Late Cenozoic Tectonic Features in Glacial Sediments
Owens Valley, California

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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ABSTRACT

The base of the eastern Sierra Nevada escarpment, between Big Pine and George Creek in Owens Valley, has been examined in detail to determine post-glacial rates of tectonic displacement. Special aerial photographs and extensive field investigations have facilitated the mapping of many fault scarps in Pleistocene glacial and Recent sediments. Correlation of these sediments with dated Sierra Nevada glacial epics, and measurements of fault displacements have resulted in estimates of tectonic displacement rates along the study area. Rates of displacement are calculated to be 0.27 to 0.4 feet per 1000 years in post-Tahoe time.
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The subject of concern in this paper is Death Valley, at the base of the impressive eastern Sierra Nevada range.

After the uplift of the Sierra Nevada and subsequent deglaciation of Death Valley, glaciers across the area have been advancing and retreating, creating a variety of erosional and depositional landforms. The effect of these processes has left behind large moraines, U-shaped valleys, and large areas of debris at the base of the glacial deposits. Some of these moraines and associated outwash have since been stripped by faulting along the base of the eastern Sierra Nevada to form tectonic slices that are preserved in the deposited sediments. These deposits enable a careful analysis of the fault ages, combined with knowledge of the age of the sediments. This will lead to a better understanding of the crustal and tectonic activity and limits of displacement along the Sierra Nevada Front.
CHAPTER 1
INTRODUCTION

Scope and Purpose

During the past 100 years many people have strived to piece together the uplift history of the Sierra Nevada Mountains and to understand the resulting effects on the adjacent areas. Methods of attacking this problem have included physiographic, geomorphic, biological, and more recently - geophysical studies. All of these have led to an increase in knowledge about the range. The subject area of concern in this paper is Owens Valley, at the base of the impressive eastern Sierra Nevada escarpment.

After the uplift of the Sierra Nevada and subsequent downdropping of Owens Valley, glaciers carved their way down existing mountain drainages. The effect of these glaciers was to leave behind sharp mountain ridges, widened valleys, and large piles of debris at the terminus of the glaciers, several reaching out into Owens Valley. Some of these moraines and associated outwash have since been displaced by faults along the base of the eastern Sierra Nevada so that today a portion of the Quaternary tectonic movement is preserved in the deposits. This project entails a careful examination of the fault scarps combined with knowledge of the age of the moraines. This will lead to a better understanding of the Quaternary tectonic activity and rates of displacement along the Sierra Nevada front.
Method of Study

Field investigations were carried out during the last half of 1978 and the beginning of 1979. The field work consisted of detailed mapping and measurements of Quaternary fault scarps located in either glacial moraines or probable glacial outwash at the base of the Sierra Nevada. A general reconnaissance of the Pleistocene and recent geomorphic features of the study area was also undertaken.

The mapping was aided by the use of special vertical aerial photographs supplied by the University of Nevada, Reno. These photographs were taken in 1968 using the low-sun angle illumination technique developed by Cluff and Slemmons (Slemmons, 1969) and are at a scale of 1:12,000. These photographs provide stereoscopic aerial coverage over the northern 3/5th of the study area. Smaller scale (1:15,840) United States Forest Service stereographic photographs obtained from the Bishop field office in California supplied coverage for both the northern and southern regions.

Data acquired from field checking the photograph interpretations was transferred to topographic maps at a scale of 1:62,500. Fault scarp attitudes were measured in the field with a Brunton compass at specific horizontal or vertical intervals. Measurements taken along the fault scarps were then graphically plotted for further analysis. Granitic boulder-weathering counts were also taken to more accurately estimate the ages of the moraines and to verify previous age interpretations (Bateman, 1965; Moore, 1963).
A boulder is classified as fresh if more than half its surface has not been roughened by weathering to a depth of the average grain diameter. Weathered boulders have surfaces roughened by deeper erosion.

Location of Study

Owens Valley is a long, narrow, fault-bounded valley that extends southward from Bishop to Owens Lake in the eastern portion of California (Fig. 1). It is bounded on the west by the Sierra Nevada and to the east by the White-Inyo Mountains. The southeast termination is along the Coso Range.

Surrounding the valley floor are large alluvial fans adjacent to the mountain slopes. Cenozoic volcanic rocks, lake deposits, and alluvial material comprise most of the southern valley sediments.

The study areas are along present river channels at the base of the Sierra Nevada between Big Pine and Lone Pine. Specifically, these are areas in Owens Valley which received deposits of glacial material that have since been offset by post-glacial valley faulting. The creeks examined include Big Pine Creek, Tinemaha Creek, Taboose Creek, Independence Creek, Shaperd Creek, North Fork and Bairs Creek, and George Creek.

Climate

The climate of Owens Valley is quite arid. Temperatures above 100°F are common in the summer months. Winter temp-
Figure 1. Location of Study Area.
eratures are cold with many days below freezing (Curry, 1969, Pl.1). The valley is in a rain shadow caused by the height of the Sierra Nevada. Little rainfall occurs except along the western valley boundary. Occasional large storms occur during the summer months producing flash floods. Winter precipitation is minor and in the form of snow.

Wind and flash floods have been important erosion mechanisms in the valley. In the past 50 years though, these mechanisms have been sporadic (Curry, 1969). As a result, slow overall physiographic changes have occurred as compared with more active periods of precipitation in the Pleistocene (Curry, 1969, Fig. 10).

The vegetation in the area will vary depending upon elevation. A zone of pinyon pine and juniper along the upper foothills of the Sierra Nevada gradually changes to a zone of sagebrush which blankets most of the valley. Groups of cottonwood and willow are also found adjacent to some streams flowing from the Sierra Nevada.

**Previous Work**

Many studies concerning the Sierra Nevada have resulted in volumes of literature dating back to the 1800's. Two publications which organize and summarize the more important reports on the Sierra Nevada are Bateman and Wahrhaftig (1966) and Christensen (1966).

Glaciation in the Sierra Nevada has been studied by several people in the last 75 years. Knopf (1918) studied
many of the glacial drainages along the eastern Sierra Nevada during a general reconnaissance. Matthes on the other hand specifically studied the glacial history of Yosemite Valley (1930), the San Joaquin basin (1960), and Sequoia National Park (1965). The most comprehensive report is written by Blackwelder (1931). He recognizes four glacial stages on the east front of the Sierra Nevada and describes several methods of glacial analysis. Putnam studied the glacial sequences in the areas of Mono Basin (1949, 1950), Rock Creek (1960), and McGee Mountain (1962).

Birman (1954, 1964) was able to correlate glacial deposits from the upper San Joaquin River to those of Rock Creek. This was the first such correlation linking glaciers on the east and west sides of the Sierra Nevada. Sharp and Birman (1963) added two new stages to the sequence of glacial events.

The literature shows uncertainty over the time of uplift and total amount of tectonic movement along the Sierra Nevada. South of the Tuolumne River good evidence is lacking (ie. gravels and volcanics) from which to tell age of uplift and deformation. This leaves most conclusions to be based upon physiographic evidence such as upland surfaces, valley-side benches, and knickpoints in stream profiles.

