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The Geology and Structures in the Northern Hiko Range, Lincoln County, Nevada

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THE GEOLOGY AND STRUCTURES IN
THE NORTHERN HIKO RANGE,
LINCOLN COUNTY, NEVADA

by

Douglas D. Switzer

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

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Department of Geoscience
University of Nevada, Las Vegas
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ABSTRACT

In the northern Hiko Range, extension occurred in four temporally distinct episodes during the Cenozoic. The extensional events are (1) prevolcanic (> 27.31 ± 0.03 Ma), (2) synvolcanic (between 22.78 ± 0.03 and 18.5 ± 0.4 Ma), (3) Tertiary (?) postvolcanic (< 14.7 ± 0.4 Ma), and (4) Pliocene (?) - Quaternary. Four fault sets are delineated based on orientation and cross-cutting relationships: (1) northeast- to northwest-striking moderately dipping prevolcanic faults, (2) east-west striking, steeply-dipping synvolcanic faults, (3) east-west- and east-northeast-striking, steeply dipping Tertiary (?) postvolcanic faults, and (4) generally north-striking steeply dipping Pliocene (?) - Quaternary faults.

Prevolcanic faults in the northern Hiko Range are interpreted to be footwall faults to an Oligocene age extensional system. These faults increase the area affected by Oligocene extension and support existing evidence that suggests this event is widespread.

A tectonomagmatic rift model has been proposed to explain synvolcanic extension during the Tertiary in the northern Basin and Range province. This model suggests that the mechanism for change in the horizontal principal stress direction, from north-south oriented $\sigma_2$ and east-west oriented $\sigma_3$ to east-west oriented $\sigma_2$ and north-south oriented $\sigma_3$, is temporally and spatially associated with the southward passage of a belt of volcanism. A few east-west-striking synvolcanic faults crop out in the Hiko Range and
can be explained by a tectonomagmatic rift model. However, the majority of the faults are postvolcanic and are not readily explained by the tectonomagmatic rift model. Both east-west- and east-northeast-striking oblique-slip faults occur along the Timpahute lineament. These faults are postvolcanic, but should be synvolcanic if the tectonomagmatic rift model applies. In addition, faults in the central part of the Timpahute lineament were active more than once since the Oligocene and the lineament may be related to transform and transverse faults formed during Precambrian rifting.

The Hiko fault zone is a segmented fault of Pliocene (?) - Quaternary age that may still be active and is interpreted to be the bounding fault of a half graben in Pahranagat Valley. A leaky segment boundary, the Hiko segment boundary (named here), is a structural boundary interpreted to be breached by faulting along the Hiko fault zone. Segment boundaries are sites where earthquakes begin or end. Earthquakes associated with the Hiko segment boundary, segments of the Hiko fault zone, and potentially active faults in the Timpahute lineament, pose seismic hazards, such as liquefaction, ground shaking, surface rupture, and rock falls, to the community of Hiko, Nevada.

The geology and the multiple generations of extensional structures exposed at the surface in the northern Hiko Range are similar to that in many of the oil fields in central Nevada. Therefore, this study may help understand complex trapping mechanisms, and thus, aid hydrocarbon exploration.
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CHAPTER 1

INTRODUCTION

Large magnitude extension and volcanism during the Tertiary are characteristic of the Basin and Range province (e.g., Stewart, 1978; Eaton, 1982). The relationship between volcanic activity and extension in the province is highly debated (e.g., Gans et al., 1989; Best and Christiansen, 1991; Axen et al., 1993). Magmatism may relate to extension in three different ways: (1) active mantle processes, where mantle convection drives extension and volcanism predates extension; (2) passive mantle processes, where plate interactions cause differential stresses within the lithosphere resulting in extension, decompression melting of the lithosphere and volcanic activity that postdates extension; or (3) a combination of those two previous ways, in which the mantle is initially passive, but later extension is sustained by mantle processes (Sengor and Burke, 1978; Bartley, 1989).

During the Tertiary, a general southward migration of an east-west trending belt of volcanism started in the Eocene and ended in the Miocene (Fig. 1a) (Stewart and Carlson, 1976; Best and Christiansen, 1991; Axen et al., 1993). The relative timing of extension was variably prevolcanic, synvolcanic, or postvolcanic depending on the location of the volcanic belt relative to extensional systems at any given time (Axen et al., 1993).

As a result, fault systems commonly described as prevolcanic, synvolcanic,
postvolcanic, and Quaternary occur in much of the Basin and Range province (Stewart, 1978; Eaton, 1982). Spatially they may overlap, be superimposed, or are separate. These temporally distinct fault systems accommodated crustal extension in the area from the Eocene to the present (e.g., Tschanz and Pampeyan, 1970; Taylor et al., 1989).

The purpose of this study is to document the geometry, timing, and kinematics of contractional and extensional structures in the northern Hiko Range, Nevada, and their kinematic relationship, if any, to nearby regional structures. The three main structural topics addressed are (1) the tectonic context and geometry of Tertiary prevolcanic faults, (2) the tectonic context, geometry, and kinematics of a regional east-west-striking fault zone, and (3) the geometry and kinematics of a range-bounding Quaternary fault zone and the development of the basin it formed. The Hiko Range is an excellent area to study these structures because the area has excellent exposure with good access, was only mapped at the scale of 1:250,000 previously, and the geographic position is important to understanding regional tectonic development.

Prevolcanic normal faults of two distinctly different ages occur in the northern Basin and Range province (e.g., Wells, 1992; Axen et al., 1993). Late Mesozoic to Eocene age and Oligocene to Miocene age extension have been recognized recently over a large portion of the northern Basin and Range province (e.g., Fryxell, 1988; Axen et al., 1990; Camilleri, 1992; Axen et al., 1993). Prevolcanic faults in the northern Hiko Range are interpreted here to be Oligocene in age. Thus, they may be related to the later of these two regional extensional events, or conversely, may indicate a local event unrelated to the regional extensional events.
During the Cenozoic, most of the extension in the Basin and Range province has been east-west directed. However, it has been shown that some synvolcanic extension is not east-west directed (e.g., Best et al., 1988, Bartley, 1989), but occurs along transverse faults. It has been argued that synvolcanic extension in the northern Basin and Range province was related to volcanic centers, north-south directed extension, or both. Some workers have suggested that localized synvolcanic extension occurred in a radial pattern in the vicinity of caldera complexes, but was minor in magnitude compared to prevolcanic and postvolcanic extension (e.g., Best and Christiansen, 1991; Axen et al., 1993; Scott et al., 1995a). Regional synvolcanic extension normal to east-west directed extension is suggested by a tectonomagmatic rifting model (Bartley, 1989). In this model, the southward migrating volcanic belt causes uplift that results in north-south directed extension (Bartley, 1989; Overtoom and Bartley, 1996). This regional north-south directed extension is of minor magnitude in comparison to east-west-directed extension in the same area (Overtoom and Bartley, 1996).

In the northern Basin and Range province, many east-west-trending lineaments, zones, or systems, cut across the province and appear to be major tectonic features (Fig. 1b) (e.g., Ekren et al., 1976; Stewart et al., 1977; Rowan and Wetlaufer, 1981; Hurtubise, 1994; Overtoom, 1994). The geometry, kinematics and tectonic or structural role of east-west-striking transverse structures or lineaments, or both, in the Basin and Range province is problematical. Some of these faults are dominantly dip slip (e.g., Overtoom and Bartley, 1994), yet others appear to be strike slip (e.g., Ekren et al., 1976). The major east-west-trending Timpahute lineament passes through the northern Hiko Range (Figs. 1b
and 2) (Ekren et al., 1976). The lineament is reported to be a strike-slip fault zone (Ekren et al., 1976; Best et al., 1989a). However, a recent study in the Timpahute Range, west of the Hiko Range, demonstrated dip-slip movement on faults in the lineament (Fig. 2) (Taylor, 1993). Data from this study show oblique slip on postvolcanic faults in the Timpahute lineament in the Hiko Range and that synvolcanic rifting can not explain this north-south directed extension.

Active faults and faults that are not historically active but cut Quaternary alluvium in the Basin and Range province pose a seismic risk to many communities. These faults produce the youngest documented episode of extension, Pliocene (?) - Quaternary in age, and control the modern day Basin and Range topography (e.g., Stewart, 1978; Eaton, 1982). Recent work on these young faults shows that many have segmented geometries and recent seismicity (e.g., King, 1986; DePolo et al., 1991). A generally north-striking range-bounding normal fault zone (the Hiko fault zone) that displaces Pliocene (?) - Quaternary age sediments was mapped on the western side of the Hiko Range and one segment boundary was identified (Fig. 3).

Segment boundaries, defined as barriers to fault propagation, can be geometric or structural (DePolo et al., 1991). If the segment boundary is structural, mapping should reveal (1) fault branches, (2) intersections with other faults or folds, or (3) terminations at cross structures (DePolo et al., 1991). If the segment boundary is geometric, mapping should reveal (1) changes in fault orientation (bends), (2) step overs or en echelon faults, or (3) separations or gaps in a fault zone (DePolo et al., 1991).

Over time, barriers to propagating faults can be breached, resulting in a "leaky"
boundary between fault segments. A leaky boundary is a segment boundary where seismicity and surface rupture occurring on one segment can cross the boundary to an adjacent segment. I suggest that a leaky segment boundary in the Hiko fault zone, here called the Hiko segment boundary, lies adjacent to the small agricultural community of Hiko, Nevada, and may pose a significant hazard.

Standard geologic techniques were used during this study in data collection and data analysis. Data collection consisted of detailed geologic mapping and included the collection of samples (Appendix A). The data were analyzed by using stereoplots of poles to faults and retrodeformable cross-section construction (see Appendix A). Point counts of thin sections were used to identify volcanic rocks and aid in unit correlations (Table 1; Appendix A).
Figure 1a. Map showing the general southward sweep of Tertiary volcanism through time across the northern Basin and Range province. Solid lines are contours of the southernmost extent of volcanic centers in Ma, except for the southern limit of all volcanic centers older than 5 Ma. The dashed line is the southern limit of > 34 Ma andesite (34a). HR denotes the location of the Hiko Range. Modified from Stewart and Carlson (1976), Best et al. (1989a), and Axen et al. (1993).

Figure 1b. Location map showing the location of major east-west trending lineaments, systems, and zones. A, B, and C lineaments from Mabey et al. (1978); N lineament from Fuller (1964) and Mabey et al. (1978); Prichards Station, Pancake Range, and Timpahute lineaments from Ekren et al. (1976), Warm Springs lineament from Ekren et al. (1976), Rowley et al. (1978), Hurtubise (1994), and Overtoom (1994); Escalante zone from Jayko (1990); Las Vegas Valley shear zone from Longwell (1960) and Burchfiel (1965); Lake Mead fault system from Anderson (1973) and Bohannon (1979). HR denotes the location of the Hiko Range. Modified from Duebendorfer and Black (1992) and Hurtubise (1994).
Figure 1c. This map shows the location of the Sevier orogenic belt and central Nevada thrust belt (CNTB). Folds exposed in Paleozoic rocks in the Hiko Range (HR) may be related to one of these thrust belts, most likely the central Nevada thrust belt.
Figure 2. Location of study area, ranges (gray), valleys (white), and major structures discussed in the text in the vicinity of the Hiko Range. Inset shows figure location on smaller scale map. HR = Hiko Range. Heavy solid lines and short dashed lines = faults. Ball and bar on downthrown side of faults. Heavy weight long and short dashed lines are approximate boundaries of major east-west trending lineaments. Dark gray line = the White River. Modified from Tschanz and Pampeyan (1970) and other sources cited in text.
Figure 3. Generalized fault map of the study area showing the location of the map area (Plate 1) and major features discussed in the text. Figure area is shown on Fig. 2. Gray area represents Paleozoic and Tertiary rock outcrops in the Hiko Range. White area represents valley fill. Concave up cusp area represents fluvial and lacustrine deposits of the White River. The topographic lows of Crystal Wash and Hiko Canyon are denoted by white lines in the Hiko Range. Strike and dip symbols show the general orientation of alluvial deposits near the White River. Heavy weight lines are faults and fault zones. The Hiko fault zone consists of fault strands in the Hiko segment boundary and Crystal Wash and Hiko Canyon segments. Heavy dashed lines are inferred faults. Ball and bar on downthrown side of faults. Light gray lines depict major highways.
CHAPTER 2

STRUCTURAL AND TECTONIC BACKGROUND

The Hiko Range lies within the Basin and Range province, an area that underwent large magnitude extension and volcanism during the Tertiary (e.g., Stewart, 1978; Eaton, 1982; Gans et al., 1989). Three major Cenozoic structures crop out in the northern Hiko Range (Fig. 3): an east-west-striking fault zone in Crystal Wash; an east-west-striking fault zone in Hiko Canyon; and the youngest structure, the generally north-south-striking Hiko fault zone, along the western boundary of the Hiko Range. In addition, northeast- to northwest-striking faults and east-northeast-striking faults are exposed throughout the Hiko Range (Plate 1).

Prevolcanic normal faults of different ages occur in many areas of the Basin and Range province (e.g., Abott et al., 1983; Lemmon and Morris, 1984; Hodges and Walker, 1990; Taylor and Bartley, 1992; Axen et al., 1993). In some areas the prevolcanic faults are late Mesozoic to early Eocene in age (e.g., Page, 1995; Camilleri, 1996), while in other areas the prevolcanic faults are clearly Oligocene (Jayko, 1990; Axen et al., 1993). Prevolcanic extension can be difficult to recognize because the evidence is hidden by a widespread cover of younger rocks (e.g., Axen et al., 1993).

The earliest extension in the Basin and Range province is late Mesozoic to Eocene
in age. This extension is documented in north central Nevada, northwestern Utah, and southeastern Idaho and is interpreted to be gravitational collapse of overthickened crust (e.g., Vandervoort and Schmitt, 1990; Wells et al., 1990; Camilleri, 1996). Evidence for Mesozoic to Eocene age extension in the vicinity of the Hiko Range does not exist.

The prevolcanic Seaman fault, located to the northeast of the Hiko Range (Fig. 2), is a large displacement, east-dipping normal fault of pre-middle-Oligocene age (Taylor and Bartley, 1992). The Seaman fault is interpreted to be the breakaway fault for the east-directed Snake-Stampede extensional system located in the vicinity of the Snake Range in the north and the North Pahroc Range in the south (Bartley et al., 1988; Gans et al., 1989; Taylor and Bartley, 1992). This extensional system reflects the oldest regional extensional episode identified near the Hiko Range.

