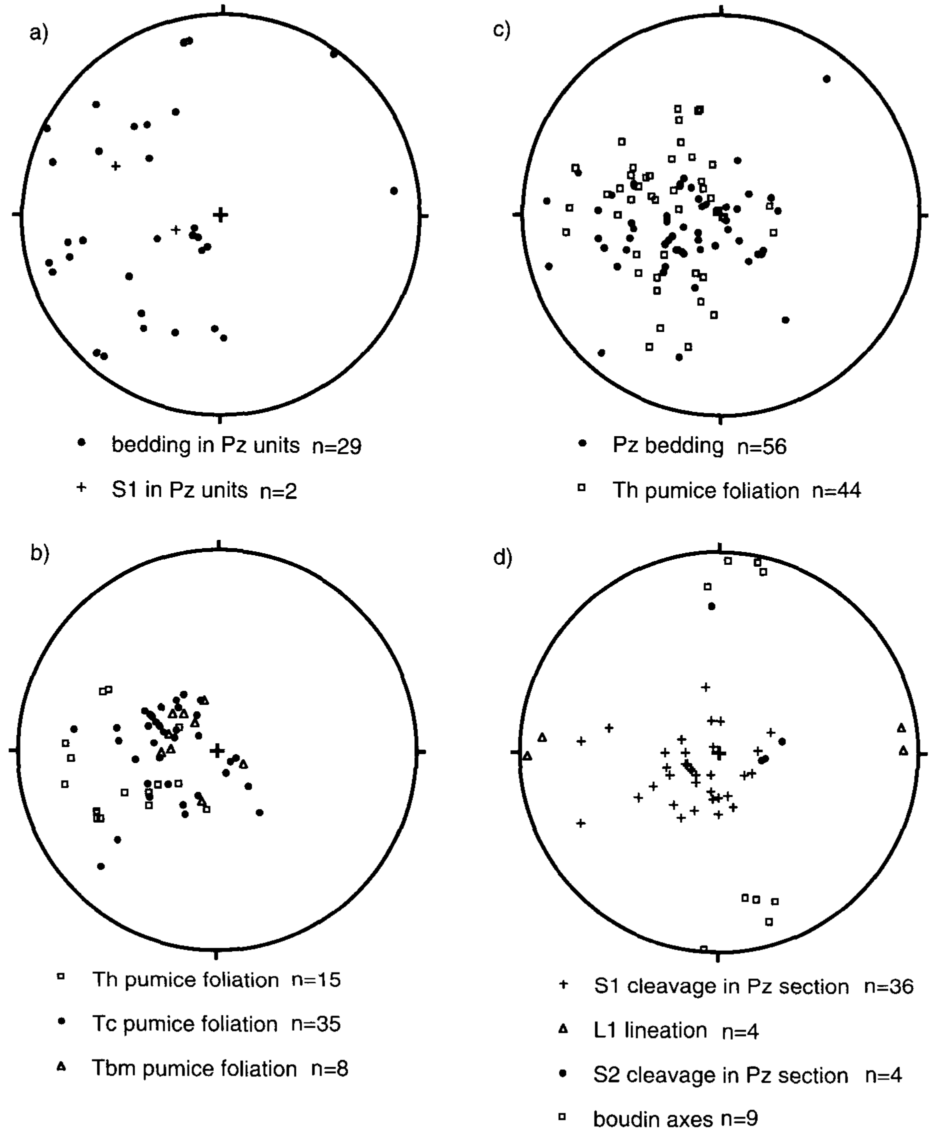


Figure 6. Stereograms of (a) bedding in Paleozoic strata in the hanging wall of the Bernd Canyon fault, (b) flattening foliation in Tertiary tuffs in the hanging wall of the Bernd Canyon fault, (c) bedding in Paleozoic units and pumice foliation in the tuff of Hall Creek in the footwall of the Bernd Canyon fault, and (d) foliations and lineations in the footwall of the Bernd Canyon fault.

unlikely in extension. Syn-eruption east tilting of the tuff would decrease the initial dip. Nevertheless, the restoration depends largely on footwall dips, and those sections are clearly in the interior of the caldera and subject only to possible tilting during asymmetric subsidence or resurgence, as noted above.