In 1904, Lawson describes extensive benches and summit uplands on granitic rock at the head of the Kern River. He assumes these to have been low relief (near sea level) erosional surfaces. The surfaces are named the Subsummit
Plateau (elevation 11,000 to 12,000 feet) the High Valley (elevation 6,500 to 10,000 feet). By approximation the erosive rates of the surfaces relative to rates of glacial erosion, he determines the time of cutting to be 24 to 3 million years ago, respectively. This suggests that uplift and rejuvenation occurred at these times.

Knopf (1918) and Matthes (1937) mapped Lawson's surfaces to the eastern portions of the range. Matthes refines Lawson's history by recognizing another erosional surface, and therefore, recognizes four periods of uplift in the Kern drainage. The highest two surfaces correspond to Lawson's Subsummit Plateau. These Matthes names the Cirque Peak Surface and the Boreal Plateau Surface. A lower surface corresponding to the High Valley was renamed the Chagoopa Surface. The final stage he names the canyon cutting stage.

Axelrod in 1962 tried to date the uplift and erosion of the Sierra Nevada by studying pollen grains incorporated in sediments of high elevations and in invertebrate-dated sedimentary rocks in Owens Valley. He concludes that the Chagoopa Surface is middle Pleistocene (Kansan) in age and that most of the uplift took place in the Pleistocene. Christensen (1966) comments on this opinion and states that the pollen age only dates a minimum age of erosion and supports the idea that a good portion of the uplift occurred prior in the Pliocene. Christensen also comments that it is very difficult to tell the exact species of pollen for correlation.
and, therefore, the dates arrived at should be taken with some reservation.

Using the physiographic evidence for uplift expressed in stream profiles, Matthes (1930) noted that upper tributaries of the Merced River flowed in broad valleys until they reached an abrupt knickpoint or slope change. From here they cascade to the Merced River which has cut a deep channel thousands of feet below. By projecting the gentle gradients downstream to where they join the Merced, Matthes is able to list a series of points marking the old channels and the present level. The existence of stream knickpoints attests to multiple periods of uplift. One he placed in the Miocene, the other in the Pliocene.

Wahrhaftig (1965) explains the development of this stepped topography as the eventual landform resulting from erosive processes. He notes that soil covered granite weathers more rapidly than exposed granite in the Sierra Nevada. Stepped topography can form at any elevation and streams flowing over the topographic features appear to inherit knickpoints. Therefore, Wahrhaftig believes many of the remnant surfaces such as the Boreal, Chagoopa, Broad Valley, and Mountain Valley to be "treads" in this step topography. Matthes' knickpoints are examples of this stepped topography. This contrary view leads one to doubt the validity of solely physiographic criteria for determining uplift histories. So far no particular uplift and erosional theory has been proven. Other supplemental evidence must be used
for dating periods of uplift.

Studies of surface faulting in Owens Valley have principally been concerned with the earthquake of 1872. These studies include Whitney (1872), Gianella (1959), Slemmons, Cliff, and Carver (1968), and Carver, Slemmons, and Glass (1969). A detailed fault investigation of the Owens Lake region was carried out by Carver (1969). The comprehensive geophysical study of Pakiser, Kane, and Jackson (1964) investigated the subsurface structure of the Owens Valley region. These last two references provided much of the background information used in this project.

Deformation along the eastern Sierra fault zone apparently began about 19 million years age (Bateman and Wahrhaftig, 1966) and has continued up to the present. K-Ar dates of volcanic rocks associated with the fault scarps and warps suggest most of the deformation took place in the last 3 million years. This is believed to account for the total relief in Owens Valley of nearly 11,000 feet from Mt. Whitney to the valley floor at Owens Lake.

The various conflicting ages of uplift show that the true tectonic history is not yet fully understood. After studying the literature available, the author agrees with Christensen (1966, p.178) that the relief along the eastern border of the Sierra Nevada has formed since the late Pliocene (about 3 million years ago).
CHAPTER 2

GENERAL GEOLOGY

PRE-CENOZOIC ROCKS

The mountain ranges on either side of Owens Valley are predominantly pre-Tertiary Age rocks. These include Paleozoic sedimentary and metamorphic rocks, or Mesozoic intrusives and associated contact metamorphic. Comprehensive descriptions of these rocks have been done by Knopf (1918), Bateman and Marriam (1954), and others. Detailed descriptions of these rocks have been written by Bateman (1965).

The core of the Sierra Nevada is composed chiefly of Mesozoic granitic rocks. Composition ranges mainly from quartz monzonite to granodiorite. These rocks were emplaced in order of increasing silica content (Bateman, 1965). The metasedimentary rocks of the Sierra Nevada occur as roof pendants or septa between granitic masses. These are composed of hornfels, marbles, shists, quartzites and metavolcanics.

Isolated islands of quartz monzonite or granite can be located in Owens Valley along the eastern portion of the Poverty Hills and the western portion of the Alabama Hills. Triassic metavolcanics from the eastern part of the Alabama Hills and western escarpment of the Inyo Mountains.

Knopf (1918) describes the sedimentary rocks of the White and Inyo Mountains. These contain about 36,000 feet of alternating quartzite, sandstone, shale, limestone, and
dolomite which range from pre-Cambrian to Triassic. Along the western escarpment, east of Big Pine, lower Paleozoic sediments predominate. Farther south, Cretaceous granitics similar to those of the Sierra Nevada form the core of the range.

Cenozoic Rocks

Of principal interest to this paper are the deposits of Cenozoic age. Several rock types of this age can be found in Owens Valley, ranging from lake beds, alluvial fans, and glacial deposits to volcanic flows, tuffs, and breccia. The following descriptions have been drawn principally from the work of Knopf (1918), Blackwelder (1931), and field observations.

Older Lake Beds. Lake beds of Pleistocene age can be found in several places in Owens Valley. These are believed to have formed during each of the major Sierra Nevada glacial periods (Carver, 1969).

The Coso Formation, a sequence of lake beds, are of late Pliocene or early Pleistocene age (Schultz, 1937). They are found southeast of the study area between the Coso Range and the Inyo Mountains. The formation is about 500 feet thick. The base consists of alluvial materials derived from the granitic core of the Coso Range. Overlying these beds are thin-bedded sandstones and shale, which are interbedded with white rhyolitic tuffs.

Other lacustrine deposits of this age are found east and south of Big Pine. East of Big Pine, in Waucoba Canyon,
are exposures of shale, sandstone, conglomerate, and limestone containing freshwater gastropods. These beds are about 150 feet thick and are unconformably overlain by alluvial fan material. Exposed south of Big Pine are several hundred feet of soft sandstone and shale which contain a fresh water fauna. These have been partly covered by a Pleistocene basalt flow (Knopf, 1918). Fault deformation of these beds south of Big Pine has resulted in a dip of 30° to the southwest.

Younger Lake Beds. The Owens Lake playa once extended about 10 miles north of Lone Pine and covered about 220 square miles (Pakiser, et al., 1964). In 1957, a drill hole driven to a depth of 920 feet near the center of Owens Lake penetrated recent clays (Carver, 1969). The drill then penetrated alternating beds of clay, sand, and silt.

Many ancient shorelines are found around the margins of Owens Lake. These represent the high water level and recessional levels of the lake during the Pleistocene glacial advances and retreats. The highest of these is found at an elevation of 3,800 feet on the edge of the Coso Range. The composition of these deposits range from sand to gravel. Detailed work on the Owens Lake area has been done by Carver (1969).