Synvolcanic normal faults of varying ages also occur in many areas of the Basin and Range province (e.g., Anderson, 1971; Proffett, 1977; Gans et al., 1989; Best and Christiansen, 1991; Taylor, 1990). These synvolcanic faults appear to be a result of the generally southward migrating sweep of volcanism coinciding in time and space with north-south trending extensional belts (e.g., Stewart et al., 1977; Best and Christiansen, 1991). Two extensional models, the caldera collapse model (Best and Christiansen, 1991) and the tectonomagmatic rift model (Bartley, 1989), have been proposed to explain synvolcanic extension. In the caldera collapse model, extension is localized and faults forms radial to the caldera. In the tectonomagmatic rift model, extension is regional and forms east-west-striking faults within an east-west-trending zone 10's of kilometers wide. Both models explain the observed reorientation of the stress field, from east-west to
north-south directed extension, and the presence of synvolcanic faults.

Several east-trending and east-north-east-trending structural lineaments, crop out in Nevada (Figs. 1a and 4) (Ekren et al., 1976; Rowley et al., 1978; Jayko, 1990; Hurtubise, 1994). The east-trending lineaments appear to (1) influence, if not control, the location of many volcanic centers; (2) form east-trending ranges; (3) interrupt north-trending valleys and ranges; (4) separate areas of contrasting extensional structural style; and (5) coincide along parts of their lengths with marked magnetic discontinuities (Ekren et al., 1976).

Two lineaments near the study area, the Timpahute and the Warm Springs lineaments (Figs. 2 and 4), contain east-west-striking faults that were active during the Cenozoic (e.g., Ekren et al., 1976; Overtoom and Bartley, 1994; Overtoom, 1994). East-west-striking faults in both lineaments have apparent left-lateral displacement (Tschanz and Pampeyan, 1970; Kleinhampl and Ziony, 1985; Scott et al., 1995a). It is presently unclear if left-lateral strike-slip faults, oblique-slip faults, normal faults, or combinations of these, are the main structures in the Timpahute lineament. A section of the lineament is still active as suggested by seismic epicenters aligned east-west along the Timpahute lineament, from the south end of Coal Valley, through the south end of the North Pahroc Range, to Dry Lake Valley (Fig. 2) (Ekren et al., 1976). In contrast, recent detailed mapping in the Golden Gate Range indicates that the apparent left-lateral displacement on the Warm Springs lineament is due to offset along normal faults followed by westward tilting of the range (Overtoom and Bartley, 1994). The Warm Springs lineament also has been referred to as the Blue Ribbon lineament (Rowley et al., 1978) or Sliver King
lineament (Hurtubise, 1994). Because the name Warm Springs lineament was the first name applied to this feature (Ekren et al., 1976), this name will be used throughout the rest of this paper.

Many Pliocene - Quaternary age faults are north-striking, range-bounding faults that are responsible for the present day north-south-trending ranges and intervening basins (Tschanz and Pampeyan, 1970; Stewart, 1978; Eaton, 1982). These young faults represent the latest stage of extension in the structural evolution of the Basin and Range province. Some faults are still active, as evidenced by recent seismic activity and fault scarps in Quaternary age deposits (Stewart, 1978; Eaton, 1982).

The Pliocene (?) - Quaternary Hiko fault zone bounds the west side of the Hiko Range (Figs. 2 and 3, Plate 1) (Tschanz and Pampeyan, 1970). Recent studies focused on similar young active faults reveal that the faults are segmented (e.g., Crone and Haller, 1991; Machette et al., 1991; Zhang et al., 1991). The segment boundaries on these faults may be the sites of significant strain, may form barriers to propagating faults, and may greatly influence the locations of earthquakes (e.g., Schwartz and Coppersmith, 1984; Bruhn et al., 1990; Susong et al., 1990; DePolo et al., 1991). The Hiko fault zone has been inactive in historical time, but lies within a westward band of seismicity of the Intermountain seismic belt that passes through south-central Nevada (Smith and Sbar, 1978).
Figure 4. Location of caldera complexes (heavy dashed lines) that are the sources of the Tertiary ash-flow tuffs exposed in the study area and regional east-west striking lineaments and zones (heavy solid lines). Gray area represents ranges and white area represents valleys. Caldera complex boundaries from Scott et al. (1995). Regional east-west striking lineaments and zones have diffuse boundaries and are at least 10 kilometers wide (Ekren et al. 1976); Escalante zone from Jayko (1990); Timpahute, Pancake Range, and Prichard's Station lineaments from Ekren et al. (1976); Warm Springs lineament from Ekren et al. (1976), Rowley et al. (1978), Hurtubise (1994), and Overtoom (1994). Lineament locations are modified from their source reference. Lineament boundaries are based the location of numerous generally east-weststriking Cenozoic faults.
CHAPTER 3

STRATIGRAPHY

Outcrops in the Hiko Range expose Devonian and Mississippian sedimentary rocks unconformably overlain by Tertiary volcanic and sedimentary rocks, and Pliocene (?) to Quaternary alluvial, fluvial, and lacustrine deposits (Dolgoff, 1963; Cook, 1965; Tschanz and Pampeyan, 1970; Ekren et al., 1977; Best and Christiansen, 1991). The Paleozoic rocks are part of the shelf succession sequence and consist of marine limestone, dolomite, shale, and sparse sandstone (Tschanz and Pampeyan, 1970). The Tertiary volcanic rocks emanated from known or inferred Tertiary calderas located 30 to 100 kilometers away from the Hiko Range (Fig. 4) (Best et al., 1993). Many of the calderas are nested, and thus, form caldera complexes (e.g., Scott et al., 1995a). Distal outflow facies of ash-flow tuffs from these volcanic vents crop out in the Hiko Range. These Tertiary volcanic rocks range in age from $27.31 \pm 0.03$ to $14.7 \pm 0.4$ Ma (Novak, 1984; Best et al., 1989a).

Detailed descriptions of each unit can be found in Appendix B.

Paleozoic Rocks

The Paleozoic rocks in the study area range in age from early Devonian to early Mississippian (Tschanz and Pampeyan, 1970). The units exposed in the field area are Devonian Sevy Dolomite, Oxyoke Canyon Sandstone, Simonson Dolomite, and Guilmette...
Formation, Devonian-Mississippian West Range Limestone (includes the Pilot Shale); and Mississippian Joana Limestone (Fig. 5). The Devonian Sevy Dolomite (Nolan, 1935) is the oldest unit exposed in the field area and is approximately 430 m thick. This unit is easily recognized by the uniform whitish-gray dolomite and the general lack of fossils. The Devonian Oxyoke Canyon Sandstone (Nolan, 1935) is a brownish-gray carbonate- or silica-cemented sandstone with cross-stratification up to 10 cm thick. The unit is about 18 meters thick in the field area. The Devonian Simonson Dolomite (Nolan, 1935) is an alternating (at the meter scale) dark- and light-gray dolomite approximately 320 meters thick. The Devonian Guilmette Formation (Nolan, 1935) forms the majority of the Paleozoic-rock outcrops in the field area and is approximately 800 m thick. The unit is limestone (upper part above dolomitized front) and dolomite (lower part) with numerous sandstone beds and minor shale interbeds. The Devonian-Mississippian West Range Limestone (Westgate and Knopf, 1932) and Pilot Shale (Spencer, 1917) is a yellowish-orange, platey limestone with local black shale in the upper part and is about 75 m thick. These two formations were mapped as one unit because the Pilot Shale is too thin to be mapped individually (see Appendix B). The Mississippian Joana Limestone (Spencer, 1917) is a bluish-gray, fossiliferous cherty limestone, up to 175 m in thickness.

**Tertiary Volcanic Rocks**

Oligocene and Miocene ash-flow tuffs unconformably overlie the Devonian and Mississippian rocks in the field area (Fig. 6). The volcanic rocks exposed in the Hiko Range are regionally distributed ash-flow tuffs that erupted from volcanic centers in four
different caldera complexes over a period of about 13 million years, from 27.31 to 14.7 Ma (Fig. 4), and clearly demonstrate, at least locally, the southward migration of volcanism through time. Even though the source areas for these tuffs vary in time and space, many of them have similar phenocryst compositions and textures that make them difficult to distinguish from one another in outcrop. Petrographic analysis, point counting of thin sections, and hand sample examination of rock constituents, combined with stratigraphic field relationships, were used to correlate the ash-flow tuffs (Table 1 and Appendix B).

The four Oligocene ash-flow tuffs that crop out in the study area erupted from a variety of different volcanic centers within the Central Nevada and Indian Peak caldera complexes. These Oligocene centers are all located to the northwest and northeast of the study area and contributed ash from 27.31 to 23.8 Ma (Fig. 4). The 27.31 ± 0.03 Ma Monotony Tuff is a dacitic ash-flow tuff that erupted from the Pancake Range caldera in the southern Pancake Range, which is part of the Central Nevada caldera complex (Ekren et al., 1971; Best et al., 1989b; Scott et al., 1995a). The trachytic Baldhills Tuff Member of the Isom Formation erupted at 25.7 ± 0.4 Ma from an undetermined source that lies southeast or west of the Indian Peak caldera complex (Fleck et al., 1975; Anderson and Rowley, 1975; Best et al., 1989b). A rhyolitic ash-flow tuff, the 26.68 ± 0.03 Ma Shingle Pass Tuff, erupted from a source area in the Quinn Canyon Range (Best et al., 1989a; Best et al., 1992). The Hole-in-the-Wall Tuff Member of the Isom Formation is a trachytic ash-flow tuff that erupted from an undetermined volcanic center southeast or west of the Indian Peak caldera complex (Anderson and Rowley, 1975; Best et al.,
I989b). No published radiometric dates exist for this unit, but the age is bracketed between the ages of the upper Shingle Pass Tuff, $26.00 \pm 0.03$ Ma, and the Leach Canyon Formation, $23.8 \pm 0.05$ Ma (Best et al., 1989b), which crop out to the north and east of the Hiko Range, but not in the study area.

Consistent with the southward sweep of volcanism, the Miocene tuffs deposited in the study area erupted from volcanic centers located south or southeast of the Oligocene centers: the Caliente and Kane Springs Wash caldera complexes (Fig. 4). The $22.78 \pm 0.03$ Ma Bauers Tuff Member of the Condor Canyon Formation is a rhyolitic ash-flow tuff that erupted from part of the Caliente caldera complex in the Clover Mountains (Rowley and Siders, 1988; Best et al., 1989b; Rowley et al., 1995). A dacitic ash-flow tuff, the $20.4 \pm 0.5$ Ma Harmony Hills Tuff, erupted from a vent in the southern part of the Caliente caldera complex (Ekren et al., 1977; Rowley et al., 1979). The northern Hiko Range is near the edge of the Harmony Hills Tuff outflow sheet, and thus, the unit was too thin to be mapped individually. The $18.5 \pm 0.4$ Ma Hiko Tuff is a rhyolitic ash-flow tuff that also erupted from the Caliente caldera complex (Rowley and Siders, 1988, Taylor et al., 1989). The Delamar Lake Tuff and Kane Wash tuffs erupted from the Kane Springs Wash caldera complex, which lies even further south of the study area (Fig. 4). The Delamar Lake Tuff is a rhyolitic ash-flow tuff (Scott et al., 1995a). Two K-Ar dates on sanidine from this unit provide ages of $15.8 \pm 0.4$ Ma and $15.5 \pm 0.4$ Ma (Novak, 1984). The $14.7 \pm 0.4$ Ma Sunflower Mountain Tuff is a rhyolitic ash-flow tuff (Novak, 1984; Scott et al., 1995a).
Pliocene (?) - Quaternary Sedimentary Deposits

The youngest units in the field area are Pliocene (?) - Quaternary alluvial, fluvial, and lacustrine (?) deposits; "older" Quaternary alluvial deposits; "younger" Quaternary alluvial deposits; Quaternary fluvial and lacustrine; and Quaternary colluvium (Fig. 6).

Three informal subunits within the Pliocene (?) - Quaternary age unit are recognized in this study and are here called the Pahranagat Valley, Mail Summit Road, and Hiko Range subunits. The tectonic significance of these units is discussed in detail in Chapter 6, but in general they are important because they place age constraints on extension in the study area and may reflect deposition in a subsiding half graben.
Paleozoic Stratigraphy in the Northern Hiko Range

Figure 5. Generalized Paleozoic stratigraphic section exposed in the northern Hiko Range. Unit thicknesses are based on regional thicknesses (Tschanz and Pampeyan, 1970). The basal and upper contacts are both exposed for only the Devonian Oxyoke Canyon Sandstone is the only unit with full exposure in the field area. The other Paleozoic units are truncated by faults or only one of their contacts are exposed. Fossil locations represent general stratigraphic position within units. Sandstone beds are abundant in the upper portion of the Guilmette Formation and locally comprise up to 50% of the rock. See Appendix B for detailed stratigraphic descriptions of units in the map area.
Figure 6. Generalized Cenozoic stratigraphic section exposed in the northern Hiko Range. Unit thicknesses shown are based on maximum unit thickness within the field area. All units are exposed in the Hiko Canyon area, except for the Kane Wash Tuff, which is exposed in Crystal Wash. Dashes represent pumice or fiamme. Welding is indicated by the density of dashes. Older Quaternary alluvium and Quaternary alluvium deposits (not shown) occur in incised washes. Quaternary fluvial and lacustrine deposits are located in flat, low lying areas on the west side of the Hiko Range. The Hiko Range and Mail Summit Road alluvium and the Pahranagat Valley Fluvial deposits are subunits of the Quaternary-Tertiary deposits.
CHAPTER 4

STRUCTURAL DESCRIPTIONS

In the study area, cross-cutting relationships among faults and between faults and folds, as well as offset stratigraphic units delineate four temporally distinct episodes of Cenozoic extension and one episode of Mesozoic to Eocene contraction. The extensional episodes are prevolcanic, synvolcanic, Tertiary (?) postvolcanic, and Quaternary in age. Different faults sets formed during each extensional episode (Figs. 7, 8, 9, and 10). The sub-Tertiary unconformity provides critical timing information as well as a structural datum. Data collected on these structures and presented in this chapter enable interpretations about them.

Prevolcanic Folds

Folds in Paleozoic rocks are unconformably overlain by Tertiary volcanic rocks (Figs. 11a and 11b; Plate 1). The folds are evidenced by different panels of rocks with different attitudes. The attitudes are relatively constant across each panel. The bedding in the panels presently strikes northwest or northeast with steep to moderate west dips or moderate to gentle east dips. Axial surfaces are not exposed, but cross-section restoration geometrically requires folds to be present. All of the Paleozoic rock panels do not have a consistent attitude when the sub-Tertiary unconformity is restored. The inconsistent
attitude between rock panels suggests prevolcanic folds are present.