This reconstruction also shows that the Pogonip Group was juxtaposed with the lower Broad Canyon Formation across the Bernd Canyon fault in the caldera wall. This indicates that ~2 km of offset occurred along the Bernd Canyon fault prior to the eruption of the tuff. The age of this offset cannot be determined. It probably reflects the earliest stage of Tertiary extension, but it could be as old as Late Ordovician. Offset on this fault is shown in Figure 4.

At each step in this restoration, some of the observed thinning and warping of strata in the footwall of the Bernd Canyon fault has been removed. Evidence for ductile stretching discussed above is spatially associated with the Bernd Canyon fault, suggesting that this stretching is Tertiary in age and that it should be removed during restoration of Tertiary faulting. The timing of arching is harder to determine, but if it is not restored, a large west-vergent anticline is created in an area where the main phase of folding and cleavage development is east vergent (Smith, 1989).

The final stage in the reconstruction is shown in Figure 7e and simply involves restoring the pre-tuff of Hall Creek offset along the Bernd Canyon fault. The geometry of this section is very simple, but this reflects a lack of control on pre-Oligocene structures rather than a conviction about the actual geometry of the section at that time. The reconstruction of these faults indicates that they were rooted features which cut at least 6 km of section, not surficial gravity slides as Boyer and Allison (1987) have suggested.

Timing of Faulting

The onset of faulting can be determined only by indirect evidence in this area. Strong tilting of the tuff of Hall Creek indicates that it was erupted early in the history of normal faulting, but some movement along the Bernd Canyon fault occurred before the eruption of the tuff (see above). Renewed deposition, beginning with the thin conglomerate and siltstone between the tuff of Hall Creek and the underlying lava flows, records the development of local topography on a previously low-relief surface. As discussed above, the lavas and the tuff of Hall Creek are poorly dated but are probably early Oligocene in age. The amount of tilting decreases systematically upward through the entire sedimentary section, indicating that normal faulting and extension persisted, perhaps episodically, from Oligocene to at least Pliocene time.

The onset of extension in central Nevada appears to be closely linked in time and space to the onset of major Tertiary volcanism, in accord with the results of more detailed studies in eastern Nevada (Gans, 1987; Gans and others, 1989). In the Toiyabe Range, crustal heating associated with the development of a large silicic magma chamber in the mid-crust and its lower crustal feeders could have raised the depth of the brittle-plastic transition, significantly reducing the overall strength of the crust.

The transition from older to younger sets of faults in this area can be dated by the changes in the pattern of syntectonic sedimentation described above. Sedimentary strata below the Miocene Bates Mountain Tuff are probably syntectonic with normal faults of the older set, including the Bernd Canyon fault. Sedimentary strata above the tuff are syntectonic with the range-front fault and, by inference, with the other steeper normal faults within the range. These interpretations imply that the older set of faults became inactive by early Miocene time and that faulting began on the younger set sometime after early Miocene time.

Extension Direction

Fault striae were not found on any of the faults in the area; therefore, the direction of extension can only be determined indirectly from structural relations. Strained *Girvanella* and boudinage near the Bernd Canyon fault indicate approximately east-west ductile stretching in the footwall, although these structures are not dated and could predate extensional faulting. Abundant, closely spaced, north-northwest–striking, subvertical to steeply east-northeast–dipping, calcite-filled veins are present in miogeoclinal rocks near the Bernd Canyon fault. The spatial association of these veins with the Bernd Canyon fault and their steep dips suggest that they are related to that fault and that they formed fairly early in the history of extension in this area. Unfortunately, there are no data that indicate the age of the veins. An east-northeast–west-southwest direction of early extension is also supported by the east-northeast tilting of the tuff of Hall Creek (Fig. 6b). The youngest set of faults strike nearly north-south to north-northeast–south-southwest, and younger tuffs dip more directly east to east-southeast, suggesting that at some point, extension direction changed to become east-west to east-southeast–west-northwest.