Alluvial Deposits. Large alluvial fans of the Quaternary age have formed along the base of the Sierra Nevada and the White-Inyo Range. Knopf (1918) differentiated two ages of alluvial fans along the White-Inyo and only one system along the Sierra Nevada. Gilbert (1941) and Rinehart
and Ross (1957) described two stages of alluvial fans along the western border of Owens Valley.

The fans along the Sierra Nevada front form a slope one to seven miles wide, the widest portion being located between Lone Pine and Independence. These rise 1000 to 2,500 feet above the floor of Owens Valley and repose at 6° and 7°. Many fans have coalesced to form a continuous apron along the base of the Sierra Nevada. These are composed of coarse, angular gravels and boulders which are poorly bedded.

Older fans (those partially overlain by more recent sediments) along the White-Inyo Mountains extend back into some of the canyons to elevations of 6,600 feet. Pakiser (1964) states that some beds have been dislocated and tilted so that they now dip up to 50° west. Portions of old fans are also found near the mouths of some canyons along the Sierra. These are composed of unsorted or poorly sorted gravels and boulders. There has been recent stream dissection into these fans, some to a depth of several hundred feet.

Carver (1969) discusses the present development of the more recent, younger alluvial fans along the White-Inyo and Sierra Nevada. These deposits overlie the older fans and show less erosion on their surfaces. The younger fans were derived from material eroded from the adjacent mountains and reworked older alluvial deposits. In addition, considerable amounts of Quaternary glacial outwash has been added to the fans bordering the Sierra Nevada, leaving granitic debris
strewn over many of the surfaces.

This division between older and younger alluvial fans is a general relationship. It is very probable that more than two ages of fans exist considering the many past climatic changes. However, any farther differentiation is beyond the scope of this paper.

Easily noted on aerial photographs is the dissection of the younger fans. These presently active stream channels are undergoing longitudinal erosion and deposition. Areas of erosion are expressed as sharp channels cut to depths up to 40 feet or more. These decrease downstream to areas which exhibit braided streams and decreased boulder size. This pattern of erosion and deposition occurs more than once along many of the stream drainages. The dissection results from two features: structural movements related to progressive depression of Owens Valley relative to the surrounding ranges (Knopf, 1918) and, greater erosive power of unloaded streams. The first process results in short lived oversteepened channels and hence the erosion-deposition cycle.

Glacial Deposits. All along the eastern escarpment of the Sierra Nevada are large piles of unstratified glacial deposits. Material eroded by the glaciers was deposited as moraines extending out of the canyons or as outwash carried by the large quantities of melt-water. These can be found extending into many of the valleys down to elevations of 3000 feet to 4,000 feet. The shape of the moraines suggests that the glaciers maintained the widths they had in the
Several periods of Pleistocene glaciation have been recognized in the Sierra Nevada. Knopf (1918) found evidence for two periods of glaciation along the eastern slopes of the Sierra in Owens Valley. The older moraines extend down to elevations of 5,000 feet covering older alluvial fans. The younger moraines were deposited on the higher slopes overlying the older moraines. Matthes (1930) established three stages of glaciation in the western Sierra Nevada in the Yosemite region. The classic work of Blackwelder (1931) recognizes four glacial periods along the eastern front. His terminology has been adopted wherever correlations with his stages are possible. These are from youngest to oldest, the Tioga, Tahoe, Sherwin, and McGee stages (see Table 1). Sharp and Birman (1963) added to his chronological sequence with the Tenaya between the Tahoe and Tioga, and the Mono Basin between the Tahoe and the Sherwin. Three more recent divisions (post-Tioga) have been added by Birkland (1964) but are not of importance to this paper.

Criteria used for developing the glacial sequence is from the work of Blackwelder (1931), whose work is based on
<table>
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<td>Sherwin</td>
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<tr>
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<td>McGee</td>
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<td>about - 2,000,000 - 3,000,000</td>
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physiographic evidence in the glaciated valleys. The following are the more useful criteria:

1) generally, the older glacial periods were more extensive than the younger; therefore, the larger the moraine, the older the glacial stage,

2) boulder weathering ratio; the ratio of boulders deeply eroded to those that are relatively fresh, the distinction made upon the depth of weathering around phenocrysts in the granodiorite, the most useful weathering criteria of this report,

3) frequency of boulders on undisturbed till; generally the younger moraines have a greater number of boulders than do older moraines per unit of sampling distance,

4) concerning the till soil; in moist areas, the Sherwin has a rusty hue, the Tahoe tends to be a light buff color, and the Tioga is ash gray.

Other criteria that may support a theory concerning age relationships include the number of boulders with striations, notching or removal of the end moraines, depths of cut ravines, depth of the wind laid deposits, and amount of sand blasting received by the boulders. A combination of these criteria should lead to a good understanding of field relationships. In a recent publication Burke and Birkland (1979) describe problems encountered while trying to differentiate the various post-Sherwin Pleistocene glaciations. They use a greater number of parameters than have been used previously.
These include submitting soil samples to laboratory analyses and recording surface weathering features which are under the same vegetation cover. They were not able to satisfactorily differentiate multiple glaciations from their data, except for the Tahoe and Tioga stages. This suggests that researchers should critically analyze their data when studying intermediate stages.

Some of the glacial deposits have radiometrically dated volcanic deposits in overlying and underlying relationships (Dalrymple, 1964a, 1964b). Therefore, the moraines can be assigned a chronological order. These approximate dates give the maximum ages that can be assumed for intersecting fault scarps. This is of crucial importance for dating post-glacial tectonic activity.

The rate of morainal weathering depends upon several factors. The most important include temperature, moisture, boulder mineral type, and grain size. The intensity of the first two factors has changed through time as evidenced by deposits of successive glacial episodes. These changes cause variations in weathering rates but are uniform through the study area. Granodiorite boulders were used in weathering ratios because of the close uniformity of grain type and prevalence in the study area.

Granodiorite-weathering ratios were first used by Blackwelder (1931) to differentiate tills of various ages. Tills with a greater percentage of fresh boulders are younger than those with a lesser percentage. His description of
the degree of weathering is quite general and has since been interpreted by others. In this study, granodiorite boulders greater than one foot in diameter are classified as weathered if more than one half the surface shows weathering to a depth of an average grain diameter. Fresh boulders show less weathering. The difference between fresh and weathered boulders can be seen not only in the depth of weathering but also in the grains. Feldspars are chalky and show little luster in the weathered boulders.

The weathering ratios were determined by walking the crests of the moraines where boulders receive similar exposure to weathering. The boulders were encountered with no selection except for choosing granodiorite. These observations were recorded and used for the ratios. Counts of fifty were used to arrive at a percent ratio. Variables which may effect the ratios include microclimate and personal bias (Birkland, 1964, p.16).