**Prevolcanic Faults**

Thirteen northeast- and northwest-striking faults crop out in the study area (Plate 1). A stereoplot of the poles to the faults and a kamb contour of the poles show consistent orientations (Figs. 8 and 9). The faults are generally planar, dip between 50 and 80 degrees to the northeast and northwest, and offset Paleozoic rocks. The stratigraphic separation along these faults is apparently normal and relatively small (generally less than 60 meters) (Figs. 11a, 11b, and 11c). Fault striae were not observed on these faults, so the slip direction is unknown. The faults cut folds in Paleozoic rocks in the Hiko Range (Figs. 11a and 11b). The Hiko and Monotony Tuffs and Quaternary alluvial deposits overlap these faults. This relationship suggests that the faults are older than the Monotony Tuff (27.31 ± 0.03 Ma), the oldest volcanic unit. The northeast- and northwest-striking faults locally are cut by east-west-striking faults (synvolcanic) and east-west-, east-northeast-, and northeast-striking faults (postvolcanic faults) (Fig. 7; Plate 1).

**Sub-Tertiary Unconformity**

The sub-Tertiary unconformity between Paleozoic and Tertiary rocks is slightly angular (< 30 degrees) in the field area, in the Hiko Range south of the field area, and in the Seaman Range (Fig. 2) (Taylor, 1989; Lisa R. Danielson, written communication, 1996). The unconformity is developed on the Guilmette Formation, West Range Limestone, and Joana Limestone in the field area, on the Sevy Dolomite in the Hiko Range south of the field area (Lisa R. Danielson, written communication, 1996), and on
the Guilmette Formation, West Range Limestone, Joana Limestone, and Mississippian Scotty Wash Quartzite in the Seaman Range north of the field area (Fig. 2) (Taylor, 1989). In the South Pahroc Range, the unconformity is developed on one area of low relief outcrops of the Ordovician Pogonip Group (?) (Moring, 1982). The unconformity has pronounced discordance in the North Pahroc Range and is developed on the Pennsylvanian Ely Limestone and the Permian Arcturus Formation (Fig. 2) (Taylor and Bartley, 1992). In the Pahranagat Range and to the west, the unconformity has locally pronounced discordance and is developed on Paleozoic strata of Late Cambrian through Pennsylvanian age (Jayko, 1990).

In the field area, a small amount of paleorelief (at least 30 m) exists along the unconformity. Exposures of the unconformity near Hiko Canyon show east-west oriented paleochannels filled with Tertiary ash-flow tuffs. The tuffs pinch out to the north and south against the sides of east-west oriented paleochannels (Plate 1). In addition, a buttress unconformity between the Guilmette Formation and the Hiko Tuff crops out in portions of the Crystal Wash area (Plate 1).

**Synvolcanic Faults**

The synvolcanic faults exposed in the study area are older than the 18.5 ± 0.4 Ma Hiko Tuff. One east-west-striking fault cuts rocks as young as the 22.78 ± 0.03 Ma Bauers Tuff Member, and is lapped by the Hiko Tuff (fault A on Fig. 7; Plate 1). Another east-west-striking fault, exposed just north of synvolcanic fault A (fault B on Fig. 7; Plate 1), cuts Paleozoic rocks and also is lapped by the Hiko Tuff. The Hiko Tuff at this locale
lies directly on Paleozoic rocks with about 30 degrees of discordance. Fault B is also probably a synvolcanic fault because of the similarities in orientation (Fig. 8), as well as, sense and magnitude of displacement as the known synvolcanic fault A. Also, faults A and B cut two of the prevolcanic faults (Fig. 7; Plate 1). A stereoplot of the poles to these two faults shows that the orientation is similar to that of some of the Tertiary (?) postvolcanic faults (Figs. 8 and 10) and suggests they may have formed under a similarly oriented stress field. The synvolcanic faults are generally planar and dip approximately 80 degrees to the north. The stratigraphic separation along faults A and B is small (approximately 20 m) and permits either normal, left-lateral, or oblique slip. The sense of slip is unknown because kinematic indicators were not found on the faults.

**Tertiary (?) Postvolcanic Faults**

The Tertiary (?) postvolcanic fault set consists of twenty-five east-west-, north-northeast-, and west-northwest-striking faults (Fig. 7). The geometry, fault striae, and cross-cutting relationships among these faults indicate that they are coeval (Fig. 7; Plate 1).

East-west- and east-northeast-striking faults are exposed throughout the study area and are most prominent in the Hiko Canyon (Fig. 11d) and Crystal Wash (Fig. 11e) areas (Fig. 7; Plate 1). These faults dip steeply (> 60 degrees) to both the north and south. The faults are non-planar and are exposed for 1 to 3 kilometers along strike. The absence of marker beds and piercing points across these faults makes the magnitude of displacement uncertain. The slickenlines observed on seven faults, have rakes ranging
Figure 7. Fault timing map of fault sets in the field area. Light weight line outlines mapped area. Quaternary faults are fault strands of the Hiko fault zone. Map area corresponds to area of Plate 1. The location of this map is labeled as study area on Figure 2. A and B are the synvolcanic faults discussed in the text.
Figure 9. Kamb contour of poles to faults for prevolcanic and postvolcanic fault sets. The faults in each set show consistent orientations. The modal attitude (small white squares) of the poles in the prevolcanic fault set is N 50° W and in the Tertiary (?) postvolcanic fault set is N 100° W.
Figure 10. Stereonet plots of poles to faults for Tertiary (?) postvolcanic and Quaternary fault sets. For the Quaternary fault set, poles represent the attitude of fault strands along the Hiko fault zone taken every 0.8 kilometer along strike for a total of forty-four data points.
Figure 11a. Cross section A-A’ through the northern part of the study area. Cross section location is shown and unit labels are defined on Plate 1.
Figure 11b. Cross section B-B' through the northern part of the field area. The Hiko fault zone is located at the west side of the cross section. Cross section location is shown and unit labels defined on Plate I.
Figure 11c. Cross section C-C' through the central part of the map area. The Hiko fault zone is located at the west side of the cross section. Cross section location is shown and unit labels defined on Plate 1.
Figure 11d. Cross section D-D’ through Hiko Canyon. Cross section shows postvolcanic faults of the Timpahute lineament. Cross section location is shown and unit labels are defined on Plate 1.
Figure 11e. Cross section E-E' through the southeastern part of the map area. Cross section shows postvolcanic faults of the Timpahute lineament. Unit label definitions and cross section location are shown on Plate 1.
CHAPTER 5

STRUCTURAL INTERPRETATIONS

In many areas of the Basin and Range province, older extensional systems are overprinted by one or more younger extensional systems. Identification of the age and kinematics of the extensional systems and the area they affected will aid in the understanding of extensional tectonics and regional structural events. In the study area, folds in Paleozoic rocks are interpreted to be related to Mesozoic contraction that has been documented in the area as the central Nevada fold and thrust belt (e.g., Bartley et al., 1993; Taylor et al., 1993). The interpretations associated with Cenozoic faults in the northern Hiko Range are summarized as follows. The prevolcanic faults are interpreted as minor footwall faults located west of the Seaman breakaway fault of the Oligocene Snake-Stampey extensional system. The synvolcanic faults along the Timpahute lineament may be related to a volcanic rift associated with the southward migration of a volcanic belt. Postvolcanic extension on oblique-slip faults along the Timpahute lineament indicates a change in the orientation of the principal stresses during the Miocene, which may or may not be due to the southward migration of a volcanic belt and related uplift. The oblique slip along these faults is inconsistent with the generally accepted role of transverse structures. The Timpahute lineament has been active from the Oligocene to the present
and may reflect an older crustal structure. The Pliocene (?) - Quaternary Hiko fault zone is a segmented fault with a leaky segment boundary. The young age and identification of segmentation along this fault zone suggests a potential seismic risk to the community of Hiko, Nevada.

**Mesozoic Contraction**

The northern Hiko Range is located between the eastern edge of the central Nevada thrust belt and the western edge of the Sevier orogenic belt, two belts of Mesozoic to Eocene age contraction (e.g., Heller et al., 1986; Bartley and Taylor, 1991). An exposed anticline and fold train in the field area are interpreted here to be related to this contraction based on age, location relative to the two thrust belts, and orientation (Figs. 11a and 11b).

The central Nevada thrust belt and the Sevier orogenic belt consist of a series of generally north-striking west-dipping thrust faults and north-trending east-verging folds. The central Nevada thrust belt extends from Eureka to Alamo, Nevada, and is bracketed between late Permian and 86 Ma in age (Fig. 1c) (Bartley and Taylor, 1991; Bartley et al., 1993; Taylor et al., 1993). The Sevier orogenic belt extends from southeastern California to northern Canada, and its age is bracketed between late Jurassic-early Cretaceous to Eocene (Fig. 1c) (Armstrong, 1968; Heller et al., 1986).

The fold train in the Paleozoic rocks in the Hiko Range strikes north and is depicted to decrease in amplitude and increase in wavelength toward the east (Figs. 11a and 11b). The orientation and geometry are similar to that of structures in the central
Nevada thrust belt (e.g., Bartley et al., 1993; Taylor et al., 1993). Thrust faults of the central Nevada thrust belt crop out in the Pahranagat, Timpahute, and Mount Irish Ranges west and southwest of the field area (Figs. 1c and 2). Fold trains in the footwall of thrust faults may die out away from the thrust. Therefore, these folds in the northern Hiko Range are interpreted to be related to the central Nevada thrust belt. In contrast, the folds would have to increase in amplitude and decrease in wavelength toward the east to be related to the Sevier thrust belt, which is located east of the Hiko Range.

Prevolcanic Extension

The prevolcanic faults in the study area may be related to one of two periods of regional extension, either late Mesozoic to Eocene or Oligocene in age. Prevolcanic extension in the Basin and Range province is important because it is the earliest Cenozoic extension, and thus, may provide data that strongly reflects on initial rifting mechanisms.

In northeastern Nevada (e.g., Pequop Mountains), northwestern Utah (e.g., Raft River Mountains), and southeastern Idaho (e.g., Albion Mountains), evidence for regional late Mesozoic to Eocene extension consists of (1) normal faults overlapped by 41 Ma volcanic rocks, (2) the high angular discordance between late Mesozoic sedimentary rocks and overlying Eocene volcanic rocks, and (3) large structural relief below the sub-Tertiary unconformity (Fouch, 1979; Vandervoort and Schmitt, 1990; Wells et al., 1990; Wells, 1992, Nutt and Thorman, 1992, Nutt et al., 1992; McCutcheon and Zogg, 1994; Camilleri, 1996). The late Mesozoic to Eocene extension appears to be regional in extent and related to gravity spreading of overthickened crust (e.g., Coney and Harms, 1984;
In the Delamar Mountains, south of the study area, west-dipping normal faults are interpreted to be late Mesozoic to early Tertiary in age (Fig. 3) (Page, 1995). The timing of this extension is poorly constrained (> 27 Ma), but cross-section restoration of one of the faults indicates 1.7 kilometers of erosion below the sub-Tertiary unconformity (Page, 1995). This event is interpreted as localized gravitational collapse of overthickened crust developed by Mesozoic thrusting (Page, 1995). No data from this nor previous studies suggest the occurrence of regional late Mesozoic to Eocene extension in or near the Hiko Range (e.g., Axen et al., 1993; Scott et al., 1995a). Documented extension of that age, however, lies far to the north. Therefore, it seems unlikely that the prevolcanic faults in the northern Hiko Range are related to the late Mesozoic to Eocene extensional episode.

Evidence for Oligocene extension is common in the Basin and Range province (e.g., Jayko, 1990; Axen et al., 1993). Because of the general southward sweep of Tertiary volcanism in the Great Basin through time (Stewart and Carlson, 1976; Best et al., 1989a), the Oligocene extension, which is approximately the same age north-south along strike, is generally synvolcanic in the north (e.g., Schell Creek and Snake Ranges) and prevolcanic in the south (e.g., North Pahroc Range) (Gans et al., 1989; Axen et al., 1993). The Oligocene extension is interpreted to be in part related to the east-directed Oligocene Snake Range decollement, Stampede detachment, and Seaman breakaway fault, which together have been called the Snake-Stampede extensional system (Taylor and Bartley, 1992).

The Seaman breakaway fault separates the Snake-Stampede extensional system
from its footwall (Taylor, 1989). The North Pahroc Range lies in the hanging wall of the Snake-Stampede extensional system. In the North Pahroc Range, the regional prevolcanic extensional system is documented by normal faults overlapped by 31 Ma volcanic rocks, prevolcanic Oligocene sedimentary rocks, a large angle of discordance across the sub-Tertiary unconformity, and large structural relief below the pre-Tertiary unconformity (Taylor, 1989). In contrast, in the footwall of the Seaman breakaway fault, normal faults are rare, the angle of discordance across the sub-Tertiary unconformity is small, and prevolcanic sedimentary rocks are absent. Much of the Oligocene extension to the northeast in the Snake Range in the hanging wall of the Snake Range decollement is synvolcanic and started around 36 Ma (Gans, 1982; Gans and Miller, 1983; Gans et al., 1989).

The prevolcanic faults in the northern Hiko Range are interpreted here to represent minor footwall faults of the east-directed Oligocene Snake-Stampede extensional system. Minor faults are common in the footwall block of major normal faults (cf., Bruhn, 1987; Wernicke and Axen, 1988, Bartley et al., 1990; Machette et al., 1991; Wernicke, 1992; Thomas, 1993; Manning and Bartley, 1994; Froitzheim and Manatschal, 1996). Footwall faults are interpreted to form due to crustal unloading, isostatic uplift, or rock volume and shape changes in the footwall block of major extensional faults (e.g., Manning and Bartley, 1994). The small displacement on the faults in the Hiko Range, the slight angularity across the sub-Tertiary unconformity, and the lack of prevolcanic sedimentary rocks in the northern Hiko Range support this interpretation.

If this interpretation is correct, then the presence of Oligocene age prevolcanic
faults in the Hiko Range confirms the suggestion by Axen et al. (1993) of a southward continuation of an eastern Oligocene extensional belt in the eastern part of the Great Basin. Furthermore, this interpretation of these faults as footwall faults implies that the southward continuation of the Seaman breakaway fault (Fig. 2) continues southward and lies to the east of the Hiko Range.