Distribution of Extensional Faulting

Extension of 100% or more is also present outside the area of detailed study. The distribution of that extension is shown in Figure 9. The amount of extension shown is calculated from the amount of tilting of Oligocene volcanic rocks, using the formula of Thompson (1960), which assumes rotation above a horizontal detachment. Although a dipping detachment can lead to errors in this calculation (Axen, 1988), the percentages in Figure 9 have been checked against palinspastic reconstruction of an eastward continuation of cross-section line A–A′ in Figure 5 (Smith and others, 1991) and have been found to be in good agreement. The transition from highly extended to less extended areas appears to be gradual, and no east-west–trending transform or accommodation faults have been recognized. The fault between the tuff of Hall Creek and the Cambrian quartzite in the study area is probably not such a fault, because it is confined to the footwall of the Bernd Canyon fault and is more likely related to caldera subsidence. In the absence of tear faults, there must be internal deformation of fault blocks in order to maintain strain compatibility across gradients in the amount of extension. In the Shoshone Mountains to the west of the study area, Oligocene to early Miocene volcanic strata are uniformly tilted 30° to the west along Miocene or younger down-to-the-east normal faults (Smith, 1989). These east-dipping faults are not clearly related to the west-dipping faults in the Toiyabe Range. Although some of the boundaries are obscured by valley fill, the pattern of tilting suggests that large-magnitude Cenozoic extension in the northern Toiyabe Range was probably confined to an area ~45 km long by 35 km wide, centered near Mount Callaghan (Fig. 9).

Amount of Extension

The amount of Tertiary tilting decreases in all directions away from the Mount Callaghan area; therefore, an estimate of extension across that area will give an upper bound on the amount of extension that has occurred across the highly extended domain. Palinspastic restoration of Tertiary faulting provides the most straightforward and accurate measure of the amount of extension. The restoration above indicates a total of 15.5 km of extension has occurred across section A–A′, which is now 21 km long and covers slightly more than half of the width of the highly extended domain. Palinspastic restoration of the entire domain along the same line of section indicates that ~21 km of extension has occurred across this zone, which is now ~35 km wide (Smith and others, 1991).

Kinematics of Detachment Faults

The Bernd Canyon fault is similar in its juxtaposition of an unmetamorphosed, highly tilted, and attenuated hanging wall with a moderately metamorphosed, domed, and penetratively deformed footwall to well-known detachment faults of the Basin and Range, although it is developed at a smaller scale (Davis, 1980; Armstrong, 1982; Frost and Martin, 1982). The Bernd Canyon fault is apparently unique, however, because Tertiary strata are present in the footwall of the detachment fault. Untilting these volcanic rocks strongly suggests that the low-angle Bernd Canyon fault initiated as a steeply dipping normal fault.

Palinspastic restoration also suggests that the arching and thinning of Lower Cambrian units in the footwall of the Bernd Canyon fault (Figs. 5 and 7) are Tertiary in age. The thinning, as well as the observed stretching of *Girvanella* and boudinage in footwall units close to the fault, was probably produced by inhomogeneous top-to-the-west, normal-sense, simple shear resulting from drag along the Bernd Canyon fault. The arching of these units is inferred to be the result of a combination of rotation of the footwall to produce overall east dips and normal-sense simple shear to drag footwall beds into shallow west dips near the fault. If Tertiary units were not preserved in the footwall of the Bernd Canyon fault, then the small bedding-to-fault angle created by shear of the footwall could easily lead to the interpretation of a shallow initial dip for the fault.