Bounder frequency, also used by Blackwelder (1931), can be used in some instances to help determine age relationships. Where two moraines are juxtaposed, it is generally the case that the older morainal surface will show fewer boulders. This will result from chemical and mechanical weathering (i.e. frost shattering, exfoliation, and fire). The assumption is made that the longer the boulders are exposed to the elements, the greater the chance of having fewer boulders one foot or more in diameter. Table 2 lists the effects of exposure on the boulders (Fleisher, 1967, p.41).
### TABLE 2 - Effect of Time On Surface Boulders

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Effect of Increasing Time of Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preservation of Glacial, Polish, or Strie</td>
<td>Decreases</td>
</tr>
<tr>
<td>Extent of Exfoliation</td>
<td>Increases</td>
</tr>
<tr>
<td>Development of Weathering Pits</td>
<td>Increases</td>
</tr>
<tr>
<td>Development of Eolian Polish</td>
<td>Increases, followed by decrease</td>
</tr>
<tr>
<td>Development of Elephant-hide Weathering Texture (erosion polygons)</td>
<td>Increases, followed by decrease</td>
</tr>
<tr>
<td>Boulder Frost and Fire Shattering</td>
<td>Increases</td>
</tr>
</tbody>
</table>
In the mapped area, Sherwin tills are recognized along the north side of the Big Pine moraine (Bateman, 1965; Fleisher, 1967) and along the north side of the moraine at Tinemaha Creek in the Big Pine quadrangle (Bateman, 1965). The surface of the till is generally hummocky with the original glacial features eroded away. Modification of the morainal form occurs as a result of erosion and deposition which lowers the crest and broadens the flanks. Bounders are generally less abundant on the surface than younger adjacent moraines, and most have been eroded. The till along Big Pine Creek has been cut by north trending faults which may have accelerated erosion and produced increased dissection. The Mono Basin moraines have not as yet been recognized in the canyons south of Big Pine. They may, however, actually be present since they exhibit similar boulder weathering ratios to the Sherwin. A distinction between Sherwin and Mono Basin is made primarily on morphologic evidence (Sharp and Birman, 1963). The Mono Basin deposits retain their original morainal form whereas the Sherwin does not.

Moraines of the Tahoe age are the most conspicuous in the study area, as well as farther to the north. These large and well developed moraines can be recognized at least as far south as Lone Pine in most of the major canyons along the Sierra front. The original geomorphic features of the Tahoe moraines are easy to recognize although the crests of the glacial ridges have been rounded by erosion and smaller
details obliterated. The fronts of the terminal lobes have since been totally breached and consumed in the flood plain. Lateral moraines are very distinctive and are usually between 500 and 1,000 feet above the present stream channels. Boulders in the till are fresher and more abundant at the surface than the older moraines.

The Tenaya and Tioga moraines are fewer in number and smaller than the earlier tills but are better preserved. Most of these moraines can be found inside the larger Tahoe moraines that proceeded them. Their crests are sharp and the terminal moraine details are clearly visible. These last two Wisconsin age glacial deposits are of little concern to this paper since no recent faulting was observed intersecting their surfaces. They generally are at higher elevations and do not cross the valley fault zones.

**Volcanic Rocks.** There have been intermittent eruptions of rhyolitic and basaltic rocks during the late Tertiary and Pleistocene along both sides of Owens Valley. These were first studied in detail by Knopf (1918) and more recently by Mayo (1941), Hopper (1947), Moore (1963), Bateman (1965), and others.

Knopf found that basalt flows occurred three times between late Tertiary to Pleistocene. Evidence of this lies in exposures located in the Inyo Mountains south of Keeler. Hopper described similar outcrops in the Coso Range that are correlative with the earlier basalts described by Knopf, as well as other olivine basalts, south of the Coso Range.
Pre-Tahoe basalt of Pleistocene age (Dalrymple, 1964) can be found west of Independence and in isolated patches on the Sierra Nevada slopes. Another conspicuous volcanic field is located around Crater Mountain and Red Mountain between Big Pine and Independence. A north-trending fault connects Creater Mountain and Red Mountain (Mayo, 1941). Other faults may link the volcanic fields at the mouth of Spook Canyon to those south of Taboose Creek.
CHAPTER 3

STRUCTURE AND TECTONIC SETTING

Regional Tectonics

Owens Valley is a tectonically depressed fault block which defines the western border of the Basin and Range Province (Fig.2). To the west, paralleling the California coast, is the right lateral San Andreas fault zone. This zone is part of the Circum-Pacific belt described by Gutenberg and Rickter (1954). Branching to the northeast from the San Andreas, running along the southern end of Owens Valley is the left lateral Garlock fault.

The valley is also located near the middle of the Winnemucca - Ventura seismic zone which extends from the California coast near to the vicinity of Winnemucca, Nevada (Ryall, Slemmons, Gedney, 1966). This zone is reported to have been the most seismically active area in the western United States during the last 100 years. It is somewhat anomalous, however, since it crosses the San Andreas fault, Garlock fault, and the Walker Lane fault zone of Nevada. This last seismic zone, located east of Owens Valley, extends in a northwest direction from the vicinity of Las Vegas to Pyramid Lake, Nevada.

Bordering Owens Valley along its western margin are the steep cliffs which form the eastern escarpment of the Sierra Nevada. The uplift of the Sierra and subsequent down-dropping of the valleys east of the range, produce displacements
FIGURE 2. REGIONAL TECTONIC SETTING.
of several thousand feet. Areas of warping are also important to the evolution of the eastern escarpment of the Sierra (ie. the Coyote Qarp west of Big Pine).

Various methods have been utilized in trying to date the displacement along the Sierra Nevada (Lingren, 1911; Blackwelder, 1931; Matthes, 1930; Hudson, 1955; Axelrod, 1962; and others). There has been general agreement that most of the displacement took place in the late Tertiary and Quaternary. Some date the dominant period of uplift during the Pliocene while others place it in the Pleistocene. It is probably correct to assume that major movements did occur prior to the Quaternary. There is also substantial evidence that vertical displacements have occurred during the Quaternary, in the Pleistocene and in recent time as exemplified by young fault scarps in glacial debris.

**Tectonics of Owens Valley**

Local tectonic features suggest that Owens Valley is more than a simple north-trending graben. Detailed studies undertaken by Carver (1969) and geophysical studies by Pakiser, et al. (1964) have unraveled many of the valley's complexities.

Three main fault zones are contained in Owens Valley (Carver, 1969). These comprise an area of predominantly dip slip movements which extend along the base of the Sierra front, secondly, another zone of dip slip faulting follows the base of the White-Inyo Mountains, and thirdly, a zone of both dip and oblique slip has produced displacements
through the center of the valley (Fig. 3). All three of these zones have been active during the Quaternary as seen in the younger sedimentary units. According to Carver (1969), the central zone appears to have been the most active recently and the eastern zone has experienced the least activity during this period.

Of primary concern to this paper is the Sierra Nevada frontal zone. This zone extends about 80 miles along the western side of the valley. It is characterized by a series of short scarps (1/2 to 4 miles long) which roughly follow the irregular basal outline of the Sierra in unconsolidated alluvial material. The north end of the study area between Big Pine and Tinemaha Creek exhibits both antithetic and normal faulting. This combination changes to the south where there is a predominance of normal faulting such that south of the Tinemaha Creek the faulting is almost exclusively of the normal type. Evidence for lateral movement in the form of en echelon fracturing, displacement of streams or other linear features is lacking. This indicates that most of the faulting has been vertical. The entire length of this frontal zone has not experienced the effects of late Quaternary faulting. Several gaps exist where older and younger alluvial fans have not been displaced. These gaps seldomly exceed five miles in length.