Sub-Tertiary Unconformity

Analysis of the sub-Tertiary unconformity is important in identifying prevolcanic extension and was used in interpreting the prevolcanic faults in the Hiko Range. Areas of low-angle discordance between Paleozoic and Tertiary rocks that lack prevolcanic sedimentary units are interpreted as unextended to slightly extended paleohighlands. Unextended to slightly extended areas would have no faults or faults with relatively small displacement, which would result in little or no block rotation, and therefore, little to no basin development. Areas of high-angle discordance between Paleozoic and Tertiary rocks that have prevolcanic sedimentary units are interpreted as moderately to highly extended areas. Moderately to highly extended areas contain faults with relatively large displacements, which would result in moderate to major block rotation, and therefore, basin development.

Comparison of data from the northern Hiko Range to regional data suggests the locations of paleohighlands and paleovalleys associated with either slightly or highly extended crust. Northeast and east of the field area, prevolcanic Oligocene sedimentary rocks crop out in the North and South Pahroc Ranges (Tschanz and Pampyan, 1970;
Moring, 1982; Taylor and Bartley, 1992). The outcrop pattern of the prevolcanic sedimentary rocks suggests deposition in a north-south trending paleovalley located in the North Pahroc Range (Taylor and Bartley, 1992). The paleovalley in the North Pahroc Range is interpreted to have formed in the hanging wall of the east directed Snake-Stampede extensional system along the Seaman breakaway fault (Taylor and Bartley, 1992). Prevolcanic sedimentary rocks are not recorded in the Seaman (Taylor, 1989) and the Hiko Ranges suggesting that these areas were probably highlands, with irregular topography and net erosion, adjacent to the North and South Pahroc Ranges. Thicker sections of Tertiary volcanic rocks in the North and South Pahroc Ranges, compared to the Seaman and Hiko Ranges, support this idea (Moring, 1982; Taylor, 1989; Taylor and Bartley, 1992; Scott et al., 1995a). Ash-flow tuffs typically pond in basins and thin in the direction of valley margins and highlands (e.g., Crandell and Mullineaux, 1973; Hoblitt et al., 1981; Wilson and Walker, 1982). In highland areas, thin ignimbrite veneer deposits that mantle topography can be traced laterally to ponded thick deposits (Walker et al., 1980). In the northern Hiko Range, the Hiko Tuff is interpreted to form ignimbrite veneer deposits (Fig. 11d). In the Hiko Range south of the field area, the Hiko Tuff also appears to form ignimbrite veneer deposits (Lisa R. Danielson, written communication, 1996).

Also, other tuffs, such as the Monotony Tuff, Bald Hills Tuff Member, Shingle Pass Tuff, Hole-in-the-Wall Tuff Member, and Bauers Tuff Member, in the Hiko Range are ignimbrite veneer deposits and or fill paleochannels (Plate 1).

South and southwest of the field area, Oligocene sedimentary rocks occur at the base of the Tertiary section (Tschanz and Pampeyan, 1970; Ekren et al., 1977; Jayko,
in the Pahranagat Range and to the west in the Jumbled Hills. The distribution of the prevolcanic sedimentary rocks suggests deposition in an east-west-trending paleovalley located in the present location of the Pahranagat shear zone (Jayko, 1990). Successively younger ash-flow tuffs lapping Paleozoic strata north and south of the Pahranagat shear zone support this interpretation (Jayko, 1990).

The northern Hiko Range is interpreted to be a highland area with net erosion since at least the Oligocene, and possibly since the Mesozoic. The present lack of Tertiary prevolcanic sedimentary deposits (and Mesozoic sedimentary deposits) and the presence of thin tuffs forming mantle veneer deposits in the northern Hiko Range compared to the presence of Tertiary prevolcanic sedimentary deposits and thick tuffs in the North and South Pahroc Ranges, supports this interpretation. This highland is here interpreted to lie in the footwall of the Seaman breakaway fault.

**Synvolcanic Extension**

Some workers have attributed timing of extension in the Basin and Range province to be mostly synvolcanic and they have related this to active-mantle models (see Chapter 1) (e.g., Segnor and Burke, 1978; Gans et al., 1989). However, other studies suggest synvolcanic extension is minor compared to prevolcanic and postvolcanic extension (e.g., Best and Christiansen, 1991; Axen et al., 1993; Overtoom and Bartley, 1996). Synvolcanic extension in the northern Hiko Range appears to be minor because these faults are the least abundant and have minor displacement. These relationships are similar to synvolcanic extension observed in the region adjacent to the study area.
Synvolcanic extension is documented in the North Pahroc Range, Golden Gate Range and in and around the area of the Caliente caldera complex (e.g., Scott and Swadley, 1992, Scott et al., 1995a). In the North Pahroc Range, evidence of a minor synvolcanic extensional episode is recognized (Taylor et al., 1989; Taylor, 1990). The age of the event is well constrained, occurring between 30 and 27 Ma (Taylor et al., 1989). In the Golden Gate Range, synvolcanic extension occurred between 31-22 Ma where the synvolcanic extension is accommodated on generally east-west-striking dip-slip faults (Overtoom and Bartley, 1996). These faults are part of the east-west oriented Warm Springs lineament (Fig. 1b and 4) (Overtoom and Bartley, 1996). This synvolcanic extension has been modeled to be the result of normal faulting coinciding with and linked to the passage of the southward-migrating mid-Tertiary volcanic belt (Bartley, 1989).

Two models, synvolcanic rifting and caldera collapse, have been suggested to explain the north-south directed extension along the Warm Springs lineament (Bartley, 1989; Best and Christiansen, 1991). Both models relate the southward migration of volcanism to the change in orientation of the principal stresses. In these synvolcanic extension models, the change of the extension direction coincides in time and space with the location of the southward migrating volcanism. The models are different in the effect of volcanism on the orientation of rifting.

In the caldera collapse model, extension is local and episodic (Best and Christiansen, 1991). The synvolcanic extension is variably oriented in a pattern radial to the caldera(s). The synvolcanic extension occurs at the same time that the ash-flow tuffs are erupted from the major volcanic centers, typically located along the lineament, and is
associated with caldera collapse.

In the Bartley (1989) model, regional north-south extension occurs across the entire east-west trending Warm Springs lineament. This synvolcanic extension is perpendicular to the east-west trending belt of volcanism. In this model, the mantle is active and causes lithospheric thinning and uplift by heating from below. The thinning and uplift cause extension. The synvolcanic extension occurs at the same time that the ash-flow tuffs are erupted from major volcanic centers within the caldera complexes along the lineament.

Tertiary volcanic rocks in areas near the Caliente caldera complex, such as the South Pahroc Range (Scott and Swadley, 1992), the eastern side of Delamar Valley (Scott et al., 1990) and Rainbow Canyon in the Caliente caldera complex, show fanning of dips that range from 10 to 55 degrees total tilting (Scott et al., 1995a). This synvolcanic extension is localized in and around the Caliente and Kane Springs Wash caldera complexes and has been interpreted to be the result of caldera collapse. Normal faults radial and concentric to calderas commonly form during tumescence and collapse.

The orientation, magnitude of offset, and location of synvolcanic faults in the northern Hiko Range suggest that in this area north-south directed extension is a result of volcanism-related faulting, coinciding with the passage of the southward-migrating mid-Tertiary volcanic belt. This interpretation is preferred because of the large distance of the Hiko Range from volcanic centers. The study area is distant enough (> 20 km) from the Caliente and Kane Wash caldera complexes that caldera collapse radial faults are not a likely interpretation.
Synvolcanic extension in the northern Hiko Range is minor compared to prevolcanic and postvolcanic extension in the area. These data support localized synvolcanic extension and that classic active mantle rifting is not responsible for the majority of the extension observed in the Basin and Range province.

**Postvolcanic Tertiary (?) to Early Quaternary (?) Extension**

Regional east-west directed postvolcanic extension in the Tertiary is widely recognized (e.g., Stewart, 1978; Taylor et al., 1989; Best and Christiansen, 1991). However, postvolcanic Tertiary (?) to early Quaternary (?) extension along the Timpahute lineament is north-south directed and is accommodated by oblique-slip faults. I suggest that the Timpahute lineament has served varying structural roles since the Oligocene, and may be related to a much older crustal feature. Therefore, the fault strike is inherited and did not form normal to regional east-west extension.

Oblique-slip faults are documented in current rift environments (e.g., East African Rift system and the Gulf of California) and are interpreted as indicating a change in stress orientation (e.g., Uwe et al., 1992; Umhoefer and Stone, 1996). East-west-striking normal faults occur along the Timpahute lineament in the Timpahute Range (Bartley and Taylor, 1992) and along a large portion of the Warm Springs lineament in the Golden Gate and northern Seaman Ranges (Figs. 1 and 2) (Hurtubise, 1994; Overtoom and Bartley, 1994). Reorientation of stresses during the Oligocene is well documented in the Basin and Range province (Zoback and Zoback, 1980; Best et al., 1988a; Bartley, 1989, Overtoom and Bartley, 1996) and could account for activity along east-west striking
This change in extension direction during the Oligocene can be documented in the vicinity of the Hiko Range. The north-south directed extension documented along the Warm Springs lineament was active between 31 and 22 Ma with syntectonic volcanism (Fig. 4) (Bartley, 1989; Taylor et al., 1989; Best and Christiansen, 1991; Friedrich, 1993; Overtoom, 1994; Overtoom and Bartley, 1996). The north-south directed extension is interpreted to be formed by faulting related to the southward-migrating volcanism (Bartley, 1989; Best and Christiansen, 1991; Axen et al., 1993). North-south directed extension is also interpreted along the Timpahute lineament (Bartley and Taylor, 1992).

In the Timpahute Range, east-west striking normal faults cut the Hiko Tuff, the youngest tuff in the area (W. J. Taylor, personal communication, 1996). In the Hiko Range, the faults also cut the youngest tuff in the area, the Sunflower Mountain Tuff, and four of the faults cut Tertiary (?) - Quaternary alluvium of an unknown age.

The Warm Springs, Timpahute, and the Pancake Range lineaments and the Escalante zone, as well as other transverse structures, have been interpreted to have different roles in crustal extension (Fig. 1b and 4) (Duebendorfer and Black, 1992). Interpretations of transverse structures include (1) strike-slip transfer faults (e.g., Anderson, 1971; Burchfiel et al., 1989), (2) accommodation zones (e.g., Faulds et al., 1990), (3) fundamental, deep-seated crustal structures (e.g., Ekren et al., 1976; Stewart et al., 1977; Rowley et al., 1978), (4) structures that bound areas of contrasting extension (e.g., Duebendorfer, 1992), and (5) structures that serve as barriers to propagating younger normal faults (e.g., Bartley, 1989; Bartley and Taylor, 1992; Overtoom and
Bartley, 1996). The Timpahute lineament appears to have served different structural roles through time.

The Timpahute lineament, a zone about 20 kilometers wide, coincides with the southern boundary of the Oligocene Snake-Stampede extensional system (Fig. 2) (Axen et al., 1993; Scott et al., 1995a). This relationship suggests that faults within the Timpahute lineament were active during the Oligocene and that the boundary separated extended areas to the north from unextended areas to the south. About 15 Ma, the Highland extensional system extended the southern part of the "Oligocene" Snake-Stampede system (Fig. 2) (Bartley et al., 1988; Taylor, 1990) as volcanism migrated to the Kane Spring Complex. The southern boundary of the Highland detachment system (e.g., Bartley, 1988) appears to coincide with the Timpahute lineament (Fig. 2). This relationship suggests that faults along the Timpahute lineament were reactivated and/or new faults formed during activity along faults in the Highland detachment system. The Timpahute lineament once again served as a boundary that separated differentially extended areas to the north and south.

The southward sweep of volcanism moved from Oligocene volcanic centers and caldera complexes along the east-west oriented Warm Springs lineament to Miocene volcanic centers and caldera complexes south of the east-west oriented Timpahute lineament about 23 Ma (e.g., Best et al., 1989a). The Caliente caldera complex, located south of the eastern end of the Timpahute lineament (Fig. 4), erupted ash-flow tuffs, from about 23 to 13 Ma (e.g., Rowley et al., 1995). Episodic extension associated with caldera collapse is documented within and near the Caliente caldera complex (Best and
Regional north-south directed extension occurred along the Timpahute lineament mainly after the eruptions of ash-flow tuffs from the Caliente and Kane Springs Wash caldera complexes.

The tectonomagmatic model of Bartley (1989) is supported by data along the Warm Springs lineament (Hurtubise, 1994; Overtoom, 1994). However, in this study and another in the Timpahute Range (W. J. Taylor, unpublished data), the east-west-striking faults along the Timpahute lineament are postvolcanic. The synvolcanic rifting and caldera collapse models do not explain the postvolcanic extension along the Timpahute lineament, although the Bartley (1989) tectonomagmatic model does offer a way to change the stress orientation that is favorable.

If the change of regional principal stress is due to the presence of the southward sweep of volcanism, a slight modification of the Bartley tectonomagmatic model may explain the postvolcanic north-south directed extension along the Timpahute lineament. I suggest that temporal differences in stresses associated with synvolcanic rifting and the plate boundary permit north-south postvolcanic extension as discussed below. The plate boundary has changed during the Cenozoic, and thus, changes in the stress regime are predicted (cf., Stock and Molnar, 1988).

The area of the eastern Warm Springs lineament underwent east-west directed crustal extension during the Oligocene (e.g., Axen et al., 1993). Oligocene extension in that area preceded the migration of the volcanic belt to the Warm Springs lineament. When the volcanic belt was situated along the Warm Springs lineament, it stayed in that area for about 10 m.y., from about 35 to 25 Ma (Best et al., 1989b). The change of stress
along the Warm Springs lineament was fairly rapid and resulted in north-south directed synvolcanic faulting. For north-south directed extension to occur, the orientation of $\sigma_3$ must change from east-west to north-south. This change could happen by a decrease of stresses at the plate boundary, the stresses caused by tectonomagmatic rifting being larger than those transmitted from the plate boundary, or a combination of the two (Bartley, 1989).

In the area of the Timpahute lineament, no major east-west extensional system was active at the time when the volcanic belt migrated there; prevolcanic extension had ceased. However, during the last few million years of eruptions from volcanic centers in the Caliente and Kane Springs Wash caldera complexes (around 15 Ma), regional east-west directed extension was occurring along the Highland Detachment (Fig. 2) (Bartley et al., 1988). The volcanism stayed in this area for about 11 m.y., from about 24 to 13 Ma (Best et al., 1989a). However, this did not result in regional north-south synvolcanic extension, but synvolcanic caldera collapse extension did occur (e.g., Scott et al., 1995a). The stress added by the east-west trending volcanic belt and associated mantle processes was either not large enough to overwhelm the plate boundary stress, or the plate boundary stress did not decrease enough to allow the stress from the volcanic belt and the active mantle processes to change the regional stress field. It is possible that the stresses added by the volcanic belt still existed along the Timpahute lineament and that when plate boundary stresses decreased, the stress associated with the volcanic belt were large enough to change the regional stress field. In the area of the Timpahute lineament, this change happened to be after the major eruptions from the caldera complexes ceased, and thus,
was postvolcanic.