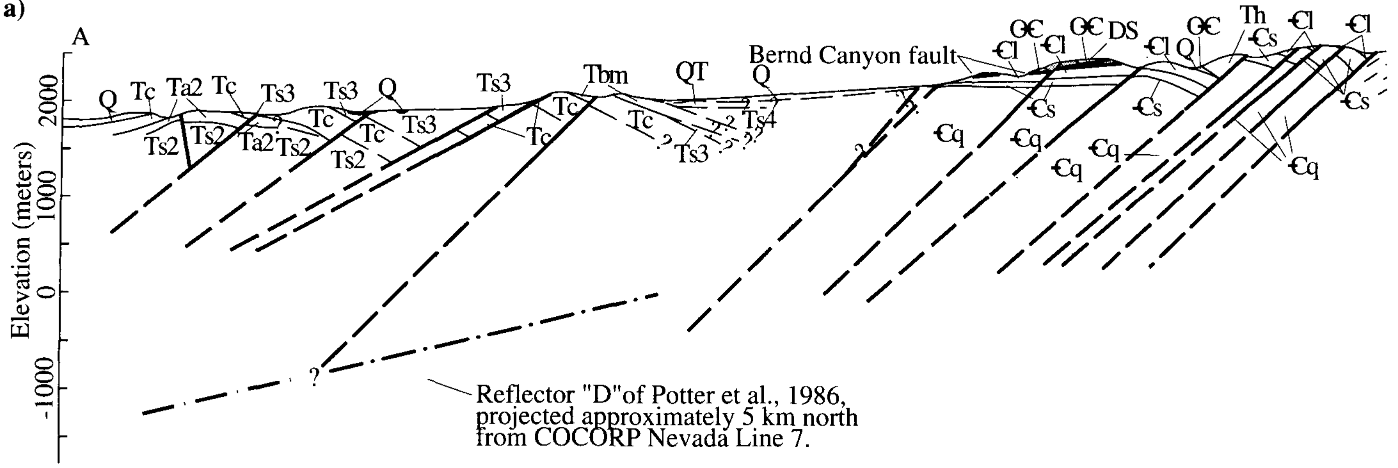
Davis (1983, 1987) has previously proposed that detachment faults originate as rotating fault zones; however, rotation is very difficult to quantify in the crystalline rocks which Davis studied. The model presented above for the Bernd Canyon fault is very similar to Davis' (1987) model, Wernicke and Axen (1988) have also proposed a model for the origin of detachment faults by rotation of extensional faults in a migrating zone of localized isostatic uplift following unloading of the footwall. Apparently simultaneous tilting of Tertiary rocks now separated by 25 km suggests that this model may not explain the tilting history in the northern Toiyabe Range, but further mapping, dating, and modeling are necessary to test the applicability of this model in this area.

In order to rotate without bending, the Bernd Canyon fault must have flattened at depth. The structure into which the Bernd Canyon fault flattened is not exposed, and it might be argued that the Bernd Canyon fault was in the upper plate of a regional low-angle fault. Unlike the broad belts of extension in eastern Nevada and along the Colorado River, extension in the Toiyabe Range is restricted in area, both along and across strike. As a result, the Bernd Canyon fault cannot easily be visualized as an upper-plate fault above a regionally extensive detachment. Instead, the fault probably flattened into the brittle-ductile transition in the mid-crust, just as modern seismically active faults are observed to do (Eyidogan and Jackson, 1985).

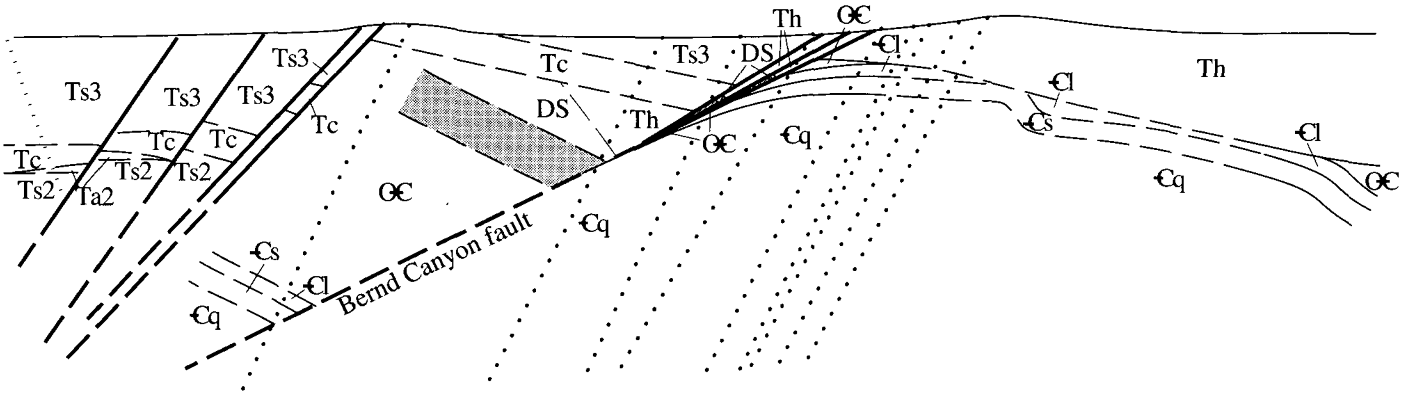
Style of Extension through Time

In addition to suggesting that some extensional detachments may have originated as steeply dipping normal faults, the relationships in the Toiyabe Range indicate that no significant difference in kinematics exists between pre-Miocene ("pre–basin and range") extension and Miocene to Recent ("basin and range") extension in this area. The Oligocene faults in the Mount Callaghan area were steeply to moderately dipping throughout much of their history. Inferred growth fault relationships suggest that movement on these faults produced asymmetric, fault-bounded basins with topographically elevated footwalls, just as modern range-bounding faults do (for example, Anderson and others, 1983). Only one large Oligocene normal fault (albeit one with abundant splays) was identified

