Kinematic evolution of a large-offset continental normal fault system, South Virgin Mountains, Nevada

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ABSTRACT

The South Virgin Mountains and Grand Wash trough comprise a mid-Miocene normal fault system that defines the boundary between the unextended Colorado Plateau to the east and highly extended crust of the central Basin and Range province to the west. In the upper 3 km of the crust, the system developed in subhorizontal cratonic strata in the foreland of the Cordilleran fold and thrust system. The rugged topography and lack of vegetation of the area afford exceptional three-dimensional exposures. Compact stratigraphy and well-defined prefaulting configuration of the rocks permitted a detailed reconstruction of the system. Reconstruction of cross sections based on more than 300 km² of detailed mapping at a scale of 1:12,000 shows that the fault system accommodated more than 15 km of roughly east-west-directed Miocene extension. Extension was initially accommodated on moderately to steeply dipping listric normal faults. As the early faults and fault blocks tilted, steeply to moderately dipping faults initiated within the fault blocks, soling into the early faults. Some of the early faults were active at dips of <20°. Isostatically driven tilting is superimposed on tilting due to active slip and domino-style rotation of the fault blocks. Collectively these processes rotated originally steeply dipping faults to horizontal orientations. The kinematics are inconsistent with the widely accepted view that many near-horizontal normal faults were rotated to their present orientations by later, crosscutting normal faults. However, examination of other areas suggests that the evolutionary sequence seen in the South Virgin Mountains may, in fact, be widely applicable.

Keywords: Egan Range, kinematics, Lemitar Mountains, normal faults, South Virgin Mountains, Yerington.

INTRODUCTION

Geologic mapping in the Basin and Range province has shown that gently dipping normal faults are common (e.g., Longwell, 1945; Anderson, 1971; Proffett, 1977; Miller et al., 1983; Wernicke et al., 1985; John and Foster, 1993), but theoretical fault mechanics suggests that such faults should not slip (cf. Anderson, 1942; Sibson, 1985; Nur et al., 1986; Agnon and Reches, 1995). These faults have been explained in a manner consistent with mechanical theory by invoking tilting to lower dips after cessation of slip (e.g., Proffett, 1977; Miller et al., 1983; Buck, 1988). For example, in the Snake Range, the Lemitar Mountains, and the Yerington district, gently dipping faults have been interpreted as the result of multiple generations of crosscutting, steeply dipping normal faults, with older faults being tilted to shallow dips above younger faults (Fig. 1A; Proffett, 1977; Chamberlin, 1982, 1983; Miller et al., 1983). Gently dipping normal faults have also been attributed to the rotation of originally steeply dipping faults after abandonment above an upflexing, tecnotonically denuded, footwall (Fig. 1B; Buck, 1988).

However, many gently dipping normal faults can not be explained by either of these mechanisms. Some of them probably initiated with shallow dips (e.g., Wernicke et al., 1985; John and Foster, 1993); others may have initiated with steep dips and remained active as they tilted to shallow dips. Tilting of these faults is probably due to combined domino-style tilting and isostatically driven footwall flexure (Fig. 1C). Many gently dipping normal faults might be best interpreted this way, rather than invoking rotation by younger structures.

Detailed geologic studies were conducted in the South Virgin Mountains of southeastern Nevada and northwestern Arizona (Fig. 2), a region well suited for testing existing kinematic models of normal faulting. Extensional faults within the Grand Wash trough and adjacent South Virgin Mountains define a relatively sharp transition from the unextended Colorado Plateau to the strongly extended Basin and Range (stretching factor β ≈ 3.5; Wernicke et al., 1988). The plateau consists of high-grade Proterozoic basement nonconformably overlain by a thin (~2 km) Paleozoic cover, and forms a headwall from which steeply east tilted normal fault blocks, bounded by both steep and shallow normal faults, including both basement and cover, were derived.

The mapped area comprises a series of eight tilted fault blocks deformed by multiple generations of normal faults in middle Miocene time (Fig. 3). These fault blocks are bounded by normal faults with 1 km or more of throw, and are internally disrupted by numerous smaller offset faults. Four of these blocks, including (from east to west) the Wheeler Ridge, Iceberg Ridge, Indian Hills, and Connolly Wash blocks, straddle the eastern end of Lake Mead, Nevada (Fig. 3). The next block to the west, interpreted to be structurally continuous with the Gold Butte crystalline block, is the Azure Ridge block. The next three blocks to the west, including Tramp Ridge,
Figure 1. Schematic cross sections of the upper crust showing three models of normal fault evolution, all of which result in both shallowly and more steeply dipping normal faults. Incipient faults are shown as dashed lines, active faults are shown as heavy black lines, and inactive faults are shown as thinner black lines. (A) Multiple generations of domino faults; only moderately to steeply dipping faults are active; shallowly dipping faults have been rotated above younger crosscutting faults (cf. Proffett, 1977; Miller et al., 1983). (B) Rolling hinge model; initially steeply dipping faults are flexurally rotated above an uplifting footwall, becoming inactive at low dips. New, steep faults break through the intact hanging wall as old faults become inactive and are abandoned on the uplifted footwall (Buck, 1988). (C) Synchronous slip model; after some slip and rotation of initially steep faults, younger steep faults break and sole into the rotated older faults. All faults remain active and rotate dominantly, as well as rotating as a result of isostatic uplift of the thinning region.

Figure 2. Location map, showing the South Virgin Mountains (stippled) and surrounding area, as well as major structural features. Light gray indicates the location of mountainous terrane. BM—Black Mountains, CP—Colorado Plateau, FM—Frenchman Mountain, GPT—Gass Peak thrust, KT—Keystone thrust, VD—Virgin detachment, LMFS—Lake Mead fault system, LVR—Las Vegas Range, LVVSZ—Las Vegas Valley shear zone, MM—Muddy Mountains, MMT—Muddy Mountains thrust, NVM—North Virgin Mountains, SR—Sheep Range, SVM—South Virgin Mountains.

Lime Ridge, and the Maynard Spring block, are north of and structurally above the crystalline block, which is a 15-km-wide basement dome, unroofed by a west-dipping normal fault (Fryxell et al., 1992).

Most of the faults within the South Virgin Mountains cut through Paleozoic to Tertiary strata. The stratigraphic section includes more than 30 mappable units in about 3 km of section. The South Virgin Mountains were little deformed by Mesozoic compression, as evidenced by the lack of contractional structures within the region, and the very gentle sub-Tertiary unconformity across the South Virgin and Beaver Dam Mountains (Bohannon, 1984; Wernicke and Axen, 1988). The faulted sections of the South Virgin Mountains must restore so as to be continuous with the flat-lying strata of the Colorado Plateau. Because the faults within the South Virgin Mountains are well exposed, have accommodated large-magnitude extension, and must restore to a well-defined structural datum, the area provides an exceptional opportunity to study the kinematic evolution of a continental normal fault system.

GEOLOGIC SETTING

During Late Jurassic and Cretaceous time, the Lake Mead area was part of the foreland to the thin-skinned Sevier thrust belt (Burchfiel et al., 1974), which developed within the sedimentary rocks of the Paleozoic miogeocline. The easternmost thrusts seem to have been localized along the hinge zone of the miogeocline, which trends roughly northeast-southwest, and runs just to the west of Lake Mead. Accordingly, the easternmost thrust sheet at the latitude of Lake Mead is exposed nearby, to the west, in the Muddy Mountains (Fig. 2; Longwell, 1949; Longwell et al., 1965; Bohannon, 1983). South of Lake Mead, the thrust belt changes to a northwest-southeast trend, and thrusting involves Precambrian crystalline basement rocks (Burchfiel and Davis, 1975).

Following Cretaceous thrusting, the Lake Mead region seems to have been tectonically stable until Neogene time. However, early Miocene to Eocene deposits filling northeastward-draining paleocanyons that cut into the southwestern part of the Colorado Plateau show that a basement high had formed to the south of Lake Mead by Eocene time (Young, 1966, 1979). Paleozoic and Mesozoic strata were erosionally removed from this basement high. The exact age and extent of this high remain unclear, due to incomplete understanding of the age and preextensional configuration of the sub-Tertiary unconformity.
The present physiographic features of the area result primarily from Miocene extension. During Miocene time, extension initiated at the edge of what is now the Colorado Plateau, accommodated on a set of west-dipping normal faults. These faults strongly control the topography of the South Virgin Mountains, as discussed above and illustrated in Figure 3.