If the above scenario is accurate, it suggests that the stress system is governed at
the plate boundary. The plate boundary stresses must weaken before the volcanic-belt-
related stresses can control the stress system. In both the Timpahute and Warm Springs
lineaments, east-west directed extension predated north-south extension. The north-south
directed extension occurred on both lineaments only after the cessation of regional east-
west directed extension and may relate to a decrease in the stresses at the plate boundary.

Portions of the Timpahute lineament served different structural roles through time.
Faults along the Timpahute lineament were active since at least the Oligocene to the
present. The multiple episodes of activity suggest that the Timpahute lineament may be an
older crustal feature that has been reactivated repeatedly. Devonian and Mississippian
rocks pinch out or change facies to the south of the Timpahute lineament. The Pilot Shale
and the Chainman Shale both pinch out south of the lineament (Poole and Sandberg, 1991;
Johnson et al., 1991). The West Range Limestone changes facies, from siltstone and silty
limestone north to just silty limestone south of the lineament (Johnson et al., 1991). The
Mesozoic Roberts Mountain thrust has an east-west trending southern border near the
latitude of the Timpahute lineament (e.g., Stewart, 1980). During the Oligocene and then
later in the Miocene, the southern boundaries of two separate major crustal extensional
systems coincided with the Timpahute lineament (e.g., Taylor, 1990; Scott et al., 1995a).
Also in the Miocene, the southward migrating belt of volcanism occupied the area of the
east-west-trending Timpahute lineament for about 11 m.y. (e.g., Stewart et al., 1977; Best
et al., 1989a). Following the cessation of volcanism, north-south directed extension
occurred on the Timpahute lineament. The Timpahute lineament also coincides with the western continuation of the intermountain seismic belt, a zone of recent seismic activity (e.g., Smith and Sbar, 1974; Ekren et al., 1976). These relationships suggest a possible pre-Devonian structural control for the Timpahute lineament. One possibility is that the Timpahute lineament is related to a oceanic transform or a continental transverse fault, or both, that formed during Precambrian rifting of western North America (e.g., Burchfiel and Davis, 1972; Stewart and Poole, 1974; Burchfiel and Davis, 1975; Stewart, 1976; Levy and Christie-Blick, 1989).

Four east-west trending lineaments in the Great Basin have been interpreted as older reactivated crustal structures. These lineaments include the Pritchards Station, Pancake Range, and Warm Springs lineament and the Escalante zone (Fig. 1b and 4). The structures correspond to (1) a boundary between different lithologies of Precambrian crystalline rocks, (2) a boundary between Paleozoic sedimentary rock facies, (3) a boundary of Mesozoic thrusting, and (4) Cenozoic fault zones and boundaries between differentially extended terranes (e.g., Ekren et al., 1976; Rowley et al., 1978; Jayko, 1990).

The east-west trend of the lineaments may be inherited. Recent studies reveal that many rift structures are preserved in basement rocks along passive margins and include transverse faults (e.g., Lister et al., 1986; Thomas, 1993; Froitzheim and Manatschal, 1996). The spacing of oceanic transforms, which can pass into a rifting continent as transverse faults (Lister et al., 1986), is on the order of 10's of km and is consistent with the spacing of east-west trending lineaments in Nevada (Fig. 1b) (e.g., Atwater, 1989;
Thomas, 1993; Froitzheim and Manatschal, 1996). Therefore, the lineaments in Nevada may represent transverse and transform faults formed during Precambrian rifting and represent basement structures that have been repeatedly reactivate through time. The Timpahute lineament is interpreted to be a transfer or transform fault developed during Precambrian rifting of western North America.

In summary, the Timpahute lineament was active since at least the Oligocene to the present and served varying structural roles through time. Oblique-slip faults along the Timpahute lineament are consistent with a change in the orientation of stress. Active-mantle models are somewhat inadequate at explaining postvolcanic north-south directed extension along the Timpahute lineament. The tectonomagmatic model of Bartley (1989) correctly explains the change in the stress orientation, but it does not account for postvolcanic faults in the Timpahute lineament. If stresses from the east-west trending volcanic belt and associated mantle processes persist in the crust for some time, then a decrease in plate boundary stresses is a prerequisite for volcanic-belt related stresses to control the system.

**Quaternary Extension and the Hiko Fault Zone**

Late Tertiary to Quaternary extension is widespread in the Basin and Range province and is responsible for the present day basins and ranges (e.g., Stewart, 1978; Eaton, 1982; Best and Christiansen, 1991; Axen et al., 1993). Seismically active range-bounding faults are of current interest because of the potential hazard these faults pose to people and their property. Detailed studies on active faults show that the identification of
fault segments reveals potential sites of earthquake hazards associated with these faults (e.g., Aki, 1994; Wallace, 1984; Coppersmith and Schwartz, 1984; King, 1986; Crone and Haller, 1991; DePolo et al., 1991; Machette et al., 1991; Zhang et al., 1991; Wu and Bruhn, 1994). The Hiko fault zone is here shown to be a segmented range-bounding fault that cuts Quaternary-Pliocene (?) sedimentary deposits (Fig. 3; Plate 1), and thus, it may pose a seismic threat.

Fault segments and the boundaries between them can be geometric, structural, or behavioral (e.g., Coppersmith and Schwartz, 1984; DePolo et al., 1991) and are scale dependent. Fault segments have been described at various scales with varying criteria, which has lead to confusion. Therefore, it is important to define the term segment. A segment, in this study as used by other authors (e.g., Susong et al., 1990), is structural and is defined by discontinuities along a fault. The discontinuities occur at the end of the fault segment and include fault bifurcation, intersections with other faults, and terminations at transverse structures. As defined, segments have lengths of 10's of kilometers. The segment boundary as used in this study and others (e.g., Susong et al., 1990; Machette et al., 1991; Zhang et al., 1991) is also structural and is defined by bedrock salients, increase in the number of faults and the width of the fault zone, increase in fault complexity, and changes of orientation of the range front and valley floor. The segment boundary is at a scale of kilometers.

The majority of the Hiko fault zone in the study area, from Crystal Wash to Hiko Canyon, is a structural segment boundary, here named the Hiko segment boundary (Fig. 3; Plate 1). The Hiko segment boundary is a wide area along the Hiko fault zone that
contains up to ten faults strands and has five or more fault strands over the majority of its length. The Hiko segment boundary also corresponds to a salient and has a transverse ridge or spur of bedrock at both Crystal Wash and Hiko Canyon (Plate 1). The overall trend of the Hiko Range and the White River changes from north-northwest to the south of Crystal Wash to north-northeast to the north of Hiko Canyon along the Hiko segment boundary (Fig. 3). Portions of two fault segments are present in the field area. The northern segment, here named the Hiko Canyon segment, strikes north-northeast. The southern segment, here called the Crystal Wash segment, strikes north-northwest. Faults related to these two segments breached the Hiko segment boundary, and therefore, the boundary is a leaky segment boundary or leaky barrier.

Structural barriers (structural segment boundaries) at the scale of kilometers can physically interfere with the propagation of a fault rupture (Sibson, 1987; Sibson, 1989). These types of structural barriers can persist for millions of years (Machette et al., 1991). These barriers can eventually be partially or completely breached by faults and form leaky barriers (Crone and Haller, 1991). The leaky barriers allow partial or complete rupture of an adjacent fault segment (e.g., Crone et al., 1987; Ostenaa, 1990).

Fault segmentation has been applied at smaller scales on segments and the smaller pieces have been called fault sections (e.g., Machette et al., 1991). Identification of smaller scale sections along fault boundaries is important because they may be terminations for partially ruptured segments and are thought to control earthquake behavior (e.g., Wallace, 1984; Coppersmith and Schwartz, 1984; DePolo et al., 1991).

Five fault sections (A, B, C, D, and E) and four fault section boundaries (AB, BC,
CD, and DE) are identified in the study area (Fig. 12). The fault sections are kilometers long and are structural. The structural section is defined by a bend in the Hiko fault zone at both ends of the section. The bends are associated with transverse footwall structures, and thus are also structural. The structural section boundaries are areas of fault bifurcation with or without fault termination. Faults in the southern section, called section E, strike north-northwest and north-northeast. Sections C and D are part of the Hiko segment boundary (Fig. 12). Sections A and B are part of the Hiko Canyon segment (Fig. 12).

In summary, the Hiko fault zone in the field area consists of the structural Hiko segment boundary and portions of the Hiko Canyon and Crystal Wash structural segments. The interpretation of the Hiko segment boundary as a leaky boundary, poses a greater chance for earthquake damage to the community of Hiko, Nevada, because fault seismic activity and fault rupture on one segment can be transferred to the other segment.
Figure 12. Generalized fault map of the study area showing the relationships among fault segments, segment boundaries, fault sections, and section boundaries. Bifurcation of fault strands, intersections or terminations, or both, with transverse structures define section boundaries. Gray area represents Paleozoic and Tertiary rock outcrops in the Hiko Range. White area represents valley fill. Dark gray area represents fluvial and lacustrine deposits of the White River. The topographic lows of Crystal Wash and Hiko Canyon are denoted by white lines in the Hiko Range. Heavy weight black lines are faults and fault zones. The Hiko fault zone consists of fault strands in the Hiko segment boundary and Crystal Wash and Hiko Canyon segments (Figure 3) and smaller fault sections A through E. Heavy dashed black lines are inferred faults. Ball and bar on downthrown side of faults. Dark gray lines depict major highways.
Sedimentological studies of basins in extensional settings reveals distinct geometries and facies distributions for sediments filling a subsiding half graben (Leeder and Gawthorpe, 1987). Data from the Hiko Range, other studies, and comparison to a nearby basin supports the interpretation that the Pahranagat Valley is a half graben or an asymmetrical graben bounded on the east by the Hiko fault zone (Fig. 13). The term "half graben" is synonymous with asymmetrical graben in this paper and is defined as a graben with one of the bounding faults active and major, and the opposing bounding fault subsidiary, inactive, or nonexistent. In this case, the Hiko fault zone is the active or major fault.

The half-graben extensional and depositional models with internal and external drainage of Leeder and Gawthorpe (1987) is exemplified by Pahranagat Valley basin fill. The models for a continental basin with internal or external drainage (Figs. 14 and 15) show an asymmetry of sedimentary deposits in an actively subsiding basin. Ponding and aggradation of coarse alluvial deposits occur adjacent to the controlling fault as seen in the formation of the Hiko Range. Alluvial fans near the subsidiary, inactive bounding fault, or unfaulted side of the basin aggrade and prograde into the basin with increasing fault offset. These fans have much longer fan head-to-toe widths than the alluvial fans adjacent to the controlling fault, as observed in the Mail Summit Road subunit. Predominantly fine-grained deposits (fluvial, pluvial, distal alluvial deposits, or a combination of these) form
the majority of the sediments in an actively subsiding half-graben basin, as in the
Pahranagat Valley subunit. This sediment distribution present in the Pahranagat Valley
also is recorded to the north in the White River Valley (DiGuiseppi and Bartley, 1991).

Two main differences distinguish the internal and external drainage models. In the
half-graben model of a continental basin with internal drainage (Fig. 14), the aggradation
of fine-grained deposits (lacustrine, fluvial, or distal alluvial deposits, or combinations of
these) occurs in the deeper parts of the basin relatively near the major fault with increasing
displacement on that fault. In the half-graben model for a continental basin with external
drainage (Fig. 15), aggradation and shifting of the active axial drainage channel, in the half
graben, toward the fault scarp occurs with increasing displacement on the controlling
fault. The models predict deposition of distinct sedimentary packages at specific sites
within a half-graben basin.

Evidence that the Pahranagat Valley is a half graben is (1) the asymmetry of basin
sediments; (2) the very low sinuosity of the White River; (3) the Hiko fault zone on the
east side of Pahranagat Valley and no similar exposed fault on the west side; (4) the
location of the White River, oriented parallel to the axis of Pahranagat Valley, near the
eastern margin of the valley adjacent the Hiko fault zone; and (5) the spatial association of
linear bluffs, interpreted to be a fault scarp of the Hiko fault zone, and displacing the Hiko
Range and Pahranagat Valley subunits near the eastern margin of the valley (Figs 2 and
16). Field data from the Hiko Range show that the basin history of Pahranagat Valley has
similarities to and differences from that of the White River Valley.

The valley fill exposed in Pahranagat Valley consists of older fluvial deposits
(Qso), distal alluvial deposits, or both that are called the Pahranagat Valley subunit (Fig. 16). These deposits are conformably overlain by younger alluvial deposits that are here referred to as the Mail Summit Road and the Hiko Range subunits (Fig. 16) (Appendix B). The Pahranagat Valley subunit is a volcanic-rich sandstone. The unit (> 5 m thick) contains clasts of the tuff of Hancock Summit, which occurs only north and west of the study area, suggesting transport from the west or north, or both to the east or south, or both (see Appendix B). The unit strikes north-northwest to northeast and dips up to 10 degrees to the west or east. The subunit is interpreted to represent fluvial deposits in a pre-White River drainage with a transport direction to the south. A transport direction to the east is not considered because the Hiko Range (the footwall highlands) forms a topographic barrier. Located east of the White River, is the Hiko Range subunit (Figs. 3 and 16; Plate 1). It is composed predominantly of conglomerate and dips gently, mostly to the west. This subunit is interpreted as an alluvial fan deposit sourced in the Hiko Range (Appendix B). Located west of the White River (Figs. 3 and 16) is the Mail Summit Road subunit. It is composed dominantly of conglomerate and dips gently, mostly to the east. The subunit is interpreted as alluvial fan deposits sourced in the Pahranagat and Mount Irish Ranges and is temporally correlative with the formation of the Hiko Range (Appendix B).