a) PRESENT DAY



b) EARLIEST MIOCENE (PRE-BATES MOUNTAIN TUFF)



c) EARLY OLIGOCENE (PRE-TUFF OF CHINA SPRINGS)

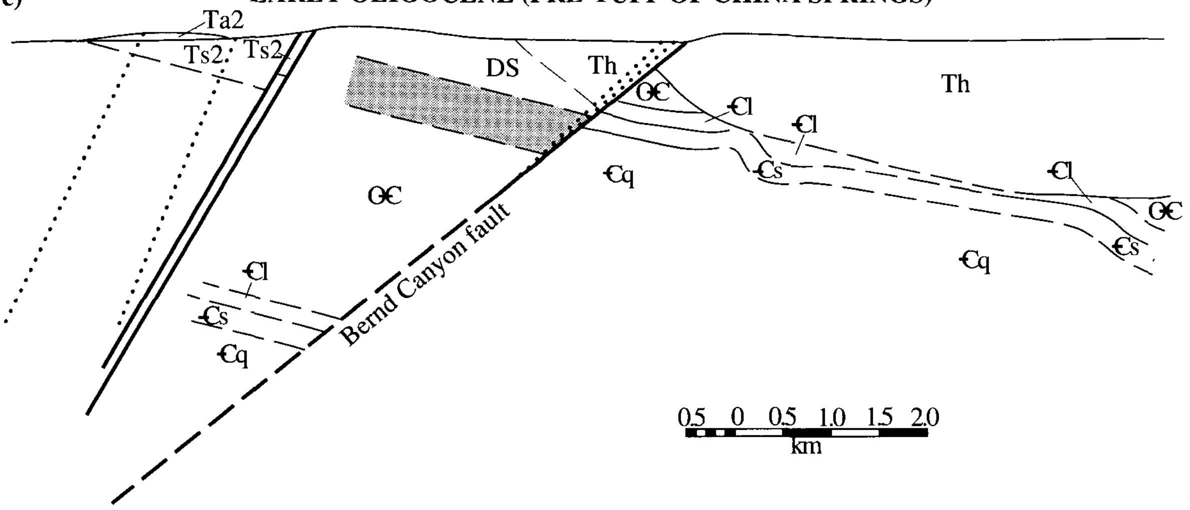
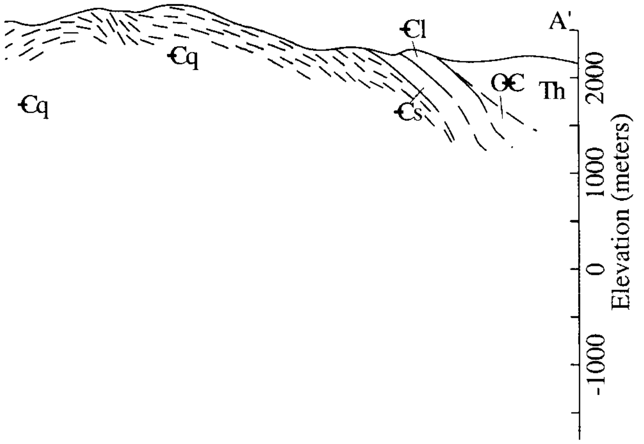
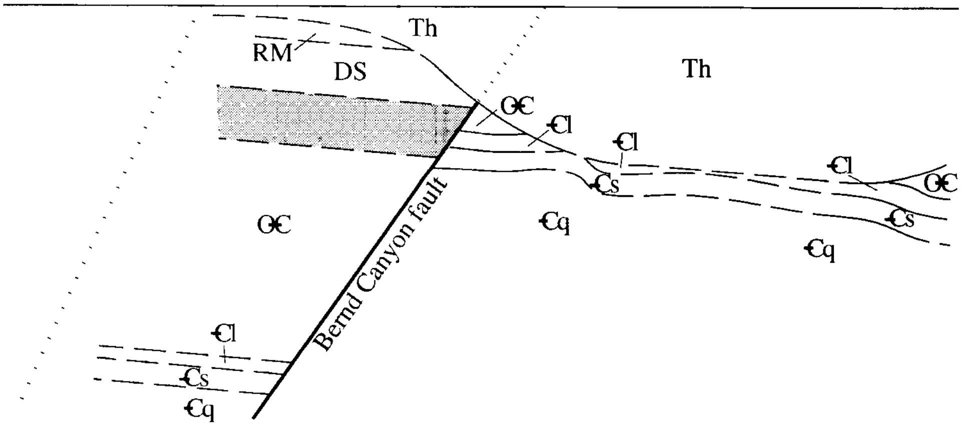