The timing of extension in the South Virgin Mountains is constrained by fission-track ages from across the Gold Butte crystalline block. Fitzgerald et al. (1991) documented apatite fission-track ages, interpreted as extensional unroofing ages, of ca. 15 Ma across the northern end of the block.

Extension in the eastern Lake Mead region was accompanied by little or no magmatism. The only Tertiary volcanic rocks in the region, excluding thin tuff beds and rare mafic volcanic vents, are the postextensional basalts of Gold Butte (9.15–9.46 Ma; Cole, 1989) and Grand Wash Trough (3.99–6.9 Ma; Feuerbach et al., 1993).

CRYSTALLINE ROCK UNITS

Proterozoic X

The oldest rock units in the crystalline complex include the 1.7–1.8 Ga (Wasserburg and Lanphere, 1965; Bennett and DePaolo, 1987; work of L.T. Silver as discussed by Stewart, 1980) orthogneiss and garnet gneiss, which account for most of the metamorphic country rock. Three other rock types of inferred Proterozoic age include hornblende granite, leucogranite, and ultramafic rocks; the two granites locally exhibit gneissic high-temperature foliation.

Garnet gneiss, the most abundant of the metamorphic rocks, contains garnet, biotite, cordierite, sillimanite, plagioclase, quartz, hercynite, and magnetite (Volborth, 1962; Thomas et al., 1988; Fryxell et al., 1992). This unit is extensively migmatitic, with 1-cm- to >10-m-thick layers of coarse-grained quartz, feldspar, and garnet; the remainder of the unit is gneissic and has a well-developed foliation with no lineation (Fryxell et al., 1992).

Proterozoic Y

The Gold Butte Granite (1.45 ± 0.25 Ga; Silver et al., 1977) is a large pluton of rapakivi
granite that forms about 30% of the basement outcrop (Volborth, 1962; Fryxell et al., 1992). It shows a distinctive texture of large (1–4 cm), early crystallized potassium feldspar phenocrysts, surrounded by a matrix of later crystallized minerals, including plagioclase, quartz, biotite, hornblende, and sphene (Volborth, 1962). Rapakivi texture, with plagioclase rimming the alkali feldspar phenocrysts, is common, but not ubiquitous. Potassium feldspar phenocryst abundance and the intrusive geometry of the granite change significantly from west to east across the pluton (Fryxell et al., 1992). The phenocryst content increases from typically <20% in the western outcrops to nearly 70% in the easternmost outcrops. The western outcrops form a complex wormy pattern within the metamorphic country rock, whereas the eastern outcrops are part of a large continuous body, with clearly defined contacts.

Diabase dikes, reported from the southern part of the crystalline block, are probably of Middle Proterozoic age, on the basis of regional correlation with other diabase dikes (Howard, K., unpublished data). Also, numerous mica-bearing pegmatite dikes intrude many of the mappable units but, due to their generally small outcrop area, they were not mapped by Fryxell et al. (1992) or earlier workers. The age of these dikes is uncertain, because they have not been reliably isotopically dated (for a more detailed discussion, see Fryxell et al., 1992).

**STRATIFIED ROCK UNITS**

**Paleozoic–Mesozoic**

A 2.5–3.5-km-thick succession of sedimentary rocks (Fig. 4) is separated from the crystalline basement rocks by the sub-Cambrian unconformity. These strata comprise a thin cratonal section just east of the Cordilleran miogeocline.

The strata comprise four major sequences; the lower two being carbonate dominated and the upper two being clastic dominated. The lower sequence is bounded at its base by the Proterozoic to Lower Cambrian unconformity, and is composed of a basal clastic succession and an overlying carbonate succession. The basal succession includes the Lower Cambrian Tapeats Sandstone and overlying shales and limestone of the Middle Cambrian Bright Angel Formation (Schonck and Wheeler, 1942; Wheeler, 1943; McKee, 1945; Wheeler and Beasley, 1948). The thickness of this succession is ~140 m, with significant variability due to tectonic thickening and thinning of the Bright Angel shales. The overlying carbonate-dominated succession varies in thickness from ~650 m in Lime Ridge to ~520 m in Wheeler Ridge. It is entirely composed of the Middle to Upper Cambrian (McKee and Resser, 1945; Longwell, 1949; Longwell et al., 1965) Bonanza King Formation, the lowest member of which is limestone (the Papoose Lake Member); the remainder of the unit is dominantly dolostone.

The top of the first sequence, and the base of the second sequence, occurs at the Upper Cambrian to Devonian unconformity. The second sequence is composed of a carbonate dominated succession, overlain by a clastic succession, in turn overlain by another carbonate succession. The lower carbonate succession is ~800 m thick, and is composed of the Devonian Mountain Springs and Sultan Formations (McNair, 1951), the Mississippian Monte Cristo Formation (Langenheim, 1963), the Pennsylvanian Callville Formation (Longwell, 1921; McNair, 1951; Lumsden et al., 1973), and the Permian Pakoon Formation (McNair, 1951; McKee, 1975). All of these units are generally described as limestones, but the Devonian and Mississippian units tend to be heavily altered to dolostone in the South Virgin Mountains. The middle clastic succession has an average thickness of about 530 m and is composed entirely of Permian rocks (White, 1929; McKee, 1933, 1969, 1975). It includes the Queantweap Sandstone, the Hermit Formation, and the Cocoono Sandstone. All three of these units vary in thickness throughout the map area due to variability in depositional thickness as well as probable tectonic thickening and thinning, particularly within the incompetent mudstones and fine sandstones of the Hermit Formation. Above this is the upper succession of limestone, made up of the Permian Toroweap and Kaibab Formations (middle Permian; McKee, 1938). It has a maximum thickness of ~270 m and thins toward the southeast, reaching zero thickness within the southeastern part of the South Virgin Mountains.

The boundary between the second and third sequences is defined by the middle Permian–Lower Triassic unconformity. The third sequence is composed entirely of clastic rocks with a maximum total thickness of about 1100 m, and a minimum thickness of 0 m, the southeasternmost outcrops occurring on the east side of Azure Ridge. It includes the Lower to Middle Triassic Moenkopi and Chinle Formations (Gregory, 1915; Gregory and Williams, 1947; Poborski, 1954; Stewart, 1957), as well as the Moenave and Kayenta Formations undifferentiated (Marzolf, 1990). The Moenave and Kayenta Formations undifferentiated were combined with the Chinle Formation for mapping purposes, because they are discontinuous and difficult to distinguish in the field.

The third and fourth sequences are separated by the basal Jurassic unconformity. The fourth sequence includes only the Jurassic Aztec Formation. The Aztec Formation is nearly 200 m thick in the northern part of the South Virgin Mountains, but pinches out to 0 m thickness within the central South Virgin Mountains, and is not exposed anywhere south of Tramp Ridge (Fig. 3).

All thickness estimates presented herein are based on averaging the mapped thickness from several locations. Most of these strata, as they occur in the South Virgin Mountains, were described in more detail by Morgan (1968) and Matthews (1976), as well as in a measured section by S.M. Rowland and V.S. Korolev (unpublished data).

**Tertiary**

Two major sequences of Tertiary strata are present; one is tilted and disconformably overlies Paleozoic and Mesozoic strata, and the other is more or less flat-lying, and in angular unconformity on all older rocks. The tilted sequence comprises the Rainbow Gardens and Thumb Members of the Miocene Horse Spring Formation (Bohannon, 1984; Beard, 1996). The thickest exposed Horse Spring section, east of Tramp Ridge, is ~600 m. The
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Figure 4. Stratigraphic section from the South Virgin Mountains; thicknesses were measured from 1:12,000 scale field maps.
basal Horse Spring beds dip nearly concordantly with underlying Paleozoic strata, and therefore predate large-magnitude extension and tilting. However, the lowest of these beds exhibit growth-fault fanning of dips where they crop out near the north end of Wheeler Ridge, and are therefore classified as early syntectonic strata. Bedding within the overlying Thumb Member fans slightly upslope, and is also considered to be syntectonic (Beard, 1996).