The zone along the White-Inyo Mountains exhibits two areas of Quaternary faulting. The northern section, along the White Mountains, contains many graben structures that
Figure 3. Fault Zones in Crens Valley (Adapted from Carver, 1958).
range from one to three miles in length. These structures intersect the range from a north-northwest direction.

South of this area in roughly the northwest corner of Owens Lake, is a zone of older faulting with little or no evidence of faulting in Quaternary deposits. Surface displacements are again observed in late Pleistocene sediments along the eastern edge of Owens Lake. These extend south parallel to the base of the Inyo Mountains to the Coso Range where the direction changes to a southwesterly orientation.

The central zone consists of a series of normal-slip and normal-oblique slip faults. Northwest trending surface faults show right oblique offsets which contrast with short, east to northeast trending faults that are often left oblique (Richardson, 1972; Carver, 1969; and Moore, 1963). This central zone is about three miles wide and extends the length of the valley. Right lateral displacement along this zone is believed to have been restricted to a few miles. Ross (1962) studied the composition and average specific gravity of the Tinemaha granodiorite southwest of Big Pine and the Santa Rita Flat pluton northwest of Independence. As a result of the noted similarities, he concludes that the two were very possibly implanted as one pluton and have since been moved apart by right lateral faults in the valley. This suggests that only limited lateral displacement has taken place since late Cretaceous. Moore and Hopson (1961) postulate this same concept based on the continuation of a swarm of mafic dikes across the valley.
Genozoic Structure

The structural features of the valley region include normal faults, broad warps, and open folds. These features result from the uplift of the Sierra Nevada and the White Mountains as well as subsidence of Owens Valley.

The normal faults and broad warps are recognized by their effect on the topography. Although modified by erosion and covered by alluvial and glacial material, the steep escarpment of the Sierra Nevada is the true fault scarp. Most of the surface scarps that follow the irregular topography indicate that faults are of the normal type. Warps are reflected in broad rounded surfaces that have deformed the original surface.

The fault block or warp on the valley side was displaced downward as the Sierra Nevada and White-Inyo escarpments developed. Thus the development of normal faulting and bent warp surfaces. In contrast to those scarps downfaulted on the valley side are the antithetic faults which show displacement on the mountain side of the fault plane. These antithetic faults are generally subsidiary features closely related to the warps (Bateman, 1965).

The antithetic faults commonly give a distorted picture as to the tectonic displacement of an area. Erosion at the base can tend to emphasize the height of the scarps where lateral drainage is present. Conversely, other antithetic scarps will pond alluvium behind the "upthrown" block hiding the total displacement. The remaining displacement seems
to be the result of a rotating block with its axis perpendicular to the axis of extension. It does not show actual vertical displacement. On the other hand, normal faults tend to be more reliable as indicators of displacement. Erosion remains a factor in smoothing the upper edge of the scarp, leaving material to be redeposited at the base. However, careful measurements of the upper and lower surfaces will still portray accurate displacement heights.

**Sierra Nevada Escarpment.** Within the study area, the Sierra escarpment shows two structural features, warping and displacement along the west valley fault. The warp, called the Coyote warp, extends northward from Big Pine toward Bishop. It is two sided with one limb facing north, the other east. The northeast axis of the structure dips toward the hills south of Bishop. An important feature of the warp is the abundance of antithetic faults on and surrounding the warp. This explains the great number of these type faults between Big Pine Creek and Tinemaha Creek, and also north of the warp along the Wheeler Crest scarp.

The escarpment south of the Coyote warp extends the length of the valley. In many places the scarp is offset laterally rather than being one continuous scarp. The principal dip for the normal fault plane is $70^\circ$ east. Although Quaternary displacement is recorded in the Sherwin and Tahoe debris, it is important to note that it is not the total Holocene displacement. Other displacement either east or west of these "glacial faults" also adds to the total
vertical tectonic movements in the valley. In essence, this data can be taken as a minimum or first estimate of post-glacial offset.

**Valley Block Subsurface Structures.** The original surface of the Coyote warp, as mentioned in Bateman (1965) is believed to extend eastward under the valley sediments and northward under the Volcanic Tableland north of Big Pine. As the surface extends eastward below the sediments, it is cut off along the fault just east of Crater Mountain (Fig. 4). This has been determined from regional geophysical studies made by Pakiser, et al. (1964) and projections of the original surface eastward by Bateman (1965).

South of Big Pine, most of the pre-Tertiary rocks extend below the sediments eastward to the central zone of faulting. This central zone extends southward truncating the basement rocks as evidenced from the previously mentioned geophysical studies (Fig. 5).
Figure 4. East-West Section across Owens Valley in the Vicinity of Big Pine (Adapted from Pakiser, et al., 1964).

Figure 5. East-West Section across Owens Valley in the Vicinity of Lone Pine (Adapted from Pakiser, et al., 1964).
CHAPTER 4

QUATERNARY SURFACE FAULTING
EASTERN SIERRA NEVADA

Introduction

As mentioned on page one, the Quaternary fault scarps along the eastern base of the Sierra Nevada are the main concern of this paper. From studies of low-sun aerial photography it has been possible to accurately locate the scarps and their occasional relationships to glacial material. The following descriptions of the offset glacial drainages will set a minimum value for the Quaternary displacement along the Sierra front. Scarps which traverse alluvial deposits were not studied because of their lack of age control. Future detailed fault studies may be able to relate the ages of the alluvial fault scarps to those studied in this report but that is beyond the scope of this project.

In the region between Big Pine and Tinemaha Creek there exists both antithetic and normal fault scarps. These exhibit short fault segments that roughly parallel the Sierra. The normal faults are of greatest interest since they reflect vertical tectonic offsets occurring in the valley. Antithetic faults are not believed to be representative of overall vertical offsets.

Fewer fault segments were studied south of Tinemaha Creek. This is a result of there being fewer glacial moraines in southern Owens Valley to be examined. Because of this, glacial outwash was substituted as the datable
sediments. These are all large outwash fans believed by the author to be of the Tahoe stage or younger as determined by physiographic evidence (ie. bounder frequency, unsorted sediments, rounded topographic expression, etc.). This segment of the study area experienced exclusively normal faulting.

Fault profiling did not reflect multiple movements on the scarps. Most of the slope angles are constant and straight over the individual profile. This might tend to suggest that only one movement has occurred. However, profiling is not conclusive and it would seem more likely to have had multiple events rather than individual displacements greater than 30 feet as seen at the Independence Creek moraine. It is possible that the erosion on the scarp faces could have obliterated subtle slope angle changes. No river terraces display fault offsets which could provide a possible field check.

Exact measurements of vertical surface displacements were difficult to obtain due to the varying amounts of erosion and deposition which has occurred along many scarp faces. In addition, the displacements vary from place to place along a scarp length. The most complete, least eroded surface was therefore profiled and measured to arrive at an estimate of displacement.

Literature concerned with subsurface faults and surface scarp relationships as well as fault projection through valley fill has been addressed by Carver (1969)
and will not be included in this report.

In order to date these fault scarps with any reliability correlation of the moraines along the eastern Sierra Nevada must first be achieved. Since direct, continuous correlation by the use of a particular marker bed is not possible, weathering and morphologic similarities must be utilized. The most reliable methods used in this paper are granodiorite-weathering ratios and topographic relationships.