The end results of the half-graben models of Leeder and Gawthorpe (1987) depict what is observed in the field area and other areas in Pahranagat Valley (Figs. 14 and 16). The aggradation of the Pahranagat Valley subunit and the aggradation and progradation of the Hiko Range subunit to the west and Mail Summit Road subunit to the east display
geometries and locations consistent with an internal drainage pattern for a half graben
(Leeder and Gawthorpe, 1987). A cessation of alluvial fan deposition, due to a change in
climate or a drop in base level of the valley, or both, resulted in the preservation of nearly
planar fan surfaces on top of the Hiko Range and Mail Summit Road subunits. The
incision of these basin units coincides with the development of a southward external
drainage pattern (the White River) (Figs. 15 and 16) and the capture of this drainage by
the Colorado River system (DiGuiseppi and Bartley, 1991), and thus, a change of base
level. The change of base level may not have been accomplished until a change in climate
or capture of adjacent basins by the White River, or both, resulted in a larger discharge
that was capable of eroding nick points. The development of the southward drainage of
the White River is recorded in White River Valley north of Pahranagat Valley (Fig. 2)
(DiGuiseppi and Bartley, 1991).

The White River Valley (Fig. 2) contains syntectonic and post-tectonic basin
deposits that fit well with the sediment facies expected for an extensional half-graben basin
(DiGuiseppi and Bartley, 1991). Comparison of basin sediments and tectonic evolution
with the development of the White River drainage system in both valleys provides age
constraints for basin-fill sediment and tectonic evolution in the Pahranagat Valley.
Detailed sedimentological studies in the White River Valley (DiGuiseppi, 1988) show that
syntectonic sediments are predominantly fine grained. Internal drainage predominated
during extension, and after extension an external drainage system developed (DiGuiseppi
and Bartley, 1991). The syntectonic sedimentary deposits are informally referred to as the
White River Narrows Formation and are Pliocene to Quaternary in age (DiGuiseppi, 1988;
Scott et al., 1995b). The White River Narrows Formation consists of an upper and lower sandstone member and middle silty carbonate mudstone member. The sandstone members are interpreted to represent distal alluvial fan deposits, and the silty carbonate mudstone represents a lacustrine environment (DiGuiseppi and Bartley, 1991). Coarse alluvial deposits of the White River Narrows Formation occur only adjacent to the east-dipping Pahroc fault that bounds the west side of the basin. Syndepositional slip along the Pahroc fault resulted in the ponding and aggradation of the coarse alluvial deposits. Only after faulting ceased did the coarse conglomerate deposits prograde into the White River Valley. A change in base level for the valley resulted in the formation of an external drainage for the basin, the White River (DiGuiseppi and Bartley, 1991). The Pahranagat Valley contains basin deposits similar to the basin deposits in the White River Valley.

The Pahranagat Valley subunit is similar in lithology to the upper and lower sandstone members of the White River Narrows Formation. The fact that the White River Narrows Formation is fine grained and a syntectonic unit suggests that the fine-grained sediments of the Pahranagat Valley subunit may also be syntectonic. It is also possible that the coarse-grained deposits in Pahranagat Valley are syntectonic.

A possible or likely scenario for the depositional and tectonic development of Pahranagat Valley is here proposed. Movement along the Hiko fault zone on the west side of the Hiko Range formed a half graben. The age of slip onset of the Hiko fault zone and the depth of basin fill are unknown, so older internal basin fill may have been deposited below the Pahranagat Valley subunit. A period of tectonic quiescence resulted in sediment of the Pahranagat Valley subunit filling of the basin and development of its
external drainage system that pre-dated the White River southward drainage system. It is likely that the Pahranagat Valley was externally drained at this time, because the Pahranagat Valley subunit is interpreted as fluvial rather than alluvial deposits (see Appendix B). Renewed fault activity on the Hiko fault zone resulted in a change from external to internal drainage and is depicted by progradation and aggradation of the basin fill of the Hiko Range subunit on the east side of the valley and the Mail Summit Road subunit on the west side of the valley. A change in climate also could have resulted in the progradation and aggradation of the conglomeratic units, as was suggested for the White River Valley (DiGuiseppi and Bartley, 1991). A fluvial system (the White River) developed on top of the alluvial basin fill. The new fluvial system connected basins with previous internal drainage to an external drainage system. The capture of the White River by the Colorado River drainage system changed the base level of the connected basins (Bohannon, 1984; DiGuiseppi and Bartley, 1991). This change of base level resulted in downcutting of the White River and its tributaries and the incision of the earlier basin fill, the Pahranagat Valley, Mail Summit Road, and Hiko Range subunits. The incision and development of the external drainage resulted in the preservation of alluvial fan surfaces. The alluvial fan surfaces in the Hiko Range subunit are offset by the Hiko fault zone. It is possible that the Hiko fault zone was active during the transition from internal to external drainage in the Pahranagat Valley. A detailed sedimentological study of the basin deposits in the Pahranagat Valley is needed to determine the effect of climate, basin subsidence, the change from internal to external drainage in the evolution of the Pahranagat Valley, and to test above scenario.
Figure 13. Schematic cross-sections of a graben, an asymmetric graben, and a half graben.
Figure 14. Schematic block diagram of a continental half graben with internal drainage (redrawn and modified from Leeder and Gawthorpe, 1987).
Figure 15. Schematic block diagram of a continental half graben with internal drainage (redrawn and modified from Leeder and Gawthorpe, 1987).
Figure 16. Generalized schematic block diagram of the proposed half graben in Pahranagat Valley. Not to scale. White area represents Paleozoic and Tertiary rocks.
CHAPTER 7

SIGNIFICANCE OF STUDY

This study has implications for both basic and applied geology. The basic research impacts the origin and structural role of transverse fault zones. This work may be applied to the occurrence of hydrocarbons and the identification of seismic hazards associated with young normal faults.

The tectonic evolution and development of continental rifts includes transverse faults and their importance has only just recently been recognized (e.g., Wernicke et al., 1982, 1984; Gibbs, 1984; Lister et al., 1996; Faulds et al., 1990; Duebendorfer and Black, 1992). The role of transverse structures in extension can be (1) strike-slip transfer faults (e.g., Anderson, 1971; Burchfiel et al., 1989; Duebendorfer and Black, 1992), accommodation zones (e.g., Bosworth, 1985; Faulds et al., 1990), (3) reactivation of older crustal structures (e.g., Ekren et al., 1976; Ron et al., 1986), or (4) separations of areas with contrasting orientations of extension (e.g., Bartley, 1989; Bartley et al., 1992; Overtoom and Bartley, 1996).

The structural role of major transverse structures in the Basin and Range province, such as the Timpahute and the Warm Springs lineaments, must be fully explained for a complete understanding of continental rifting. The Timpahute lineament has been shown
to be a strike-slip transfer fault during the Oligocene (Axen et al., 1993; Scott et al., 1995a) and again during the Miocene (Bartley, 1988; Taylor, 1990). Later in the Miocene, the lineament was an area with north-south orientation of extension (Bartley and Taylor, 1991; this study). Thus, some transverse structures may have served more than one role in continental extension through time. An interpretation of the tectonic role from one area along a transverse fault may not be the same as for another area, although spatial and temporal differences need a geologically sound explanation. Also, the Timpahute lineament, as well as other east-west-trending lineaments, zones, and systems, may have formed during Precambrian rifting of western North America.

The geology and structures in the northern Hiko Range are similar to the geology and structures in and around the producing oil fields in Railroad Valley (Fig. 4). In Railroad Valley, hydrocarbons sourced from the Mississippian Chainman Shale and Eocene Sheep Pass Formation have been produced from reservoirs in Oligocene volcanic rocks, the Sheep Pass Formation, and Devonian to Pennsylvanian marine rocks, including the Sevy and Simonson Dolomites and the Guilmette Formation (Poole et al., 1983; Poole and Claypool, 1984; Flanigan, 1988; Read and Zogg, 1988). The oil traps are structural with most oil production corresponding to areas of topographic highs buried beneath valley fill (Bortz and Murray, 1979; Foster, 1979; Flanigan, 1988). All the reservoirs on the east side of Railroad Valley are complexly faulted and brecciated fault blocks (Bortz and Murray, 1979; Poole and Claypool, 1984; Veal et al., 1988; Hulen et al., 1991; Lund et al., 1993). Studies generally relate the oil traps to horst and graben structures formed during Cenozoic extension (e.g., Bortz and Murray, 1979; Flanigan, 1988; Foster and
Vincelette, 1991; Lund et al., 1991), but more recently transverse faults have been considered important to hydrocarbon trapping (e.g., Harding, 1984; Morley, 1989; Nelson et al., 1992; Johnson, 1993; Lund et al., 1993; Grabb, 1994; McCutcheon and Zogg, 1994).

The east-west trending Pancake Range and Pritchards Station lineaments pass through Railroad Valley and are expressed by generally east-west striking faults in the Pancake, Grant, Horse, and White Pine Ranges (Fig. 4) (e.g., Moores, 1968; Ekren et al., 1976; Langrock, 1995). These faults have geometries similar to the faults in the Timpahute lineament in the Hiko Range. The majority of Paleozoic rocks in the northern Hiko Range consist of the Sevy and Simonson Dolomites and the Guilmette formation. Reservoir rocks in Railroad Valley include these units. Therefore, the structures mapped in the northern Hiko Range may aid in understanding buried faults in Railroad Valley that produce the structural traps for hydrocarbon accumulations, but such an undertaking is beyond the scope of this study.

The community of Hiko lies within the western extension of the Intermountain seismic belt (Smith and Sbar, 1974). Earthquakes on faults in this area are typically small, however, a magnitude 6.0 earthquake occurred in the Clover Mountains in 1966 (Fig. 2) (Gawthrop and Carr, 1988). The potential for seismic activity along the Hiko fault zone exists. The fault in this area has not moved in historical times and does not displace rock units younger than the Pliocene (?) - Quaternary alluvium. The age of the fault is poorly constrained, and it is not clear if it is still active. Because the fault has not moved in such a long time, the fault is either inactive or it is due for another event soon.
Mapping along the Hiko fault zone reveals the potential of seismic hazards to Hiko, Nevada. The identification of the Hiko segment boundary next to Hiko is important because segment boundaries are the sites where earthquakes begin or end. Therefore, seismic activity on either the Crystal Wash or Hiko Canyon segment will effect this town. Because the Hiko segment boundary is interpreted to be leaky, the potential is larger for more than one of the segments to rupture during a seismic event. The main types of seismic hazards to the town of Hiko include liquefaction, surface ruptures and associated ground shaking. Minor rockfalls may also occur.

The majority of the buildings in Hiko are built on unconsolidated fluvial and lacustrine deposits of the White River and its flood plain. If these fine-grained deposits are saturated during a seismic event along the Hiko fault zone, then these deposits may behave as a liquid and flow, a process called liquefaction. Ground water levels in the area are high as evidenced by the presence of the perennial Frenchy and Nesbitt lakes. Also, the irrigation used to grow agricultural crops in the area increases the saturation of the sediments. Liquefaction can cause buildings to tilt or sink and buried tanks and pipes may float to the surface.

Surface ruptures and associated ground shaking can cause structural damage to buildings, buried tanks, and pipelines. The Hiko fault zone crosses U.S. Highway 93 near Crystal Wash and surface ruptures in the road would be a serious hazard to vehicles and people within them.

Rock falls are probably not a great threat to Hiko, but a few houses are built next to the range front. Rock falls onto U.S. Highway 93 near Crystal Wash are another
potential hazard to motorists and this major transportation and supply route.
CHAPTER 8

SUMMARY AND CONCLUSIONS

The structural history of the northern Hiko Range is defined by Mesozoic contraction and Cenozoic extension and volcanism. A Mesozoic contractional event and four temporally distinct episodes of Cenozoic extension were documented in the field area through detailed geologic mapping; retrodeformable cross sections; and geometric, kinematic, and temporal analysis of faults. The Cenozoic extensional events are prevolcanic, synvolcanic, postvolcanic, and Pliocene (?) - Quaternary.

Folds in Paleozoic units are prevolcanic in age. Based on structural and geographic associations, the folds are interpreted as footwall deformation related to the Mesozoic central Nevada thrust system, whose thrusts crop out to the west of the Hiko Range.

The folds are cut by Oligocene prevolcanic faults. The Oligocene Snake-Stampede extensional system is the oldest regional extension documented near the Hiko Range and the first tectonic event after Mesozoic contraction. Prevolcanic faults in the northern Hiko Range are interpreted as footwall faults to the Snake-Stampede extensional system. Documenting the occurrence of these faults increase the area known to be affected by this extensional system and supports existing evidence for widespread Oligocene extension.
The presence of these faults suggest that a continuation of the Seaman breakaway fault for
the Snake-Stampede extensional system is located to the east of the northern Hiko Range.

Synvolcanic faults are the least common type of faults in the field area. The minor
displacement and rarity of these faults support existing evidence that synvolcanic extension
is minor compared to prevolcanic and postvolcanic extension. The east-west strike of
these faults suggests a change in orientation of the stresses, causing first east-west
directed then north-south directed extension. The synvolcanic rifting model of Bartley
(1989) best explains these faults.

Postvolcanic faults occur along the Timpahute lineament. These east-west-striking
oblique-slip faults indicate a change of the horizontal principal stress direction during the
Miocene. A modification of the synvolcanic rifting model of Bartley (1989) best explains
these faults. Modification is required because the extension is not synvolcanic. If plate
boundary stresses controlled extension in the Basin and Range province, then only when
this stress decreases relative to mantle stresses from the southward sweeping volcanic belt
can regional north-south directed extension occur. The north-south postvolcanic
extension along the Timpahute lineament is interpreted to be faulting associated with the
southward passage of a volcanic belt (Bartley tectonomagmatic model). The stresses from
the volcanic belt and associated active mantle processes were less than plate boundary
stresses until after eruption from volcanic centers along the Timpahute lineament ceased.
Thus, north-south directed extension on the Timpahute lineament is postvolcanic and
occurred when east-west directed extension had ceased.

The Timpahute lineament corresponds to boundaries between facies and
thicknesses of Paleozoic rocks, the southern boundaries to the Oligocene Snake-Stampede and Miocene Highland extensional systems, an area of north-south directed Miocene extension, and a zone of seismic activity. These relations suggest that the Timpahute lineament effected in the Devonian and sedimentation patterns may have been reactivated episodically through time. Because of protracted episodic movement along the lineament, it is suggested here that the Timpahute lineament is a deep crustal structure, probably related to transverse and or transform faults formed during Precambrian rifting. Transverse faults are fundamental to extensional models and must be fully explained before continental rifting can be completely understood.

The geology and structural complexity of the northern Hiko Range is potentially analogous to structural traps and reservoir rocks in the oil fields in Railroad Valley. Applying the geometry of exposed structures in the northern Hiko Range can aid hydrocarbon exploration.