The more or less flat-lying rocks of the Grand Wash trough are in sharp angular unconformity above the Horse Spring Formation (Lucchitta, 1967; Bohannon, 1984). They include a unit composed of red sandstone and siltstone with occasional tuff beds, overlain by interfingered gyspsum, conglomerates, and basalts. The red sandstone unit (ca. 11.9–10.6 Ma; Bohannon, 1984) is approximately correlative in age with the red sandstone unit of White Basin and Frenchman Mountain in the western Lake Mead region, but was probably not part of a connected depositional system, because all three localities were apparently isolated basins at the time of deposition (Bohannon, 1984). A succession of generally flat-lying conglomeratic units overlies the red sandstone in the Grand Wash Trough. The conglomerates were divided into three types by Lucchitta (1967); one includes class of Gold Butte granite as well as other crystalline clasts, a second includes crystalline clasts but no Gold Butte granite, and a third includes dominantly sedimentary clasts. Within the mapped area, most of the conglomerates contain clasts of Gold Butte granite. The sedimentary-clast-dominated conglomerates occur closer to the Grand Wash Cliffs, and the conglomerate that has crystalline clasts, but no Gold Butte granite clasts, occurs farther south, in the Grand Wash Trough (Lucchitta, 1966; Bohannon, 1984). The Hualapai Limestone overlies these conglomerates; the age of the limestone is not directly known, but has been inferred based on its relationship to datable rocks elsewhere (ca. 10.8–3.8 Ma; Blair, 1978; Blair and Armstrong, 1979; Bohannon, 1984; Faulds et al., 1997). In places, the red sandstone and fanglomerates of the Grand Wash Trough are overlain by the basalts of Grand Wash Trough (ca. 4–7 Ma; Cole, 1989), but these basalts are not seen above the Hualapai Limestone.

Conglomerates similar to those included in the rocks of the Grand Wash Trough are abundant on the west flank of the South Virgin Mountains, and are generally included in the Muddy Creek Formation (Longwell, 1936; Bohannon, 1984). Near the western end of the Gold Butte fault, these conglomerates are overlain by the Gold Butte basalt (ca. 9.5–9.5 Ma; Cole, 1989). Except where overlain by the Gold Butte basalt, the ages of the conglomerates are not constrained, and may be as young as Quaternary (the Muddy Creek Formation can not be older than 10.6 Ma, and is generally younger than 8 Ma; Bohannon, 1984).

There are younger conglomerates, gravels, and sands stratigraphically above the rocks of the Grand Wash Trough and the Muddy Creek (?) conglomerates. Some of these deposits, including an outcrop of Chemehuevi Formation at Sandy Point and scattered roundstone gravels, are probably ancient Colorado River deposits. There are also numerous levels of Quaternary alluvium. Within individual drainages two to four different levels of Quaternary alluvial terraces are common, but these can not easily be correlated from drainage to drainage.

STRUCTURE

The South Virgin Mountains were essentially undeformed by Mesozoic compression events, but strongly deformed by Tertiary extension and strike-slip faulting. The only structures within the mapped area that were probably formed by Mesozoic compression are a series of small-amplitude (~10 m) folds in Permian to Triassic strata of northeastern Lime Ridge (Fig. 5). North of the mapped area (but still within the South Virgin Mountains), there is a thrust fault that places Pennsylvanian strata over Triassic and Jurassic strata, adjacent to the Bitter Ridge fault (Fig. 3). This may be a Mesozoic thrust, because it

Ridge-Bounding Faults and Related Folds

South of the Lime Ridge fault (Fig. 5), the South Virgin Mountains include seven major ridge-forming fault blocks, bounded by normal faults that have each accommodated 1 km or more of offset (Figs. 5 and 6). These faults, listed from east to west, include the Grand Wash fault zone, the Wheeler Ridge fault, the Iceberg Canyon fault, the Indian Hills fault, the Million Hills Wash fault, the Garden Wash fault, the Lime Canyon fault, and the Maynard Spring fault.

The Grand Wash fault zone, easternmost of the major faults, separates the Wheeler Ridge block from the adjacent Colorado Plateau.
(Fig. 5). Because the strata of Wheeler Ridge are downthrown by about 3.5 km relative to the plateau and folded into a roll-over anticline, at least one, and possibly more, normal faults must separate Wheeler Ridge from the edge of the plateau (Fig. 6, section B–B’). However, the fault or faults are nowhere exposed due to burial by sedimentary rocks of the Grand Wash trough.

The next ridge-bounding fault to the west of the Grand Wash fault zone is the Wheeler Ridge fault (Fig. 5). It was first mapped by Longwell (1936) as a 60° west-dipping fault where it crossed the Colorado River, in outcrops now submerged beneath Lake Mead. The normal separation on this fault where it crosses Lake Mead is ~2.1 km. The Wheeler Ridge fault seems to continue to the north as a single fault plane for a minimum of ~20 km and to the south for ~8 km (Fig. 5). Beyond the north end of the clearly exposed bedrock of Wheeler Ridge, the fault remains visible for about 12 km, juxtaposing strata of the Horse Spring Formation and rocks of the Grand Wash Trough in its footwall against younger (late Tertiary?) sedimentary strata in its hanging wall. This is probably a depositional, rather than tectonic contact, with the younger strata lapping against the fault scarp. Farther to the north, the Wheeler Ridge fault becomes buried under younger Tertiary to Quaternary conglomerates and gravels, so its location is unknown. To the south, the fault splits into several strands near the south ends of Wheeler and Iceberg Ridges. Some of the displacement on the Wheeler Ridge fault is transferred to the Airport fault (Matthews, 1976), which cuts across to the east side of Wheeler Ridge, and becomes buried under Grapevine Mesa (Fig. 5). The rest of the displacement is distributed onto two major, and a number of minor, fault strands that lose displacement southwestward and eventually merge again near South Cove. One of the major faults is the South Cove fault, which was originally mapped by Matthews (1976) as a southwest-northeast–striking left-lateral strike-slip fault that cut entirely across southern Iceberg Ridge. More detailed mapping has shown that this fault turns southwestward and runs along the east side of southern Iceberg Ridge, and is continuous with the Sunfish Cove fault of Matthews (1976). Both parts of this fault are included in the South Cove fault in Figure 5. The other major strand is the Sheep Canyon fault, which merges with the South Cove fault east of South Bay. South of South Bay, these faults are buried under younger sedimentary rocks. Farther to the south, the fault that carries the Gregg basin in its hanging wall has been interpreted to be the southward continuation of the Wheeler Ridge fault (Faulds et al., 1997). This southern portion of the fault offsets the Hualapai Limestone by more than 300 m, and folds it into a roll-over anticline.

The next major fault to the west of the Wheeler Ridge fault is the Iceberg Canyon fault, first mapped by Longwell (1936, 1945), prior to the filling of Lake Mead. This fault has a normal separation of ~1.2 km, is gently listric in cross section, and cuts bedding in its hanging wall at 60°–90°. It dips 35° to the west where it cuts through Permian limestones in its hanging wall, and its dip decreases to 10° to the west where it cuts Mississippian strata in its hanging wall (Longwell, 1936, 1945).

The next fault to the west is the Indian Hills fault, which dips between 0° and 12° to the east and therefore has a very sinuous fault trace that runs generally north-northeast through the Indian Hills. It forms several klippen of Cambrian rocks on Proterozoic basement and of Mississippian strata on Cambrian (Fig. 5). Where it crosses the line of crosssection A–A’ shown in Figure 6, it accommodates a normal separation of the Tapeats Sandstone of ~1.5 km. Hanging-wall bedding cutoff angles range from about 50° to 70°, except in part of the western Indian Hills, where the fault forms a hanging-wall flat for ~200 m in the shales of the Bright Angel Formation. West of this hanging-wall flat, the fault again cuts downslope to the west, giving it an overall ramp-flat-ramp geometry. Immediately above this flat is a tight roll-over anticline that

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**Figure 7. Fault orientation and slip lineation data.** (A) Kamb contoured stereoplot of poles to normal faults. These poles are from surfaces that were exposed and measured directly, with no three-point solutions. Note that mean fault dip direction is 302°, or N58W. (B) Kamb contoured stereoplot of measured slip lineations; mean slip direction is ~301°, or N59W. (C) Rose diagram of slip lineation trends. Together with A and B, this suggests deformation by dominantly dip-slip normal faulting, with extension oriented ~300° or N60W. (D) Stereoplot of slip lineations and fault planes from the Gold Butte fault, suggesting left-oblique normal faulting.
affects the upper unit of the Bright Angel Formation and higher Cambrian units (Fig. 8).

The fifth fault in the stack, and the last one to crop out east of the Gold Butte crystalline block, is the Million Hills Wash fault, which apparently increases in offset from south to north. It has a well-exposed surface trace that defines the south end and southwest margin of the Azure Ridge block. It has an average dip of near 12° to the northwest, and is slightly listric in cross section. Bedding cutoff angles in the hanging wall are typically between 70° and 90°. Normal offset on the Million Hills Wash fault is <100 m where it occurs as a small klippe above the Connoly Wash block, increasing to ~1.1 km at the south end of Azure Ridge, and to slightly greater than 2.4 km under central Azure Ridge (Figs. 5 and 6).