It can be concluded that after comparison of other weathering ratio data, correlations of valley glacial deposits along the east slope of the Sierra Nevada can be made on the basis of topographic relationships and checked with weathering ratio counts. The variation in data suggests that several counts should be taken on each deposit before weathering ratios are used for correlation purposes. A summary of this data is included on Tables 3 and 4.

The four southernmost creeks examined are lacking in moraines at the canyon mouths. Therefore the ages of the faulted deposits have not been dated as reliably as have the moraines. It is, however, the belief of this author and others (Gillespie, personal communication) that the large alluvial and glacial outwash debris is of Tahoe age or younger. This is based on the fact that these alluvial fans overlap older adjacent fans (as differentiated in Chapter 2) suggesting younger active deposition. Also there is a higher concentration of large, fresh granodiorite boulders in these alluvial deposits as compared to that found in nonglaciated canyons.
Table 3. Sherwin Age Boulder-Weathering Ratios.

<table>
<thead>
<tr>
<th></th>
<th>Blackwelder (1931)</th>
<th>Dalrymple (1964)</th>
<th>Fleisher (1967)</th>
<th>Burke and Birkeland (1979)</th>
<th>Fink (This Report)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Slope</td>
<td>Sawmill Ck</td>
<td>Big Pine Ck</td>
<td>Sawmill Ck</td>
<td>Tinemaha Ck</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0:30:70</td>
<td>10:90</td>
<td>26:22:2</td>
<td>6:94</td>
<td>10:90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:88</td>
<td></td>
<td>6:94</td>
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<td></td>
<td></td>
<td></td>
<td>14:86</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Fresh: Moderate: Weathered
** Fresh: Weathered
*** Fresh: Weathered: Grus
Table 4. Tahoe Age Boulder-Weathering Ratios.

<table>
<thead>
<tr>
<th>East Slope</th>
<th>Sawmill Ck</th>
<th>Bishop Ck</th>
<th>Big Pine Ck</th>
<th>Baker Ck</th>
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<tr>
<td></td>
<td>31:69</td>
<td>20:80</td>
<td>16:84</td>
<td>12:88</td>
</tr>
<tr>
<td></td>
<td>34:66</td>
<td>22:78</td>
<td>18:82</td>
<td>18:82</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Gillespie (Personal Communication)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independence Ck</td>
</tr>
<tr>
<td>F:W:D***</td>
</tr>
<tr>
<td>1:23:35</td>
</tr>
<tr>
<td>2:48:37</td>
</tr>
<tr>
<td>9:66:9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Burree and Fink (This Report)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawmill Ck</td>
</tr>
<tr>
<td>F:W:G****</td>
</tr>
<tr>
<td>48:2:10</td>
</tr>
<tr>
<td>47:3:10</td>
</tr>
</tbody>
</table>

| * Fresh: Moderate: Weathered  
| ** Fresh: Weathered            
| *** Fresh: Weathered: Decomposed  
| **** Fresh: Weathered: Grus    |
This alluvial debris has been deeply cut by river erosion from subsequent wet climatic periods in post-Tahoe time. Several erosional benches exist in the river channels attesting to periods of rejuvenation and a higher energy flow.

**Drainage Faulting**

**Big Pine Creek.** Extensive glacial activity along Big Pine Creek has occurred during the Quaternary. Large, well-formed Tahoe age lateral moraines extend from the mouth of Big Pine canyon westward toward the base of the mountain peaks. These range in height from 300 to 800 feet above the valley floor. All traces of a terminal moraine have been removed. North and adjacent to the large lateral moraine is an older Sherwin moraine with no morainal form. The eastern-most portions of these moraines are of interest for this paper.

Bateman (1965) mapped these two moraines as Tahoe and Sherwin in age. He bases these dates as do others in the Big Pine 15 minute quadrangle upon physiographic and general weathering characteristics. These include spatial relationships, degree of dissection, relative abundance of faults, the abundance of boulders at the surface, and the general condition of the weathered boulders (1965, p. 161-165). A more quantitative investigation was later undertaken by Fleisher (1967) who substantiated these ages with weathering ratio, boulder count, and other data. The granodiorite-weathering ratio for the Sherwin he found to average 9:91 (Fresh:Weathered). This is consistent with data from other
previously investigated drainages in Owens Valley (Table 3). His Tahoe weathering ratios average 24:76, again within the range for this age group (Table 4).

Four alluvial deposits have been mapped just east of the moraines (Figures 7 and 8). This author believes all of these to be post-Tahoe in age. This is based upon the existence of a great abundance of fresh boulders on the surfaces and a lack of deep river erosion or gullies. Any Sherwin outwash has either been buried or stripped off by later outwash.

The faulting in this area has been almost exclusively antithetic (mountain-down). The scarps vary in length from a few yards to approximately two miles. This antithetic faulting has occurred in the Sherwin moraines and post-Tahoe age outwash. Recent alluvial material can be found ponded behind all of the major scarps. Younger outwash material which was deposited on top of older material (Qa\textsubscript{3} on Qa\textsubscript{4}, Fig. 7) has since been faulted. This has possibly changed the course of the river northward to its present location. Vegetation growth has also greatly increased behind major antithetic faults as seen on Figure 7. Several of these faults have displaced pre-Cenozoic bedrock and display vertical offsets of about 60 feet (Fig. 9).

The only normal faults (valley-down) are located in the right lateral Tahoe moraine (Fig. 8). These probably extended to either side of the lateral but have since been weathered by post-Tahoe erosion. Displacements measured
Figure 6. Faulted Sherwin and Tahoe Age Moraines and Outwash West of Big Pine, California (NE Corner of the Big Pine 15' Quad, Adapted from Bateman, 1965, Scale 1:62,500).

- Glacial outwash associated with moraine
- Tahoe age moraine
- Sherwin age (or older) moraine
- Fault trace, ball on downthrown side
Figure 7. Big Pine Area, Photograph #OV-9-9-6, Scale 1:12,000.
Figure 8. Big Pine Area, Photograph #OV-9-9-8, Scale 1:12,000.
Figure 9. Big Pine Area, Photograph #0V-9-8-46, Scale 1:12,000.
along these scarps are 16 and 15 feet.

Scarp profiles were measured on several of the antithetic faults and the two normal faults in an attempt to observe multiple offsets. This proved to be of little value since no noticeable breaks in slope were detected when the data was plotted (Figures 10, 11, 12). The author thinks that multiple faulting probably occurred on several of the large antithetic faults. This seems more reasonable than the assumption of a single occurrence causing several feet of displacement. Future trenching across the scarps may lead to a definite answer.

Tinemaha Creek. This drainage has received large glacial deposits, yet less extensive than those of Big Pine Creek. The Tahoe age lateral moraines as high as 220 feet bound the south side of the creek (Fig. 14). The terminal moraine has also been removed from this drainage. An older moraine, lacking in any morainal form exists north of Tinemaha Creek. The eastern extent of these deposits have been examined in this study.

These deposits were previously mapped by Bateman (1965). The distinct lateral moraine is dated as being of Tahoe age, the northern moraine is dated as Sherwin. Bateman used the same physiographic criteria here as in Big Pine Creek and Taboose Creek drainages.