The Hiko fault zone in the field area consists of the Hiko segment boundary and portions of the Crystal Wash and Hiko Canyon fault segments. The identification of segment boundaries are important in evaluating seismic hazards because they are the sites of earthquake initiation and termination. The Hiko segment boundary is a leaky barrier to the propagation of faults and is breached by the fault segments. Leaky segment boundaries can allow seismic activity from one segment to cross over on to another. The town of Hiko, Nevada, is located next to the Hiko segment boundary. Seismic risks to the community of Hiko include liquefaction, ground shaking, surface rupture, and rock falls.
APPENDIX A

METHODS

The methods employed during this study include geologic mapping, cross-section construction, stereonet analyses, and thin section point counting. These methods constitute the entire data collection and subsequent analyses for this project. A short description of each method follows.

**Geologic Mapping**

Geologic mapping was the basic data collection technique used in this study. I mapped 18 square miles (approximately 29 square kilometers) in the northern Hiko Range, Lincoln County, Nevada, at a scale of 1:24,000. Geologic data was placed on the Ash Springs, USGS 7.5 minute topographic quadrangle base map, using standard geologic mapping techniques. I used black and white aerial photographs to aid in locating geologic features.

**Cross-Section Construction**

Cross sections were produced to generate a three-dimensional view of strain, in conjunction with the geologic map. Retrodeformable cross sections were constructed using standard cross-section techniques. Fault orientations were calculated using the
three-point method or structure contour method where fault surface attitudes could not be measured. Cross sections were balanced using line length extensional balanced cross-section techniques (e.g., Rowand and Kligfield, 1989; Nunns, 1991). Cross sections D-D' and E-E' (Figs. 11d and 11e) do not and should not balance because material has moved through the pane of the section, and thus violates plane strain assumption of cross-section balancing.

**Stereonet Analyses**

Mean and mode fault set orientations were calculated using R. Allmendinger's (1989) stereonet program for the MacIntosh, version 4.3. Plots generated from this program aided in the interpretation of the extensional history and kinematic links of faults in the northern Hiko Range.

**Point Counts**

Point counting of thin sections of Oligocene and Miocene ash-flow tuffs exposed in the field area, in conjunction with stratigraphic field relations, was performed to correlate units with regional ash-flow tuffs. Ash-flow tuff samples were collected, cut into billets on a masonry trim saw, and made into thin sections. Thin sections of the Tertiary ash-flow tuffs were examined using a petrographic microscope. The thin sections were point counted for rock constituents using a fixed grid and a spacing of two millimeters between points. For all but one of the samples, two thin sections oriented at 90 degrees to each other, and perpendicular to the rock's foliation, were used to minimize the differences in volume percentages caused by grain distribution within the rock. Samples HR92-1,
HR94-2, HR94-3, HR94-4, and HR94-5 have over 1,000 points per sample. Sample HR95-22 only had one thin section counted for over 300 points. The remaining units were counted for at least 600 points per sample. Both modal and volume percentages for each sample were determined (see Table 1).
APPENDIX B

STRATIGRAPHIC DESCRIPTIONS

Stratigraphic units in the study area consist of Paleozoic rocks that are unconformably overlain by Oligocene and Miocene volcanic rocks. Pliocene (?) to Quaternary sedimentary rocks and deposits unconformably overlie both Paleozoic and Tertiary volcanic rocks. The Paleozoic rocks are part of the passive margin sedimentary sequence and consist of marine limestone, dolomite, shale, and sparse sandstone or quartzite (Tschanz and Pampeyan, 1970). The Oligocene and Miocene volcanic rocks are regionally widespread ash-flow tuffs and range in age from 27 to 15 Ma (Cook, 1965; Noble and McKee, 1972; Marvin et al., 1973; Fleck et al., 1975; Novak, 1984; Best et al., 1989; Taylor et al., 1989; Scott et al., 1995a). Descriptions of rocks units in the field area are given below.

Paleozoic Sedimentary Rocks

Devonian and Mississippian marine platform rocks crop out in the field area. Units were mapped based mainly on rock type and correspond to regional rock units (Tschanz and Pampeyan, 1970). Detailed sedimentological analyses of these units are beyond the scope of this study. Map units are described below for field recognition. Regional
thicknesses for these units are provided below (e.g., Tschanz and Pampeyan, 1970) because upper and lower contacts are not exposed.

**Devonian Sevy Dolomite (Dse)**

The Sevy Dolomite consists of whitish gray weathered, tan- to pinkish gray fresh, fine-grained dolomite. Beds are 15 cm to 1 m thick and contain rare 1- to 5- mm thick laminations. Unit is generally devoid of fossils and forms steep, step-like slopes. Unit is approximately 430 m thick. The basal contact is not exposed in the field area. Unit was named by Nolan (1935).

**Devonian Oxyoke Canyon Sandstone (Do)**

The Oxyoke Canyon Sandstone is an orange-brown to dark-brown weathered, light-brown-gray fresh, fine- to medium-grained quartz-rich sandstone with either carbonate or silica cement. Contains many cross beds, up to 10 cm thick, at 10- to 25-degree angles to bedding that are truncated at the top. Sole marks are common. Unit is approximately 18 m thick in the field area. The contact with the underlying Sevy Dolomite is the base of the first dominantly quartz sandstone or quartzite bed with the top of a dolomite bed. The contact is sharp and conformable. Unit was named by Nolan (1935).

**Devonian Simonson Dolomite (Dsi)**

The Simonson Dolomite consists of dark-gray weathered, lighter fresh, coarse-grained dolomite interbedded with light-gray weathered, darker fresh, fine-grained
Devonian Guilmette Formation (Dg)

The Guilmette Formation is a dark-gray weathered, generally darker fresh, coarse-grained dolomite and limestone alternating with light-gray weathered, usually lighter fresh, fine-grained dolomite and limestone, and medium-gray to bluish-gray weathered, darker fresh, medium-grained dolomite and limestone. Beds are 20 cm to 1 m thick, with some massive dark-gray, medium-gray, and bluish-gray beds up to 10 m thick. Laminations, 1 to 5 mm thick, occur in most beds.

The Alamo breccia described by Warme et al. (1991) is present in the lower portion of the Guilmette Formation and crops out on the west side of the Hiko Range near Crystal Wash. The Alamo breccia is normally graded and contains clasts of dolomite. At the southwest corner of Crystal Wash, the Alamo breccia contains clasts of a yellowish
gray weathered, medium-brownish gray fresh, thin-bedded, silty dolomite that appear to be from the yellow slope former that regionally occurs at the base of the Guilmette Formation.

The upper portion of the unit contains numerous orange-brown to dark-brown weathered, tan-gray fresh, medium-grained quartz-rich beds, with either carbonate or silica cement, that pinch out along strike. The quartz-rich beds are 1 mm to approximately 30 m thick and contain cross beds at 5 to 20 degree angles to bedding that are truncated on top. This sandstone-rich portion of the unit is equivalent to the sandy limestone facies of Tschanz and Pampeyan (1970).

The unit is commonly silicified and brecciated where cut by faults, and red-orange to dark-brown weathered, yellow-gray to light-gray fresh, in these fault and stratabound jasperoids. The unit forms steep, step-like slopes and cliffs and is approximately 800 m thick. The basal contact is not exposed. The unit was named by Nolan (1935).

Devonian/Mississippian West Range Limestone and Pilot Shale (Mp)

The West Range Limestone, which makes up approximately 95% of the map unit, is red-gray to pale yellow-orange weathered, yellow-gray to tan-gray fresh, fine-grained, platey limestone, siltstone, and shale. Beds are 2 to 150 mm thick with laminations in some of the thicker beds. Brachiopod, gastropod, bryozoan, and crinoid fossils are common. The Pilot Shale, which makes up approximately 5% of the map unit, consists of medium-gray weathered, dark-gray to black fresh, calcareous shale. Beds are 2 mm to 1 cm thick with laminations in the thicker beds. The unit is approximately 75 m thick and
forms slopes. The basal contact is not exposed. Spencer (1917) defined the Pilot Shale and Westgate and Knopf (1932) defined the West Range Limestone.

I chose the duel name for the unit because Tschanz and Pampeyan (1970) included the West Range Limestone in the Pilot Shale, but the majority of the unit more closely resembles the West Range Limestone at the type section as described by Westgate and Knopf (1932). Only the top 5 m of the unit in the field area resembles the type section of the Pilot Shale described by Spencer (1917).

**Mississippian Joana Limestone (Mj)**

The Joana Limestone is a blue-gray to medium-gray weathered, lighter fresh, medium- to coarse-grained limestone. Beds are 20 cm to 15 m thick. The thin beds commonly contain 1- to 5-mm-thick laminations and the thicker beds are commonly homogeneous. Crinoid fossils, ranging from 1 to 10 mm in diameter, are abundant. Bryozoan and coral fossils also occur. Dark-gray to dark-red chert nodules and beds are locally present. The unit forms step-like slopes and cliffs. The unit is at least 25 m thick and the upper portion is eroded away below the sub-Tertiary unconformity. The regional thickness of the unit is approximately 175 m. The basal contact is defined as the bottom of a blue-gray to medium-gray, coarse-grained massive limestone and the top of a yellowish-gray to dark-gray silty or platey limestone or shale.

**Tertiary Volcanic Units**

The Oligocene stratigraphic sequence consists of regional rhyolitic, dacitic, and trachytic ash-flow tuffs. The Miocene stratigraphic sequence consists of regional rhyolitic
and dacitic ash-flow tuffs. Textural, mineralogic, and outcrop features observed in the study area are described below. Modal and volume percentages of components in each unit were determined from point counts (Table 1). Modal percentages are used in descriptions.

**Oligocene Monotony Tuff (Tm)**

The Monotony Tuff is a light-gray to light-yellow-gray weathered, light-gray to pink-gray fresh, moderately welded, dacitic ash-flow tuff. Welding decreases downward over lower 5 m to a nonwelded base. Unit contains about 5%, 5 to 20 mm across, white to very-light-gray pumice that decreases upward to < 1% and yellow-tan spherulites, up to 10 mm across, some of which are weathered away to form voids. Compaction foliation is not obvious. Unit has 42.7% phenocrysts, consisting of 9.1% quartz up to 2 mm across, 6.7% sanidine up to 2 mm across, 49% plagioclase up to 4 mm across, 24% biotite up to 5 mm across, 3.9% amphibole up to 2 mm across, 3.1% pyroxene up to 2 mm across, and 3.9% Fe-Ti oxides up to 1 mm across. Smaller and fewer phenocrysts occur near the base of the unit. The unit forms rounded slopes, is up to 15 m thick, is not laterally continuous, and unconformably overlies Paleozoic rocks. The unit is recognized by its stratigraphic position, abundance of phenocrysts, and size of phenocrysts (e.g., Cook, 1965).

The Monotony Tuff erupted from the southern Pancake Range in the central Nevada caldera complex (Fig. 4) (Ekren et al., 1972; Scott et al., 1995). $^{40}\text{Ar}/^{39}\text{Ar}$ dates on sanidine from this unit give an age of $27.31 \pm 0.03$ Ma (Best et al., 1989). Cook (1965) first described this unit and Ekren and others (1971) defined and named it.
Oligocene Baldhills Tuff Member of the Isom Formation (Tlp)

The Baldhills Tuff Member of the Isom Formation is a medium-gray, dark-gray, black, and orangish-red weathered; darker fresh, densely welded, trachytic ash-flow tuff. Welding grades downward over the lower 1 m to a medium-gray, partially welded base. A dark-gray to black vitrophyre, with an orangish red devitrified top, occurs above the partially welded base and is approximately 2 m thick. Pumice, up to 4 cm across, makes up about 10% of the unit. The pumice is blackish gray and vesicular in the partially welded zone, and yellowish tan in the densely welded zone. Most of the pumice in the densely welded zone is weathered out which gives the rock a slotted appearance. Unit contains 4.8 to 11.7% phenocrysts, consisting of 60 to 70% plagioclase up to 5 mm across, 12 to 25% pyroxene up to 3 mm across, and 7.8 to 27.3% Fe-Ti oxides up to 1 mm across. Fewer phenocrysts occur near the base of the unit. Unit forms cliffs, is up to 3 m thick, and is not laterally continuous. The unit conformably overlies the Monotony Tuff or unconformably overlies the volcaniclastic sandstone (see below) and Paleozoic rocks. The unit is identified by its stratigraphic position, phenocrysts of plagioclase and pyroxene, thickness, and presence of a vitrophyre (e.g., Anderson and Rowley, 1975).

The Baldhills Tuff Member of the Isom Formation erupted from an undetermined source that lies southeast or west of the Indian Peak caldera complex (Fig. 4) (Anderson and Rowley, 1975; Best et al., 1989b). K-Ar whole rock and plagioclase dates provide an age of 25.7 ± 0.4 Ma (Fleck et al., 1975). Mackin (1960) first named and described the Isom Formation. Anderson and Rowley (1975) later divided it into three members: the Blue Meadows, Baldhills, and the Hole-in-the-Wall Tuff Members.
A discontinuous volcaniclastic sandstone, up to approximately 30 cm thick, occurs between the Monotony Tuff and the Baldhills Tuff Member southeast of Hiko Canyon. The volcaniclastic sandstone is brownish red and contains subangular to subrounded Paleozoic clasts up to 1 cm across. The sandstone was included in this unit where present.

The Baldhills Tuff Member of the Isom Formation was not thick enough to map individually in the field area, therefore, the Baldhills Tuff Member was mapped with the Shingle Pass Tuff as one unit (Tlp).

**Oligocene Shingle Pass Tuff (Tlp)**

The Shingle Pass Tuff is a pink-gray, brown-gray, orange-gray, and red-gray weathered, darker fresh, partially to densely welded, rhyolitic ash-flow tuff. Welding grades downward over the lower few meters to a brown-gray to pink-gray, partially welded base. The densely welded zone is reddish gray to orangish gray and approximately 20 m thick. Unit contains about 5% light-gray and tan pumice, up to 5 mm to 3 cm across. Unit has 8.1 to 21.7% phenocrysts consisting of 11.3 to 14% quartz up to 2 mm across, 38.3 to 71% sanidine up to 3 mm across, 3.8 to 41% plagioclase up to 1 mm across, 0 to 2.2% biotite up to 1 mm across, 0 to 6.6% pyroxene up to 1 mm across, 3.8 to 10% Fe-Ti oxides up to 1 mm across, and 0 to 2.2% fayalite up to 2 mm across. The unit forms rounded cliffs, is up to 25 m thick, and is not laterally continuous. The unit conformably overlies the Baldhills Tuff Member and unconformably overlies Paleozoic rocks. The unit is recognized by its stratigraphic position, phenocryst assemblage, and multiple colored pumice (e.g., Cook, 1965).
The Shingle Pass Tuff erupted from a source area in the Quinn Canyon Range (Fig. 4) (Best et al., 1992). $^{40}\text{Ar}/^{39}\text{Ar}$ dates on sanidine give this unit an age of $26.68 \pm 0.03$ Ma (Best et al., 1989). Cook (1965) first named and described the Shingle Pass Tuff.