Northwest of the Million Hills Wash fault is the Garden Wash fault, which is responsible for translating Tramp, Lime, and the northernmost outcrops of Azure Ridge westward relative to the rest of Azure Ridge (Fryxell et al., 1992). The outcrop pattern of the Garden Wash fault suggests that it dips gently to the northwest; however, there are few exposures of the fault plane, making direct measurement of its orientation difficult. Furthermore, because the Garden Wash fault is linked to the east end of the Gold Butte fault, and splays off it to the north, the orientation of the fault is presumably changing rapidly as it bends northward near the east end of Azure Ridge. The bending of the fault plane, combined with a limited number of widely scattered outcrops, makes it difficult to precisely determine the fault-plane orientation from its surface trace. Detailed mapping of Azure, Tramp, and Lime Ridges generally corroborates the earlier mapping of the Garden Wash fault by Fryxell et al. (1992), with only a few modifications. At the northern end of Azure Ridge, Fryxell et al. (1992) mapped a segment of the Garden Wash fault as a low-angle structure placing Mississippian Redwall Limestone (equivalent to the Monte Cristo Formation) over Cambrian dolostone. This was remapped as Permian Toroweap and Kaibab Limestones over Cambrian Bonanza King dolostones. In addition to this change, a small outcrop immediately east of Horse Spring Ridge, mapped by Fryxell et al. (1992) and Morgan (1967) as Permian limestone, is instead the Mississippian Anchor Member of the Monte Cristo Formation and may be part of a megabreccia deposit within the Thumb Member of the Horse Spring Formation. Just east of this outcrop, a large area of Thumb Member of the Horse Spring Formation is irregularly mantled by a thin veneer of gravel (Fig. 5). Farther east, ~1.4 km north of Azure Ridge, small outcrops of Permian Toroweap Limestone were found directly along strike with those to the south in Azure Ridge (Fig. 5). These outcrops are interpreted to be part of a continuous ridge of Permian strata, which is visible as a pale stripe on air photos for at least 3.1 km to the north of Azure Ridge. This partially buried ridge of Permian limestone has an east-west separation of ~8 km relative to equivalent strata on Tramp Ridge.

It is proposed here that the Garden Wash and Gold Butte faults comprise part of the South Virgin–White Hills detachment (Duebendorfer and Sharp, 1998), along with the
Lakeside Mine fault zone (Fryxell et al., 1992), the Salt Spring Wash fault, and the Cyclopic detachment (Cascadden, 1991), because these form an apparently continuous series of top-to-the-west Miocene normal faults (Fig. 3). The Garden Wash fault accommodated ~8 km of westward translation of Tramp Ridge relative to Azure Ridge and is probably linked southward, via the Gold Butte fault, with the Lakeside Mine fault zone, which unroofed the Gold Butte crystalline block ca. 15 Ma (Fitzgerald et al., 1991; Fryxell et al., 1992). Although the Lakeside Mine fault zone is partially buried under younger sediments, it appears to be continuous southward with the Salt Spring Wash fault, which also exposes Proterozoic crystalline rocks in its footwall and carries ca. 16 Ma growth-fault strata in its hanging wall (Cascadden, 1991). Still farther to the south, the Cyclopic detachment also has Proterozoic crystalline rock in its footwall and is probably continuous with the Salt Spring Wash fault (Cascadden, 1991).

The Lime Canyon fault is west of the Garden Wash fault. It dips to the west at ~10°, and accommodates ~8 km of westward separation of the Paleozoic section in western Lime Ridge relative to the corresponding section in Tramp Ridge (Figs. 5 and 6).

The Lime Canyon fault appears to have evolved from two major faults and a number of minor anastomosing splays, which all merged downward. This interpretation is based on a retrodeformable cross section of the Lime Canyon and Perkin’s Spring area (Figs. 6 and 9). The westernmost of the two main splays crops out clearly around the head of Lime Canyon, where it is a flat-lying fault, carrying relatively simple imbricate fault blocks of east-dipping Mississippian and Pennsylvanian strata in its hanging wall, with bedding cutoff angles between 35° and 45° (Figs. 5 and 9). The eastern splay crops out on westernmost Tramp Ridge, where it carries Lower Cambrian units down against Proterozoic basement (Fig. 6, cross-section A–A’). This splay projects just above the basement block that separates Tramp Ridge from Lime Ridge, and crops out again as a detachment that underlies the Perkin’s Spring area (Figs. 5, 6, and 9). In order for this projection to work, the offset on the faults that bound the east and west sides of the basement block between Tramp and Lime Ridges must first be restored, suggesting that the basement block is a later uplifted horst. The offset on these horst-bounding faults is relatively small (Fig. 9), although offset on the eastern fault increases significantly to the north. Near the north end of the basement block, the upper part of

Figure 9. Detailed cross section and restoration of the Perkin’s Spring area. This cross section coincides with part of cross-section A–A’ from Figure 6A. Across the entire section, shallowly dipping normal faults separate a thin veneer of extensionally imbricated Paleozoic rocks from Precambrian basement. These shallowly dipping faults are all considered to be part of the Lime Canyon fault, although only the western strand, which crops out at Lime Canyon, is labeled on the section.
the Cambrian section in Tramp Ridge is juxtaposed against basement, requiring ~600 m of throw on the fault.

The western splay of the Lime Canyon fault may have a ramp-flat-ramp geometry, which would explain the relatively flat-lying, little extended strata of northern Lime Ridge. At Lime Canyon, the fault cuts bedding at a moderate angle (~40°), and therefore cut through this part of the section with an initially moderate west dip. Its initial dip is less well constrained where the fault cuts through the rest of the Paleozoic section; however, creation of an area-balanced cross section seems to require the fault to have flattened to dips as low as 15°–20° where it cut through the lowest part of the section. Therefore, it was apparently a shallowly dipping listric fault that included a flat near the base of the Cambrian section (Fig. 6). A northward increase in the length of this flat might result in a wide block of hanging-wall strata being carried westward over a flat surface, undergoing only minor internal disruption and rotation.

Near Perkin’s Spring, between Tramp Ridge and Lime Ridge, the Lime Canyon fault is nearly flat-lying, and its hanging wall is structurally complex (Figs. 5 and 9). To the west of Perkin’s Spring, a set of west-dipping, top-to-the-west normal faults within the hanging wall of the Lime Canyon fault carry east-dipping panels of Cambrian strata down against Proterozoic basement. These panels of east-dipping Cambrian strata are overlain by a west-dipping panel of the Permian Toroweap Formation, carried on an east-dipping fault.

The arrangement of fault slices near Perkin’s Spring may have been achieved by collapsing a stack of imbricate fault slices, bounded by predominantly west dipping, west-side-down normal faults, onto a shallowly dipping detachment (Fig. 9). In order to achieve their present configuration, the imbricate slices must have initiated in an eastward-stepping and downward-stepping sequence. This would result in slices of stratigraphically higher Pennsylvanian Callville Formation being carried downward, and to the west of the, the stratigraphically lower slices from the Banded Mountain Member of the Bonanza King Formation, which would in turn be carried downward and to the west of slices of the Papoose Lake Member of the Bonanza King Formation. All of these fault slivers would then be carried westward and downward against Proterozoic basement rocks. The occurrence of west-dipping panels, separated by east-dipping, top-to-the-east normal faults, can be explained by top-to-the-west simple shear within the fault-bounded imbricate slices (Fig. 10). Within each fault sliver shown in Figure 9, it is reasonable to expect a top-to-the-west rotation of blocks, bounded by top-to-the-east faults.

The westernmost ridge-bounding fault is the Maynard Spring fault. It separates roughly north striking strata of Lime Ridge from northeast-striking strata that comprise the westernmost outcrops of the range (Fig. 5). This fault is well exposed for about 1 km south of the Lime Ridge fault. Farther south it becomes buried under alluvium. For an additional 1.4 km to the southeast, small exposures of fault-bounded Permian Toroweap Limestone are found; these are probably part of the hanging wall of the Maynard Spring fault. This fault differs from other ridge-bounding faults in so far as the strike of hanging-wall strata is markedly different from footwall strata. Hanging-wall strata strike ~N65E, whereas strata in the adjacent parts of Lime Ridge strike due north, suggesting clockwise vertical-axis rotation of ~65° of the hanging-wall rocks in addition to extension.