The author field checked these moraines and took granodiorite-weathering ratios to verify the ages. The ratios taken on the older moraine substantiated the Sherwin
Legend - Big Pine Creek

- \( Q_r \) = Present River Channel
- \( Q_{al1} \) = Recent Ponded Alluvial Fill
- \( Q_{al2} \) = Prior River Outwash of Post-Tahoe Age
- \( Q_{al3} \) = Older Alluvial Outwash of Tahoe - Post-Tahoe Age
- \( Q_{al4} \) = Older Alluvial Outwash of Tahoe Age
- \( Q_{ta} \) = Tahoe Age Moraine
- \( Q_{sh} \) = Sherwin Age Moraine
- \( B \) = Bedrock

Fault, Dashed Where Approximate, Ball On Downthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 10. Scarp Profiles - Big Pine Ck.
Figure 11. Scarp Profiles - Big Pine Ck.
Figure 12. Scarp Profiles - Big Fine Ck.
Figure 13. Faulted Sherwin and Tahoe Age Moraines and Outwash at Tinemaha and Taboose Creeks (SE Corner Bis Pine 15' Quad, Adapted From Bateman, 1965, Scale 1:62,500).
Figure 14. Tinemaha Creek, Photograph #OV-9-8-38, Scale 1:12,000.
agé, averaging 10:90 (Table 3). This is consistent with other Sherwin moraines along the eastern slope of the Sierra Nevada. The Tahoe moraine was also verified with six counts averaging 30:70 (Table 4). Other criteria that support the ratio results include (1) the Tahoe lateral maintains its morainal form whereas the Sherwin is void of form, (2) the relative abundance of boulders on the surface of the Tahoe moraine is greater than the Sherwin, (3) the soil color of the Tahoe moraine is greyish whereas the Sherwin has a reddish-brown hue, and (4) the Tahoe moraine is much less eroded and contains fewer gullies.

Alluvial deposits east of the moraines can be broken into four groups. Recent alluvium is found ponded behind major antithetic faults. The next two units form benches above the present stream channel suggesting multiple periods of down cutting. These are believed to be related to wetter, post-Tahoe climates and to tectonic rejuvenation. Because of its proximity to the Sherwin moraine, the oldest glacially related alluvial deposit is believed to be of Sherwin age. Younger glacial debris has been deposited farther to the south and east so that no interfingering has occurred.

Faulting in this region has occurred in the Sherwin moraine and outwash debris. No fault scarps have been found extending into the Tahoe moraine or younger deposits. These scarps are exclusively antithetic and presently exhibit about 6 feet of vertical offset in the outwash material. It is highly probable that the scarps originally displayed
greater displacement but have since ponded recent alluvium thus decreasing the apparent offset. The base of the scarp located in the Sherwin moraine has been modified and cut deeper by erosion. No true displacement measurements can be taken at this location due to past erosion and deposition. These scarps have altered Fuller Creek which borders the Sherwin moraine. They have caused the old river to change its course to its present northern location. Vegetation growth behind these scarps has increased due to ponded subsurface water.

Five scarp profiles were measured in an attempt to detect any break in slope (Figures 15, 16). This failed to produce any usable data from which to infer multiple movements. These results were expected considering the local erosion and deposition. The fault scarps have been well rounded by erosion and ponded alluvium has collected behind the antithetic faults. The data has been included for future reference.

**Taboose Creek.** When aerial photographs of the Taboose Creek drainage were first examined the left lateral moraine appeared to have been displaced by normal faulting. Bounded weathering ratios averaging 22:78 (Table 4) and physiographic evidence substantiated Bateman’s belief that the moraine is of Tahoe age (1965).

Later examination of the outwash terraces leads the author to believe that the moraine has not been faulted. Three distinct terraces have been cut at the mouth of the canyon (Fig. 17). The oldest terraces, Qal3, are situated
Legend - Tinemaha Creek

Qr = Present River Channel
Qal₁ = Recent Ponded Alluvial Fill
Qal₂ = Prior River Bench
Qal₃ = Post-Tahoe Outwash
Qal₄ = Post-Sherwin Age Outwash, May Include Tahoe Outwash
Qf = Alluvial Fan, May Include Post-Sherwin Outwash
Qta⁻ = Tahoe Age Moraine
Qsh = Sherwin Age Moraine
B = Bedrock

--- Fault, Dashed Where Approximate, Ball On Downthrown Side
----- Unit Contact, Dashed Where Approximate
---- Cross Section Location

Figure 15. Scarp Profiles - Tinemaha Ck.
Figure 16. Scarp Profiles - Tinemaha Ck.
Legend

Qr = Present River Channel
Qal₁ = Recent Ponded Alluvial Fill
Qal₂ = Prior River Bench
Qal₃ = Older River Bench
Qf₁ = Alluvial Fan Deposits
Qf₂ = Older Alluvial Fan
Qta = Tahoe Age Moraine
B = Bedrock

Fault, Dashed Where Approximate, Ball on Downthrown Side.

Unit Contact, Dashed Where Approximate.

Figure 17. Taboose Creek, Photograph #OV-9-8-34, Scale 1:12,000.
between the two lateral moraines north of the present river channel. One of the \( Qa1_3 \) terraces is located at the eastern base of the left lateral forming a lineation at the contact. This lineation is therefore erosional and not fault related. This belief is substantiated by the lack of lateral extent for this lineation.

**Independence Creek.** The eastern portion of the lateral moraines at Independence Creek were the next to be examined (Fig. 19). In this area of the canyon the moraines extend in height to 300 feet above the present river channel. The morphology of the laterals is well preserved although the end moraine has been totally eroded away. Smaller, younger moraines exist higher up the canyon, however these do not exhibit fault displacements.

The lateral moraines of interest to this report are dated Tahoe in age by Moore (1963). He bases this upon physiographic age criteria as did Bateman for the Big Pine quadrangle. An in depth study of the Independence Creek - Onion Valley geology is presently being done by Gillespie (personal communication). He presently agrees with Moore that these particular laterals are of Tahoe age and bases this upon preliminary granodiorite-weathering ratios as well as physiographic evidence.

Two normal faults have cut the Tahoe lateral moraine which is located on the south side of Independence Creek. These scarps have good expression but can only be traced to the morainal boundary. The westernmost fault (II) can again
Figure 18. Faulted Tahoe Moraine at Independence Creek (SE Corner Mt. Pinchot 15' Quad, Adapted From Moore, 1963 Scale 1:62,500).
Figure 19. Independence Creek, Photograph #ELI-3-233, Scale 1:15,840.
be found extending into the bedrock and alluvial deposits north of Independence Creek. No scarps were located in the northern lateral or outwash material. Vertical displacements on these two scarps were measured at 33 and 40 feet. Measurements for scarp profiles were also taken to reveal the occurrence of multiple events (Fig. 20). The profile for scarp I1 does not reflect a break in slope. Scarp I2, however, shows a subtle slope break between 21° and 25°. This implies the occurrence of two faulting events since the moraine was deposited.

Sheperd Creek to George Creek. South of Independence Creek, in the vicinity of Symmes Creek, begins a single, normal fault scarp which extends southward for many miles. This fault trace intersects talus slopes, alluvial and outwash deposits at the base of the range.