**Oligocene Hole-in-the-Wall Member of the Isom Formation (Tuff)**

The Hole-in-the-Wall Member of the Isom Formation is a dark-gray, black, and red-orange weathered, darker fresh, densely welded, trachytic ash-flow tuff. Welding grades downward over the lower m to a dark-gray, partially welded zone. A black vitrophyre, with a few meters of a reddish orange devitrified top, occurs above the partially welded base and is approximately 3 m thick. Pumice, up to 3 cm across, makes up about 15% of the unit. The pumice is dark gray in the partially welded zone, black in the densely welded vitrophyre, and dark gray to blackish red in the densely welded devitrified zone. The unit contains 5.2 to 12.6% phenocrysts consisting of 66 to 84.5% plagioclase up to 2 mm across, 11.9 to 22% pyroxene up to 1 mm across, and 3.6 to 12% Fe-Ti oxides up to 1 mm across. The unit forms cliffs, is up to 5 m thick, and is not laterally continuous. The unit conformably overlies the Shingle Pass Tuff and unconformably overlies Paleozoic rocks. The unit is identified by its stratigraphic position, phenocrysts of plagioclase and pyroxene, thickness, and presence of a vitrophyre (e.g., Anderson and Rowley, 1975).

The Hole-in-the-Wall Tuff Member of the Isom Formation erupted from an undetermined source southeast or west of the Indian Peak caldera complex (Fig. 4) contains ovoid cavities, and is approximately 8 m thick. The unit contains about 15% light-gray and gray-brown pumice, up to 10 cm across. Unit contains approximately 20% phenocrysts consisting of mostly sanidine and plagioclase with lesser amounts of biotite, pyroxene, and Fe-Ti oxides. The unit forms rounded cliffs and is up to 10 m thick. The unit conformably overlies the Hole-in-the-Wall Member of the Isom Formation and unconformably overlies Paleozoic rocks. The unit is recognized by its stratigraphic position, phenocryst assemblage, and slotted appearance (e.g., Cook, 1965).
unit give an age of $20.4 \pm 0.5$ Ma (Best et al., 1995). Mackin (1960) first named and described it as a member of the Quichapa Formation. Cook (1965) later raised the rank of this unit to the Harmony Hills Tuff (formation status) of the Quichapa Group.

The Harmony Hills Tuff was not thick enough to map as a single unit. Where the Harmony Hills Tuff occurs, it was mapped with the overlying Hiko Tuff as Th.

**Miocene Hiko Tuff (Th)**

The Hiko Tuff is a brown-gray to tan weathered, pink-gray, medium-gray, pale-purple fresh, non- to densely welded, rhyolitic ash-flow tuff. Welding decreases downward over the lower 5 m to a non- to partially welded base. The basal portion contains up to 5% dark-red volcanic lithic fragments, rare Paleozoic rock fragments, and medium-gray inclusions which may be cognate. The unit contains about 10% light-gray pumice that is 10 to 30 mm across and becomes highly flattened and vitric, producing an eutaxitic texture just above the non- to partially welded base. The amount of pumice decreases upward to less than 1% and, consequently, compaction foliation becomes indistinct. Unit has 33.3 to 50.7% phenocrysts consisting of 9.8 to 10.3% quartz up to 5 mm across, 15 to 23.5% sanidine up to 3 mm across, 49.3 to 58% plagioclase up to 3 mm across, 9.6 to 10% biotite up to 2 mm across, 1.4 to 2% amphibole up to 2 mm across, 2.4 to 2.9% pyroxene up to 1 mm across, 2.3 to 3.6% Fe-Ti oxides up to 1 mm across, and trace sphene up to 2 mm across. Boulder-sized spherical weathering is well developed as are nearly vertical, hexagonal columnar joints. The unit forms cliffs and is over 100 m thick. The Hiko Tuff is the most widely distributed ash-flow tuff in the field.
area. The tuff conformably overlies the Bauers Tuff Member and unconformably overlies the Shingle Pass Tuff and Paleozoic rocks. The unit is recognized by its stratigraphic position, phenocryst assemblage, purple-tinted quartz phenocrysts, and fiamme (e.g., Cook, 1965).

The Hiko Tuff erupted from the Caliente caldera complex (Fig. 3) (Rowely and Siders, 1988). ⁴⁰Ar/³⁹Ar biotite dates from this unit give an age of 18.5 ± 0.4 Ma (Taylor et al., 1989). Dolgoff (1963) defined and named this unit.

**Miocene Delamar Lake Tuff (Tdl)**

The Delamar Lake Tuff is a dark-reddish brown to orangish red weathered and fresh, partially welded, rhyolitic ash-flow tuff and may be a surge deposit. The unit contains about 5% grayish-brown and tan pumice, up to 3 cm across. The rock contains about 5% phenocrysts, mostly of quartz and adulariascent sanidine, with lesser amounts of pyroxene and trace biotite. The unit is a slope former and is at least 5 m thick. The basal contact is not exposed. The unit is identified by its stratigraphic position, phenocryst assemblage, and the presence of adulariascent sanidine (e.g., Novak, 1984).

The Delamar Lake Tuff erupted from the Kan Springs Wash caldera complex (Fig. 4) (Scott et al., 1995a). Two K-Ar sanidine dates from this unit provide ages of 15.8 ± 0.4 Ma and 15.5 ± 0.4 Ma (Novak, 1984). The unit was named and defined by Scott et al. (1993) and was previously member O of the Kane Wash Tuff (Novak, 1984). The Kane Wash Tuff was first named and described by Cook (1965) and was later redefined by Noble (1968) to exclude lava flows and sedimentary rocks that were included in the
original definition.

**Miocene Sunflower Mountain Tuff (Tsm)**

The Sunflower Mountain Tuff is a purple-gray, pale-yellow-brown, and red-gray weathered, darker fresh, partially welded to moderately welded rhyolitic ash-flow tuff. The unit contains about 5% light-gray pumice, up to 2 cm across. The rock contains 8.5% phenocrysts consisting of 22.4% quartz up to 2 mm across, 56.1% sanidine up to 1 mm across, 6.1% plagioclase up to 1 mm across, 1% biotite up to 1 mm across, 6.1% pyroxene up to 1 mm across, and 8.2% Fe-Ti oxides up to 1 mm across. The unit forms cliffs, is about 10 m thick, and caps mesas in the eastern portion of Crystal Wash. The tuff conformably overlies the Delamar Lake Tuff. The unit is identified by its stratigraphic position, phenocryst assemblage and abundance, and the presence of light-gray pumice (e.g., Novak, 1984).

The Sunflower Mountain Tuff erupted from the Kane Springs Wash caldera complex (Fig. 4) (Scott et al., 1995a). A K-Ar sanidine date from this unit reveals an age of 14.7 ± 0.4 Ma (Novak, 1984). The unit was named and defined by Scott et al. (1993) and was previously member W of the Kane Wash Tuff (Novak, 1984). The Kane Wash Tuff was named and described by Cook (1965). Noble (1968) later redefined the unit to exclude lava flows and sedimentary rocks that were included in the original definition.

**Quaternary Stratigraphy**

Pliocene (?) to Quaternary alluvial, fluvial, lacustrine (?), and spring deposits crop out in the field area. Units were mapped based on stratigraphic succession, textures, and
rock type. Map units are described below for field recognition.

**Pliocene (?) - Quaternary Alluvium (QTa)**

This unit occurs predominantly on the west side of the Hiko Range and is broken here into three subunits: the Pahranagat Valley subunit, the Hiko Range subunit, and the Mail Summit Road subunit. Two of the subunits occur in the field area. A third subunit occurs west of the White River in the Pahranagat Valley and was only observed in field reconnaissance.

The Pahranagat Valley subunit is a dominantly light-gray to gray-tan volcanic-rich sandstone. Volcanic detritus in the sandstone consists of phenocrysts and minor pumice. Minor conglomerate lenses within the unit contain clasts of an ash-flow tuff with smoky quartz phenocrysts that was identified as the tuff of Hancock Summit (W. J. Taylor, personal communication, 1995). The tuff of Hancock Summit occurs in mountain ranges to the west and north of the field area (Best et al., 1989a; W. J. Taylor, personal communication, 1995), but is absent in the Hiko Range, both in the field area and to the south of the field area (Lisa R. Danielson, unpublished data, 1995), suggesting transport from the west or north, or both. Sedimentary structures observed in the unit are trough cross beds defined by biotite phenocrysts, north-south oriented cut and fill structures, clast imbrications that dip to the north, and thin mud layers that may be overbank deposits. The unit occurs as dissected fluvial and alluvial deposits on the west side of the Hiko Range, and dips predominately to the west. The unit forms slopes, is at least 5 m thick, and is overlain by the Hiko Range subunit. The basal contact is concealed.
The Hiko Range subunit is a predominantly medium-gray-brown to light-yellow-gray, weakly consolidated to consolidated, conglomerate. Clast composition of the unit reflects the adjacent rock units that crop out on the west side of the Hiko Range. Subrounded to subangular, pebble- to boulder-size clasts consist predominantly of Paleozoic dolomite and limestone, with minor sandstone (quartzite), jasperoid, and locally Tertiary ash-flow tuff. East-dipping imbricated clasts were the only sedimentary structure observed in this unit. Unit forms rounded cliffs and slopes. These dissected alluvial fan deposits, up to 15 m thick, are topographically higher than units Qa, Qoa, QI, and Qoac along the western side of the northern Hiko Range and in Crystal Wash. The unit unconformably overlies the Pahranagat Valley subunit.

The Mail Summit Road subunit is a predominantly medium-gray-brown to light-yellow-gray, weakly consolidated to consolidated, conglomerate. Clast composition in this unit is consistent with a source area in the Pahranagat and Mount Irish Ranges. Subrounded to subangular, pebble- to boulder-size clasts consist of Paleozoic dolomite, limestone, sandstone, jasperoid, and Tertiary ash-flow tuff. Unit forms rounded cliffs and slopes. Unit occurs as dissected alluvial fan deposits, up to 15 m thick, and is topographically higher than units Qa, Qoa, QI, and Qoac along the western side of the White River. The basal contact was not observed.

The subunits of Pahranagat Valley, Mail Summit Road, and the Hiko Range are most likely Pliocene - Quaternary in age. This age originates from the tentative correlation of these units to Pliocene - Quaternary age deposits in White River Valley. In the White River Valley, Pliocene to Quaternary alluvial-fan and lacustrine deposits are
overlain by younger alluvial-plain and terrace deposits (DiGuiseppi and Bartley, 1991). It is reasonable to assume that the climatic conditions that produced the progradation and aggradation of coarse alluvial deposits in the White River Valley were also present approximately 15 miles to the south in the Pahranagat Valley (Fig. 2). In the Pahranagat Valley, the Mail Summit Road and the Hiko Range subunits are coarse-grained alluvial deposits that overlie the Pahranagat Valley subunit. The coarse-grained alluvial deposits in both valleys share similar geomorphic features and the same stratigraphic relationship to the older basin deposits of the Pahranagat Valley subunit. Thus, the Mail Summit Road and the Hiko Range subunits formed under the same climatic conditions as the coarse-grained alluvial deposits in the White River Valley, which are Pliocene - Quaternary in age.

Pliocene (?) - Quaternary Surfaces (So and Sy)

These geomorphic units on the top of the formation of the Hiko Range are gently sloping, relatively planar surfaces. Two surface units of different ages were mapped on the west side of the Hiko Range. Surface So is the former alluvial fan surface developed on top of the Hiko Range subunit. Surface Sy records either the progradational deposition of unit Qoa or a fluvial terrace associated with the incision of the White River. Surface So records the last progradational deposition of the Hiko Range subunit and is the highest topographic surface on the Pliocene (?) - Quaternary alluvial deposits. Surface Sy is topographically lower than So and is developed adjacent to a wash that incises the Pliocene-Quaternary alluvium. Thus, surface So is older than surface (or terrace) Sy.
Pliocene (?) - Quaternary Spring Deposits (QTs)

The unit is a dark brownish gray weathered, lighter fresh, limestone tufa. The unit occurs adjacent a strand of the Hiko fault south of Hiko Canyon on the west side of the Hiko Range. The unit unconformably overlies the Pilot Shale and West Range Limestone.

Quaternary Colluvium (Qc)

The unit is unconsolidated to consolidated talus. Unit consists of angular clasts ranging from pebble to boulder size. Color and clast type are inherited from source rock, which is typically immediately uphill. The clasts consist of Paleozoic dolomite, limestone, and sandstone, and Tertiary ash-flow tuff. Unit occurs at the base of steep slopes developed on Paleozoic sedimentary and Tertiary volcanic rocks.

Older Quaternary Alluvium (Qoa)

The unit is medium-gray to medium-red-brown to medium-brown, unconsolidated to weakly consolidated silt, sand, and gravel with clasts ranging from pebble to boulder size. The clasts are rounded to subangular Paleozoic dolomite, limestone, sandstone, and Tertiary ash-flow tuff. The unit occurs as older alluvial fan deposits and is incised 0.5 to 3 m by channels that are filled with unit Qa.

Quaternary Fluvial and Lacustrine (?) Deposits (Ql)

Unit is light-gray, tan, and dark-brown, unconsolidated clay, silt, and sand. Only the surface of the unit was observed in the field area. The thickness is unknown. Unit occurs in the channel or meander plain of the White River. The unit includes agricultural
features, such as dikes and farm fields, near the community of Hiko, Nevada.

**Quaternary Alluvium (Qa)**

The unit is light-gray to light-brown unconsolidated silt, sand, and gravel with clasts ranging from pebble to boulder size. Clasts are rounded to sub-angular jasperoid, Paleozoic dolomite, limestone, and sandstone; and Tertiary ash-flow tuff. Unit is about 1 m thick. The unit occurs as channel deposits in active washes that have incised older units. Fan lobes extend into the White River. The basal contact was not well exposed.

**Quaternary Alluvium, Older Alluvium, and Colluvium (Qoa and Qc)**

Unit mapped on west side of the field area where Qa, Qoa, and Qc cropped out adjacent to one another but were too small to be mapped individually. Descriptions as above.
Table 1. Point-count data for volcanic units in the Hiko Range. Abbreviations used in table: Phen = Phenocrysts, Qtz = Quartz, San = Sanidine, Plag = Plagioclase, Biot = Biotite, Amp = Amphibole, Pyx = Pyroxene, and M = Member.

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