Minor Imbricating Faults and Related Folds

Numerous smaller offset faults are found within each of the major fault blocks. These faults typically have offsets in the range of 5–100 m; a few have offsets of several hundred meters. They accommodate internal deformation and extension of the major fault blocks and usually merge downward with the major ridge-bounding normal faults (Fig. 11). They dip more steeply and have higher bedding cutoff angles than the ridge-bounding faults. Most of these smaller offset faults have hanging-wall bedding cutoff angles of ~90°; some are >115° (Fig. 12).

Nearly all of the smaller offset faults merge with, or are truncated by, shallowly dipping, large-offset, ridge-bounding faults. Of 33 cases where a more steeply dipping fault clearly intersects a shallowly dipping ridge-bounding fault, the more steeply dipping fault is truncated by, or merges with, the shallowly dipping fault in 31 cases. The two more steeply dipping faults that do cut a shallowly dipping, block-bounding fault are close together, subparallel, and each accommodates ~30 m of west-side-down normal separation. They cut through the southern end of the Mississippian on Cambrian klippe formed by the Indian Hills fault just north of Devil’s Cove (Fig. 5). The intersection of these faults with the underlying Iceberg Canyon fault is not exposed, so it is unclear whether they also cut the Iceberg Canyon fault.

Nearly all of the minor imbricating normal faults are synthetic to the ridge-bounding detachments. There are a few antithetic faults, all of which have been rotated so that they now appear to be reverse faults (the two most significant of these can be seen in cross-section A–A’ of Fig. 6; one under eastern Azure Ridge, and one under central Tramp Ridge).

Two large-amplitude, broadly folded, roll-over anticlines in the strata of the western half of Azure Ridge and the eastern part of Lime Ridge are associated with sets of small-offset synthetic normal faults (cross-section A–A’, Fig. 6). These folds are cut by fanning sets of synthetic normal faults, in which the faults to the west dip more steeply than those to the east. Rather than being due to measurable
Figure 11. (A) Map of the southern tip of Azure Ridge, showing anastomosing, moderately dipping faults soling into the nearly horizontal Million Hills Wash fault. The moderately dipping faults typically dip between 20° and 40° to the west; bedding mostly dips between 45° and 60° to the east. Hanging-wall bedding cut-off angles are mostly between about 65° and 100°. (B) Photograph looking north at the south end of Azure Ridge, showing approximately the eastern half of the area mapped. The Million Hills Wash fault extends along the break in slope at the base of the Paleozoic strata.
Figure 11. (Continued).

Figure 12. Photograph looking north at moderately west dipping imbricate normal faults in the hanging wall of the Indian Hills fault. These faults merge downward with the Indian Hills fault (not visible in this photograph). Note that the bedding cutoff angle is about 115° where Pennsylvanian strata are cut by the most steeply dipping fault (photograph is looking approximately along strike of this bedding-fault intersection). See the legend in Figure 9 for an explanation of stratigraphic labels.
folding of any individual panel of strata, these antiforms result from a gradual westward decrease in dip of bedding from one fault block to the next.

Crosscutting Faults

The extensional structures recognized in the South Virgin Mountains include a number of subvertical faults that cut all other normal faults and are upthrown on the side closest to nearby crystalline blocks. East of the Gold Butte crystalline block these faults are consistently east-side-down, i.e., they are upthrown on the side closest to the Gold Butte crystalline block. North of the Gold Butte block, within the Tramp Ridge–Lime Ridge area, steeply east- and west-dipping crosscutting faults bound a horst of crystalline rocks between Tramp Ridge and Lime Ridge (Fig. 5 and 6). Also, two steeply west-dipping faults within Lime Ridge cut across moderately and shallowly dipping faults and are upthrown on the east side, i.e., the side closest to the crystalline block between Tramp Ridge and Lime Ridge.

Many of the steep crosscutting normal faults are localized along the basement-cover contact. An en echelon series of these faults is located along the western edge of Azure Ridge (Fig. 5 and 6). A similar fault was mapped by Longwell (1936) near the south end of Iceberg Canyon, but it is now covered by the waters of Lake Mead. The faults bounding Azure Ridge dip vertically to steeply eastward and have east-side-down normal separations ranging from a few meters to >150 m. The fault near the south end of Iceberg Canyon, as described by Longwell (1936), is a steeply west dipping structure that places Proterozoic granite against mid(?)-Cambrian Bonanza King, making it a steep reverse fault with a minimum throw of 500 m. The faults that bound the horst between Tramp Ridge and Lime Ridge accommodate between a few meters and >500 m of normal separation, juxtaposing Paleozoic strata ranging from the Cambrian Tapeats Sandstone to stratigraphically highest Cambrian Bonanza King against Proterozoic crystalline rocks.

A number of steeply dipping faults crosscut the Paleozoic strata east of the Gold Butte crystalline complex, as bedding-parallel shear surfaces. These faults are difficult to observe, except where they offset younger normal faults (Fig. 13). They apparently decrease in abundance and offset with increasing distance from the crystalline complex; there are no examples observed east of Iceberg Canyon.

Steep Northeast-Striking Faults

Three major northeast-striking faults appeared on previous maps of the South Virgin Mountains. From north to south, these include the Bitter Ridge, Lime Ridge, and Gold Butte faults (Anderson, 1973; Bohannon, 1979, 1984; Beard, 1996) (Fig. 3). All were considered to be steeply dipping strands of the left-lateral Lake Mead fault system. Campagna and Aydin (1994) showed that the Bitter Ridge fault is a subvertical structure with
Figure 13. (Continued).

slickenlines plunging gently to the southwest, supporting the interpretation that this is a strand of the Lake Mead fault system. However, Fryxell et al. (1992) reinterpreted the Gold Butte fault as a right-lateral tear fault in the hanging wall of the Garden Wash fault zone, suggesting that it is not a branch of the Lake Mead fault system.

The Gold Butte fault was completely remapped during this study. The mapping showed it to be a vertical to steeply north dipping structure; only three clear slip lineations are observed, and these plunge steeply to the west (Fig. 7D).

New mapping along part of the Lime Ridge fault shows that it is not a simple, steeply northwest dipping plane. Where remapped at the north end of Lime Ridge (Fig. 5), the fault exhibits a sinuous trace, and based on its outcrop pattern where it cuts up and over eastern Lime Ridge, its dip is only ~50° to the northwest.

Steeply Plunging Folds

There are three large steeply plunging folds within the South Virgin Mountains; all are clearly visible in map view and appear to be either right-lateral or left-lateral deflections of steeply tilted ridges adjacent to fault zones. Two of these occur north of and directly adjacent to the Gold Butte fault, producing right-lateral deflection of Horse Spring strata in Horse Spring Ridge and of basal Cambrian strata in southernmost Lime Ridge (Fig. 5). The third fold is apparently left lateral, and is outlined by a gradual change in strike of bedding in the ridges east of the Gold Butte crystalline block. The average strike of bedding changes northward from ~N30E in Wheeler Ridge, Iceberg Ridge, and the southern Indian Hills to ~N05E in northern Azure Ridge (Fig. 5).

Interpretation of Subsurface Geometries of Concealed Faults

Most of the major normal faults of the South Virgin Mountains are well exposed, but three of the major ridge-bounding normal faults or normal fault zones are concealed by alluvium along much or all of their traces. These faults are the Grand Wash fault zone and the Wheeler Ridge and Garden Wash faults. The late, steep, crosscutting fault of southern Iceberg Canyon is also covered by the waters of Lake Mead. The location, geometry, and offset of all of these faults can be constrained reasonably well using a variety of geologic arguments, as well as observations of Longwell (1936), made prior to the formation of Lake Mead.

The Grand Wash fault zone must include one or more west-side-down normal faults. These faults are inferred to be relatively steep listric structures, rotated only a few degrees from their initial orientations. The inference of only minor rotation is based on the absence of structurally lower faults with major offset, and on the observation that the next higher structure (the Wheeler Ridge fault) is apparently only slightly rotated from its original orientation. The inference of initially steep dip and listric geometry is based on the observed rollover geometry of Wheeler Ridge, an interpreted listric geometry on seismic reflection data ~30 km farther south, beneath the Hualapai basin (Faulds et al., 1997), and analogy with higher and lower normal fault zones, where listric curvature is directly observed. These include the Hurricane fault and Iceberg Canyon fault, both of which had initially steeply dipping listric geometries. The Hurricane fault cuts the Colorado Plateau ~65 km east of the Grand Wash fault zone, is vertical where it cuts Permian strata, and shallows to an ~60° westward dip where it cuts through...
the lower part of the Cambrian section (Hamblin, 1965). The 30° of shallowing across ~2 km of section is similar in curvature to the Iceberg Canyon fault, which shallows at a rate of ~16°/km.