Figure 7. Step-by-step palinspastic restoration of cross-section A–A′ in Figure 5. Diagrams (a) through (e) show progressive steps in the restoration, starting with the present-day section in 7a. See text for detailed description.



d) EARLIEST OLIGOCENE (POST-TUFF OF HALL CREEK)



e) PRE-OLIGOCENE

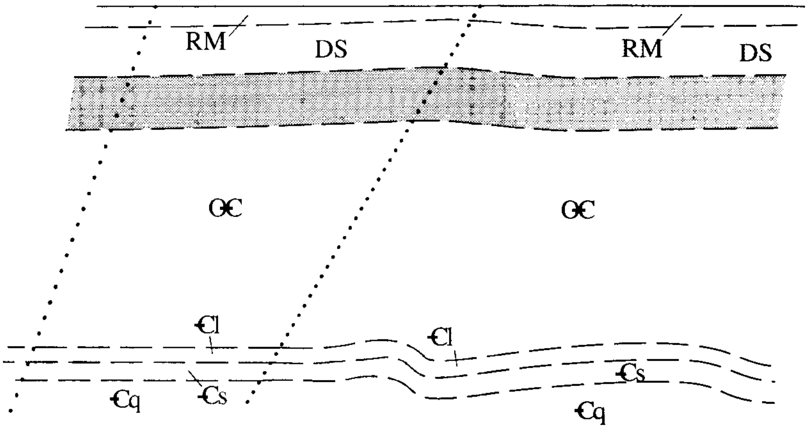


Figure 7. (*Continued*).

in the study area, and so it also seems reasonable to infer that major normal faults were spaced tens of kilometers apart in Oligocene time, just as they are today.

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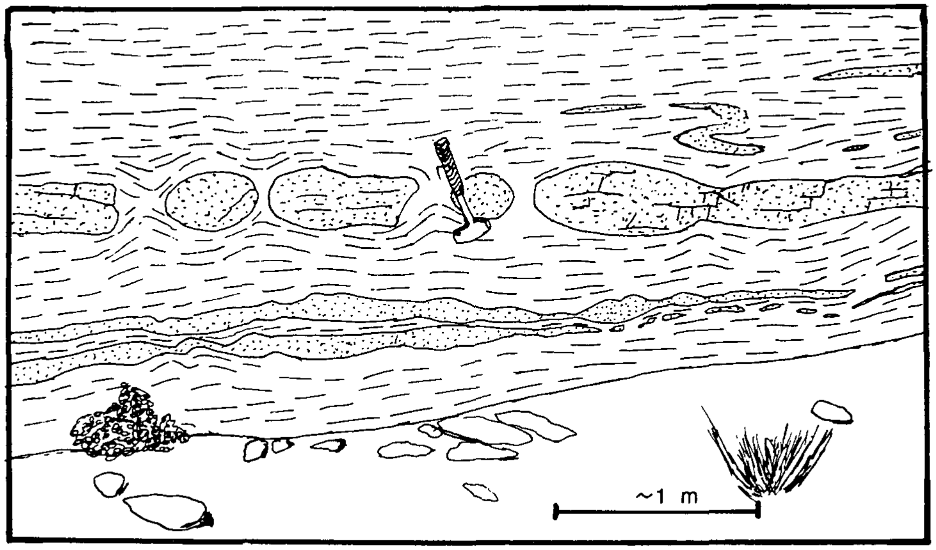

Figure 8. Line drawing from a photograph of boudinaged quartzite beds (location 3 in Figure 5), beneath the Bernd Canyon fault.