Our preferred interpretation of the Grand Wash fault zone is that it includes two or more normal faults, which have served to downdrop the east side of the Wheeler Ridge block by ~3.5 km relative to the Colorado Plateau (Fig. 6). Projection of beds from Wheeler Ridge to the inferred location of the westernmost strand of the Grand Wash fault zone suggests that almost all of this 3.5 km offset can be accommodated on the westernmost strand. The amount of offset on the other fault or faults under Grand Wash Trough is unknown, but is probably not large on any one fault, because large offset on a listric fault should have resulted in hanging-wall rotation and consequent creation of a tilted fault-block ridge where the Grand Wash Trough currently exists.

The location of the western strand of the Grand Wash fault zone is constrained by geometric arguments, but it is nowhere observed due to burial beneath younger sediments. This fault is shown in Figures 5 and 6 near its westernmost allowable position, because strata are shown as having cutoff angles slightly >90°. Hanging-wall cutoff angles of slightly >90° are reasonable for an initially west dipping fault because a small increase in cutoff angle could result from collapse of the hanging wall into the potential void adjacent to the listric fault surface. However, these angles would become unreasonably large if the fault was drawn farther to the east, and the bedding within the Wheeler Ridge block continues eastward at a constant dip or with an eastward-steepening dip due to roll-over. The westernmost allowable position of the fault strand is immediately east of the bedrock exposures of Wheeler Ridge, because it clearly doesn’t crop out onto Wheeler Ridge.

The location of the easternmost strand of the Grand Wash fault zone is inferred from a number of small scarps in alluvium, ~1 km from the exposed bedrock of the Grand Wash Cliffs. These scarps are visible on air photos of the region, and are consistent with formation by a west-side-down normal fault, but do not form a continuously exposed feature and are therefore suggestive, rather than compelling, evidence. Other small-offset normal faults may exist under the Grand Wash Trough. If so, no surface expression of these faults has been observed.

An alternate interpretation of the Grand Wash fault zone as consisting of only one fault that projects to surface near the eastern edge of the Grand Wash trough can not be entirely ruled out, but is not preferred. To be consistent with the interpreted shallow depth of the Grand Wash trough (~1–2 km; Saltus and Jachens, 1995), and to avoid hanging-wall cutoff angles of much greater than 90° with the roll-over strata of Wheeler Ridge, the fault would have to flatten at a depth of about 1 km. It would be required to slip earlier than the faults farther to the west because palinspastic restoration of such a shallow flattening fault requires that the structurally higher faults be back-rotated through vertical to initial east dips. Because it is unlikely that the faults initiated as east-dipping reverse faults, this would suggest that they initiated after the strata in Wheeler Ridge had been rolled over above the Grand Wash fault. This interpretation is not preferred because: (1) it requires the Grand Wash fault to have a geometry much different from that of better exposed nearby analogs and different from its geometry as imaged by seismic reflection data to the south (Faulds et al., 1997); and (2) it requires a diachronity of slip on the major ridge-bounding normal faults, which can not be ruled out with the current data. However, this seems unlikely, because there is no structural evidence for diachronous slip within the better exposed fault blocks farther to the west. The available geochronologic evidence suggests that all of the major ridge-bounding faults were active during a very short interval of time (Brady, 1998).

As discussed earlier, the surface trace and
KINEMATIC EVOLUTION OF A LARGE-OFFSET CONTINENTAL NORMAL FAULT SYSTEM

dip of the Wheeler Ridge fault, where it is now covered by Lake Mead, was constrained by observations of Longwell (1936). However, its cross-sectional shape can only be inferred. As with the fault(s) of the Grand Wash fault zone, the Wheeler Ridge fault is inferred to have a listric geometry similar to the Hurricane fault farther east and the Iceberg Canyon fault farther west. This interpretation is supported by the fact that the Hualapai Limestone forms a roll-over anticline in the hanging wall of the Wheeler Ridge fault farther south in Gregg basin (Faulds et al., 1997).

The Garden Wash fault, the northernmost part of the South Virgin–White Hills detachment, is mostly buried, yet its location and offset are constrained by geologic mapping of the north of Arizona Ridge. At least one major normal fault is to the east of, and roughly parallel to, Horse Spring Ridge. This fault separates the Tertiary strata that crop out on Horse Spring Ridge and immediately to its east from the partially buried ridge of Permian Toroweap Formation that continues north from the Garden Wash fault (Fig. 5). The normal offset on this fault must be equal to or greater than the 8 km separation of Permian strata in the Arizona Ridge block from equivalent strata in Tramp Ridge. Farther south, across the Gold Butte fault, the South Virgin–White Hills detachment is interpreted to have unroofed the Gold Butte crystalline block. The crystalline block is a more or less intact upper crustal section, through which the unroofing fault cut with an initial dip of ~60° (Fryxell et al., 1992). The fault is not currently exposed on the west side of the crystalline block, except as a zone of chlorite breccia near the margins of the block, but presumably dips gently away from the domiform Gold Butte crystalline block. In order to denude the crystalline block, assuming a 60° initial dip of the denuding fault zone and a currently exposed width of ~18 km (basement plus cover), the minimum throw on the denuding fault zone is ~15 km (Fryxell et al., 1992). This interpretation of very large normal offset on the South Virgin–White Hills detachment is supported by the fact that to the north of the Gold Butte crystalline block, where hanging-wall blocks are still present, the cumulative westward translation of strata in the Maynard Spring block relative to equivalent strata in the Arizona Ridge block is ~19 km (Fig. 5).

The total east-west extension accommodated by the Garden Wash fault appears to remain fairly constant from south to north, and the width of its hanging wall (Tramp Ridge) also remains constant; however, the amount of extension and structural style within the hanging-wall block changes northward. This may indicate a northward change in the initial geometry of the Garden Wash fault. Given that the east-dipping strata along the east side of Tramp Ridge have a more or less constant strike of about N20E, and the correlative strata in the buried northward continuation of Azure Ridge apparently maintain a strike of about N10E, the westward displacement of strata within Tramp Ridge relative to strata of Azure Ridge changes little from south to north. The southern end of Tramp Ridge is significantly internally extended on moderately west dipping normal faults, but farther north, it is very little extended on steeply dipping normal faults. If the Garden Wash fault initiated as a steeply dipping listric fault near its south end, but developed a ramp-flat-ramp geometry farther to the north, and the entire length of the fault accommodated a similar amount of east-west extension, it would result in a relatively highly extended southern Tramp Ridge and a wide, relatively unilted northern Tramp Ridge, with a roll-over on its east side (Fig. 5). A smaller scale analog is seen in the southern Indian Hills, discussed above, where the Indian Hills fault forms a flat in the Bright Angel Shale, above which a roll-over anticline is developed (Fig. 8).

The steep reverse fault of southern Iceberg Canyon, described by Longwell (1936), is now covered by Lake Mead. This fault is the only significant apparent compressional structure reported from the South Virgin Mountains. Because all other faults in the area are normal faults, rather than reverse faults, it is reasonable to suggest that this structure was also active as a normal fault. This fault was probably active as a steeply east dipping normal fault, and was later rotated a few degrees into a steeply west dipping, apparently reverse orientation. This rotation could have occurred either by late-stage slip on the Wheeler Ridge fault and/or Grand Wash fault zone, or as a result of upflexing of the crust adjacent to the uplifting Gold Butte crystalline complex.

KINEMATIC EVOLUTION OF THE SOUTH VIRGIN MOUNTAINS NORMAL FAULT SYSTEM

The large-offset, block-bounding normal faults of the South Virgin Mountains appear to have initiated as subparallel west-dipping listric faults. The Iceberg Canyon fault is the best documented and least disrupted of the large-offset, block-bounding faults. Its current listric geometry and hanging-wall bedding cutoff angles, which range from ~90° where it cuts through Mississippian–Pennsylvanian strata, show that it initiated as a steeply west dipping listric fault. The Wheeler Ridge fault also clearly initiated with a steep west dip, because it still dips 60° to the west. The Indian Hills, Million Hills Wash, and Maynard Springs faults all have hanging-wall bedding cutoff angles between 50° and 90°, consistent with initially steep west dips. The hanging walls to these faults have been internally deformed, so it is difficult to establish whether they were initially listric, but the mapped relationships permit this possibility. Because of the preponderance of evidence that the large-offset, block-bounding normal faults of the South Virgin Mountains initiated as steeply west dipping listric structures, it is inferred that the buried Grand Wash fault zone and South Virgin–White Hills detachment also initiated as steeply west dipping listric structures.

Absolute ages of initiation are not known for all of the block-bounding faults; it is therefore possible that there was some diachronity in the timing of their initial slip. Nevertheless, because they do not crosscut any other structures, they have similar spacings and offsets, and other faults with lesser displacements and generally larger bedding cutoff angles sole into them, they are interpreted to be the earliest extensional structures to affect the region.

The smaller offset imbricating faults that internally disrupt the major ridge forming blocks are interpreted to have initiated later. The hanging-wall cutoff angles for these faults are typically near 90°, but reach values >120° (Fig. 12 and Table 1). This variation in cutoff angles may result from variations in initial dip or time of initiation of these faults, higher cutoff angles resulting from faults initiating after some amount of rotation of the major fault blocks. These two possibilities are indistinguishable, because none of the minor imbricating faults cut each other. Rather, they tend to anastomose in map view and occasionally are seen to splay upward. The cutoff angles greater than 90° require that the faults either initiated as reverse faults, then rotated to become normal faults, or initiated as normal faults after some amount of top-to-the-east tilting of bedding had already occurred due to slip on the ridge-bounding faults. The latter explanation is preferable, since it simply requires one evolving extensional fault system, whereas the former requires extension followed by compression, then resumed extension, all accommodated on the same set of faults, with no other preserved evidence of a compressional event.

In almost all cases where the intersection can be seen, imbricating faults clearly merge.
with the block-bounding faults, requiring synchronous slip of the two fault sets. Because they had to slip synchronously, the hanging-wall bedding cutoff angles of the imbricating faults can be used to constrain the dip at which the block-bounding faults were active. As the first-generation faults and adjacent fault blocks tilted, the hanging-wall cutoff angles of later faults would increase. The minimum amount of tilting of bedding and adjacent block-bounding faults, prior to initiation of the later faults, can be calculated by assuming that the later faults initiated with 90° dips (Fig. 14). For example, the later imbricating faults near the southern tip of Azure Ridge have bedding cutoff angles that range from \( \sim 70° \) to 124°. For the 124° case, if the initial dip of the splay was 90° or less, the Azure Ridge block and the faults bounding it must have tilted by at least 34° prior to initiation of the later imbricating fault. Thus, the block-bounding fault below Azure Ridge, which initiated with its deeper portions dipping at about 60°, was actively slipping with dips at least as low as 26° at the time of initiation of the internal imbricating fault. Similar arguments can be made for other block-bounding faults (Table 1). These data suggest that major block-bounding faults remained active at dips of <20°.

If the smaller offset imbricating faults initiated only after the major fault blocks had been tilted to some extent, then these imbricating faults should be absent or at least less common in the relatively less tilted eastern fault blocks, and they should be more abundant to the west. In fact the abundance of small offset imbricating faults does increase from east to west, or upward in the structural stack of major fault blocks (Figs. 5 and 6).

Only a few imbricating faults affect most of Wheeler Ridge and Iceberg Ridge. The structurally higher and more tilted hanging wall to the Iceberg Canyon fault includes a number of imbricating faults but is still a nearly intact homoclinal block. The still higher and more tilted fault blocks of the northern Indian Hills, Azure Ridge, Tramp Ridge, and Lime Ridge are all highly disrupted by imbricating faults.

As extension continued in the South Virgin Mountains, the South Virgin–White Hills detachment eventually became the dominant extensional structure. It accommodated the unroofing of the 15-km-wide Gold Butte crystalline block, as well as the ~8 km westward translation of Tramp Ridge relative to Azure Ridge.

The hanging wall to the Gold Butte crystalline block has been translated farther westward than the Tramp Ridge and Lime Ridge blocks, requiring a tear fault within the hanging wall of the South Virgin–White Hills detachment. Because the change in offset on the detachment coincides with the Gold Butte fault, the hanging-wall tear fault must have been immediately above the Gold Butte fault. This interpretation was suggested by Fryxell et al. (1992), and implies that the Gold Butte fault was part of, or at least connected to, a right-lateral structure in the hanging wall of the South Virgin–White Hills detachment. However, the Gold Butte fault can not be satisfactorily explained as a tear fault that cut through only the hanging wall of a near-planar normal fault. A slightly more complex interpretation is required to account for the apparently right-lateral vertical axis folds in the ridges adjacent to the Gold Butte fault, as well as the apparently left-lateral smearing of thin fault slivers of Permian strata at the south end of Tramp Ridge, and the steep north dip of the fault in the subsurface. These observations can be explained in at least two ways. (1) The tear fault in the hanging wall of the South Virgin–White Hills detachment coincided with a northward-deepening lateral ramp in the fault zone and/or (2) isotropically driven uplift of the Gold Butte crystalline block was focused beneath the hanging-wall tear fault due to the sharp gradient in amount of extension and depth of unroofing. In either case, the Paleozoic strata of Tramp Ridge and Lime Ridge are offset in a left-lateral or left-lateral oblique-normal sense relative to the Gold Butte crystalline block, and in a right-lateral or right-lateral oblique-normal sense relative to the Paleozoic cover that has been transported westward off of the Gold Butte crystalline block.

The late, steep, crosscutting faults observed

<table>
<thead>
<tr>
<th>Bounding fault</th>
<th>Maximum hanging wall cutoff angle for imbricating faults in superjacent block (β)</th>
<th>Minimum required rotation of bounding fault (R)</th>
<th>Maximum value of lowest initial dip for bounding fault* (α)</th>
<th>Maximum value of lowest active dip for bounding fault (R)</th>
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<td>0°</td>
<td>44°</td>
<td>44°</td>
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</tbody>
</table>

Note: Variables correspond to those used in Figure 13.
*Assumes that initial dip did not decrease below base of Cambrian strata.
*Assumed, base on geometry of Hurricane fault.

Figure 14. Diagram showing the relationship between the dip of active block-bounding normal faults and hanging-wall cutoff angles of bedding against the block-bounding and imbricating normal faults. The figure shows the fault system at the time of initiation of an imbricating fault. As the system continues to extend, fault and bedding dips will change, but the bedding cutoff angles will remain more or less the same. \( α = \text{hanging-wall cutoff against the block-bounding fault} \), \( β = \text{hanging-wall cutoff against the imbricating fault} \), \( γ = \text{initial dip of the imbricating fault} \), and \( θ = \text{dip of the active block-bounding fault} \). The amount of rotation (R) of the block-bounding fault is the same as the amount of rotation of bedding in its hanging wall. If bedding was initially horizontal, then the amount of rotation of the block-bounding fault is given by: \( R = β − γ \). The dip of the block-bounding fault is equal to its original dip minus its rotation; thus, its dip can be calculated using: \( 0 = α−R = α−(β − γ) \). Because the imbricating normal faults had to initiate with dips of \( γ = 90° \) or less, a maximum value for the dip of the active block-bounding fault (\( 0_{\text{max}} \)) can be calculated using: \( 0_{\text{max}} = α−(β − 90°) \).
in the South Virgin Mountains are interpreted to be isostatic rebound structures that allowed uplift of extensionally denuded crystalline blocks in an area affected by regional extensional stresses. This interpretation is consistent with the observed features of these faults, including the following. (1) They have accommodated vertical movements of as much as several hundred meters, but relatively little extension, as evidenced by their little-rotated steep dips. (2) They are invariably upthrown on the side nearest to large denuded crystalline blocks. (3) Their abundance and magnitude of offset decrease away from the uplifted Gold Butte block. (4) They are the latest structures to affect the area, consistent with their formation being a response to extensional denudation.

The isostatic uplift of the Gold Butte crystalline block was probably accommodated in part by flexural folding of the upper crust. This folding is evident in the fanning of first-generation fault dips east of the crystalline complex. The near-surface dip of these faults decreases drastically from east to west, although they apparently initiated with parallel dips. Near-surface fault dips for the first-generation structures vary from a probable 60°–90° for the fault(s) of the Grand Wash fault zone and Wheeler Ridge to a 12° east dip on the Indian Hills fault, only 9 km to the west (Figs. 5 and 6). While some of this fanning can be explained by active slip of a stack of listric domino blocks, at least some of it must be explained by another mechanism, because top-to-the-west normal faults, such as the Indian Hills fault, were not slipping with eastward dips. Much of the fanning of dips may be due to flexure caused by the uplift of the unroofed crystalline block. Unfortunately, the amount of rotation due to flexure is difficult to constrain, due to the difficulty of calculating the amount of rotation of faults that bound internally deforming listric domino blocks. If these calculations could be made, it would then be possible to accurately separate the effects of flexural rotation from rotation due to slip on a stack of listric domino blocks.