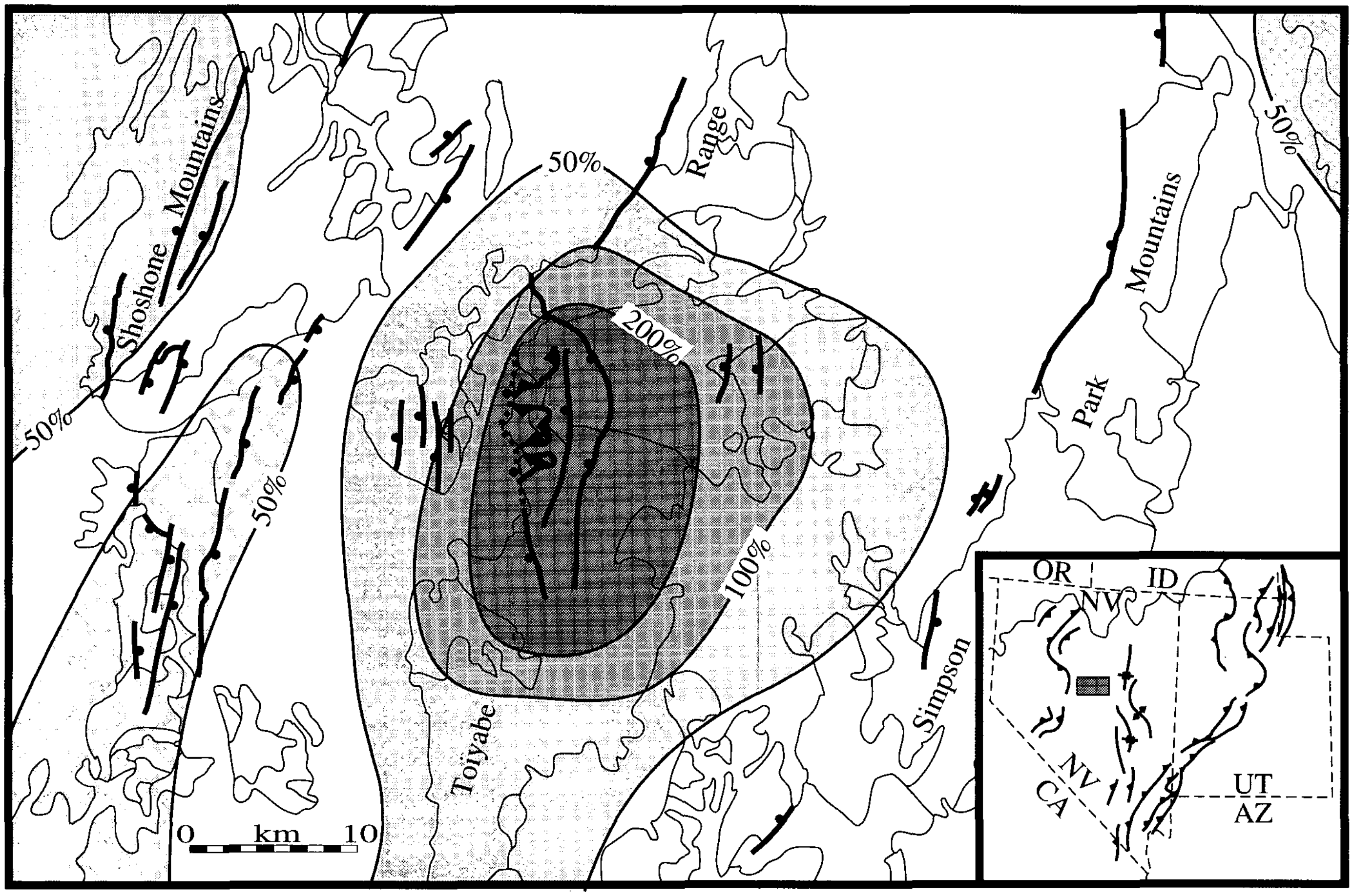

Figure 9. Map of the distribution and approximate amount of Cenozoic down-to-the-west extension in the northern Toiyabe Range, based on the restoration in Figure 7 and on the tilting of Oligocene strata. Cross-hachured pattern indicates domain of Miocene and younger down-to-the-east extension.

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