**Alternative Interpretations of the Gold Butte Fault**

As described above, the preferred interpretation of the Gold Butte fault is that it coincided with a right-lateral tear in the hanging wall of the South Virgin–White Hills detachment. This tear may coincide with a ramp in the footwall and may have been reactivated as an isostatic uplift fault after the Gold Butte crystalline block was unroofed. This scenario explains the steep north dip of the Gold Butte fault, the steeply plunging lineations observed on it (Fig. 7D), and the right-lateral map-view folds of southernmost Lime Ridge and Horse Spring Ridge.

Alternatively, the Gold Butte fault may be interpreted as a left-lateral strike-slip fault, apparently a splay of a left-lateral system of faults known as the Lake Mead fault system (Anderson, 1973; Bohannon, 1979, 1984; Beard, 1996). This interpretation does not explain the observed right-lateral folds, or the slip lineations, and is inconsistent with the apparent continuity of Permian strata northward from Azure Ridge. Furthermore, it does not explain the observed low-angle contact of Tertiary Horse Spring Formation over Proterozoic basement at the south end of Horse Spring Ridge (Fig. 5), unless the Gold Butte fault has deviated southward at that point, and is hidden within the crystalline block. However, if the trace of the Gold Butte fault does deviate southward into the crystalline block south of Horse Spring Ridge, and northward around the Permian subcrop at the north end of Azure Ridge, then it could still be interpreted as a left-lateral fault (with a highly irregular surface trace). If this interpretation is correct, then Tramp Ridge may be the offset equivalent to Azure Ridge, as suggested by Longwell et al. (1965), Bohannon (1984), and Beard (1996). In this case, the Garden Wash fault would be equivalent to the Million Hills Wash fault, rather than being continuous with the South Virgin–White Hills detachment. This interpretation places more emphasis on strike-slip faulting, and reduces the total extension calculated across the seven major fault blocks of the South Virgin Mountains. As measured from the cross sections of Figure 6, the total extension across these blocks would change from ~15 km if the Gold Butte fault is interpreted as a lateral ramp to ~7 km if it is interpreted as a later left-lateral strike-slip fault.

While this alternative significantly affects the total extension estimated along a transect across the Gold Butte fault, it has no effect on the total extension estimated along a transect across the Gold Butte crystalline complex. Such a transect would require a minimum of ~4 km extension across the fault blocks east of the crystalline complex, in addition to the ~17 km of extension required to unroof the exposed width of the crystalline block, giving a total extension across the South Virgin Mountains of ~21 km.

**Kinematic Summary**

Early extension near the western margin of the Colorado Plateau was directed roughly east-west, and was accommodated on steeply west-dipping, listric normal faults. After a significant amount of slip and rotation had been accommodated by the initial set of faults, a second set of steeply west dipping, anastomosing normal faults developed in the higher fault blocks. The later faults soled into the earlier faults, rather than crosscutting them. This requires that the early fault surfaces remained active to very shallow dips while the later faults were slipping. The early faults have accumulated normal offsets that range from ~1 km to perhaps >15 km, and have been rotated to subhorizontal dips. Some of the rotation of the originally steeply dipping faults can be attributed to folding accompanying isostatic uplift of the Gold Butte crystalline complex.

**RELEVANCE TO INTERPRETING OTHER EXTENDED REGIONS**

The observations that (1) slip on normal faults continued to relatively low dips, and (2) rotation of faults and fault blocks did not occur on crosscutting sets run counter to both the multiple-domino models (e.g., Morton and Black, 1975; Miller et al., 1983) and flexural rotation models (e.g., Buck, 1988), where all slip is accommodated on steeply dipping faults. This raises the question of whether either of these concepts is broadly applicable to the formation of normal fault systems with strongly rotated faults and fault blocks. Both are based on the assumption that slip on low-angle normal faults can not occur, rather than on kinematics of well documented normal fault systems. Here we evaluate published mapping from the highly extended southern Cherry Creek Range and Egan Range, Nevada (Gans and Miller, 1983), and from two areas previously regarded as examples of the multiple-domino model, the Yerington District, Nevada (Proffett, 1977; Proffett and Dilles, 1984), and the Lemitar Mountains, New Mexico (Chamberlin, 1982, 1983), in order to test whether the geology of these regions is consistent with the fault-system evolution deduced for the normal fault system of the South Virgin Mountains.

The southern Cherry Creek Range and Egan Range comprise a series of tilted normal fault blocks, each of which is internally extended by fanning-upward splays and bounded by an originally steeply east dipping listric normal fault that has accommodated >1 km of offset (Gans and Miller, 1983). A sequential reconstruction of the region shows that the deeper portions of the major block-bounding faults remained active to dips as low as 0° (Fig. 12 of Gans and Miller, 1983). Further-
Figure 15. An approximately west to east cross section through the central Singatse Range, just north of the Yerington Mine: (A) as interpreted by Proffett and Dilles (1984), with steeper faults generally crosscutting shallower faults; (B) reinterpreted, assuming that steeper faults tend to merge into shallowly dipping faults. This reinterpretation honors all of the observations recorded by Proffett and Dilles (1984).
more, the reconstruction suggests that the block-bounding faults were rotated through horizontal, to gentle westward dips, due to uplift of the adjacent highly attenuated Schell Creek Range and Snake Range. This structural evolution is virtually identical to that deduced for the normal fault system of the South Virgin Mountains.

The primary source of data for the Yerington District was the map and cross sections of Proffett and Dilles (1984). A roughly east-west-trending cross section was constructed through the Singatse Range, just north of the Yerington Mine. This cross section coincided with the eastern part of cross-section D–D′ from Proffett and Dilles (1984). This cross section, as interpreted by Proffett and Dilles, and as reinterpreted by us, is shown in Figure 15. The reinterpretation honors the geologic mapping of Proffett and Dilles, as well as the contacts intersected by boreholes and other contacts drawn as solid lines on their cross section.

The reinterpretation of the Yerington District cross section shows that the model of normal fault evolution deduced for the South Virgin Mountains is consistent with the faults of the Yerington District. It is possible to honor all of the geologic data and have the later, steeper normal faults merge into the earlier, more gently dipping structures. Only the Montana-Yerington fault demonstrably cuts the older, gently dipping structures, and this cross-cutting fault can not explain much rotation of the older structures, as it appears to be nearly planar and is shown as accommodating <400 m of normal separation.

In examining the Lemitar Mountains, the map and cross sections of Chamberlin (1982) were used. Cross-section D–D′ from Chamberlin (1982) was partially restored by taking out the displacement on the latest stage of steeply dipping normal faults (Fig. 16). These faults are probably related to the formation of the modern basins and ranges of the Socorro area, and formed ca. 7–4 Ma, whereas most extension in the region probably occurred between 31 and 27 Ma (Chamberlin, 1983). With the effects of late-stage faulting removed, the cross section shows a pattern of normal faulting that is entirely consistent with that seen in the South Virgin Mountains and Yerington, in that no large-displacement faults that could have accommodated significant rotation are observed to cut the shallowest faults.

Overall, analysis of data sets from the southern Cherry Creek and Egan Ranges, as well as the Yerington District and the Lemitar Mountains, suggests that the normal fault systems responsible for Oligocene extension in these three widely separated regions evolved in the same manner as the Miocene normal fault system of the South Virgin Mountains. This suggests that the model of normal fault evolution (shown schematically in Fig. 1C) discussed throughout this paper may be applicable to many extended continental regions.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grant EAR-96-28262. We thank G. Spinelli and M. Herrin for field assistance. Discussions and field excursions with L.S. Beard, K. Howard, J. Faulds, and S. Rowland have contributed to the ideas presented here, although they are in no way liable for any errors in fact or interpretation. Stereonet by R.W. Allmendinger was used for the analysis and plotting of data. Constructive and
thoughtful reviews by James Faulds and L. Sue Beard improved the manuscript.

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MANUSCRIPT RECEIVED BY THE SOCIETY JUNE 15, 1998
REVISED MANUSCRIPT RECEIVED AUGUST 20, 1999
MANUSCRIPT ACCEPTED SEPTEMBER 17, 1999
Printed in the USA