No glacial moraines extend from the canyon mouths in this region so other criteria must be used to establish a time horizon. Large outwash fans have been deposited beyond the canyons and are believed by the author and Gillespie (personal communication) to be of Tahoe age or younger. This is based upon physiographic evidence located at the mouths of Sheperd, North and South Bairs, and George Creeks. The outwash fans contain a high percentage of fresh granitic boulders as compared with adjacent older alluvial fans. These are believed to have been deposited as the Tahoe glaciers melted higher up the canyons. This formed large fans with a high concentration of boulders. If the outwash were older, the boulders
Legend - Independence Creek

Qr = Present River Channel
Qal = Recent Post-Tahoe Outwash Plain
Qta = Tahoe Age Moraine
B = Bedrock

Fault, Dashed Where Approximate, Ball On Downthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 20. Scarp Profiles - Independence Ck.
would be less frequent and show greater weathering effects as on the Sherwin moraines farther north. Some degree of benching has also occurred above the present stream channels. These forms probably were cut during wetter climatic periods in post-Tahoe time.

On the north side of Sheperd Creek, the normal fault trace has offset this outwash material (Fig. 22). Measurements taken show that 22 feet of vertical displacement has occurred although scarp profiles indicate only one period of offset (Fig. 23). None of the old stream benches or younger deposits display any offset.

The fault scarp continues south to North Fork Bairs Creek and beyond. Again, the fault has only cut the upper surface of the fan and not the younger stream features. Measurements on the north and south side of the creek show 22 and 27 feet of normal displacement. Scarp profiles display smooth surfaces with no major slope breaks.

At South Fork Bairs Creek and George Creek, the normal displacement has only offset the older surfaces and not the younger benches (Figures 26, 28). Measurements on the scarps reveal 26 and 28 feet of displacement, respectively. The profiles, again, form smooth surfaces (Figures 27, 29).

The scarp data in the region south of Independence, is very similar from drainage to drainage. This indicates that the tectonic movements along the fault zone in post-Tahoe time have been rather minor. Detailed trenching investigations in the future could substantiate the number of events that
Figure 21. Faulted Tahoe Glacial Debris, Sheperd to George Creek (NE Corner Mt. Whitney and NW Corner Lone Pine 15' Quads Scale 1:62,500.
Figure 22. Sheperd Creek, Photograph #ELI-4-210, Scale 1:15,840.
Legend - Sheperd Creek

Qr  = Present River Channel
Qal₁  = Recent River Channel
Qal₂  = Post-Tahoe Age Outwash
Qal₃  = Alluvial Fan Deposits
B  = Bedrock

Fault, Dashed Where Approximate, Ball On Downthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 23. Scarp Profile - Sheperd Ck.
Figure 24. North Bairs Creek, Photograph #ELI-4-212, Scale 1:15,840.
Legend - North Bairs Creek

Qr = Present River Channel
Qal\(_1\) = Post-Tahoe Age Outwash
Qal\(_2\) = Younger Alluvial Fan Deposits
Qal\(_3\) = Older Alluvial Fan Deposits
B = Bedrock

Fault, Dashed Where Approximate, Ball on DOWthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 25. Scarp Profile - North Bairs Ck.
Figure 26. South Bairs Creek, Photograph #ELI-5-195, Scale 1:15,840.
Legend - South Bairs Creek

Qr = Present River Channel
Qal₁ = Post-Tahoe Outwash
Qal₂ = Alluvial Fan Deposits
B = Bedrock

Fault, Dashed Where Approximate, Ball On Downthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 27. Scarp Profile - South Bairs Ck.
Figure 28. George Creek, Photograph
#ELI-5-153, Scale 1:15,840.

Figure 29. Bosoy Profile - George Creek.
Legend - George Creek

Qr = Present River Channel
Qal₁ = Post-Tahoe Outwash
Qal₂ = Post-Tahoe Outwash, May Include Minor Morainal Material
Qal₃ = Alluvial Fan Deposits
Qt = Talus
B = Bedrock

Fault, Dashed Where Approximate, Ball On Downthrown Side
Unit Contact, Dashed Where Approximate
Cross Section Location

Figure 29. Scarp Profile - George Ck.
have actually occurred. Scarp profiles indicate only one fault event although the author believes in the occurrence of two or three tectonic events which would have produced 20 feet of displacement. All the fault measurement data is summarized on Table 5.

Discussion

The data contained in the previous pages can be used to estimate rates of recent tectonic movement along the eastern Sierra Nevada. This can be done by comparing the amount of normal displacement in glacial debris with the age of the debris. The author believes these rates reflect a cumulative trend. This trend is comprised of major earthquakes in the given period of time as opposed to constant displacement. Carver cites (1969) the comparison of deformation of a sequence of old shorelines from Owens Lake and the precision of measurements of U.S.G.S. and U.S.C. and G.S. benchmarks between 1905 and 1962 to show that no significant changes in elevation have occurred at a constant rate in recent time.

Wallace (1977) has generated graphs relating the slope angle to the age of scarps. An attempt has been made by this author to relate these curves to the Owens Valley scarps.

In the northern part of the study area, faulting is mainly of the antithetic type and related to the formation of the Coyote Qarp. Only two normal faults are located and measured, those being in the Big Pine drainage. These display about 16 feet of vertical displacement in the Tahoe till.
Table 5. Fault Measurements.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type Deposit</th>
<th>Maximum Age</th>
<th>Type Fault</th>
<th>Vertical Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Pine BP1</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Antithetic</td>
<td>5'</td>
</tr>
<tr>
<td>Big Pine BP2</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Antithetic</td>
<td>8'</td>
</tr>
<tr>
<td>Big Pine BP3</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Big Pine BP4</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Big Pine BP5</td>
<td>Moraine</td>
<td>Tahoe</td>
<td>Normal</td>
<td>15'</td>
</tr>
<tr>
<td>Big Pine BP6</td>
<td>Moraine</td>
<td>Tahoe</td>
<td>Normal</td>
<td>16'</td>
</tr>
<tr>
<td>Big Pine BP7</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Antithetic</td>
<td>9'</td>
</tr>
<tr>
<td>Big Pine BP8</td>
<td>Moraine</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>12'</td>
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<td>Big Pine BP9</td>
<td>Moraine</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>12'</td>
</tr>
<tr>
<td>Big Pine BP10</td>
<td>Moraine</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>8'</td>
</tr>
<tr>
<td>Big Pine BP11</td>
<td>Moraine</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>11'</td>
</tr>
<tr>
<td>Tinemaha Ck T1</td>
<td>Outwash</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>3'</td>
</tr>
<tr>
<td>Tinemaha Ck T2</td>
<td>Outwash</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Tinemaha Ck T3</td>
<td>Outwash</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Tinemaha Ck T4</td>
<td>Outwash</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Tinemaha Ck T5</td>
<td>Outwash</td>
<td>Sherwin</td>
<td>Antithetic</td>
<td>6'</td>
</tr>
<tr>
<td>Independence Ck I1</td>
<td>Moraine</td>
<td>Tahoe</td>
<td>Normal</td>
<td>33'</td>
</tr>
<tr>
<td>Independence Ck I2</td>
<td>Moraine</td>
<td>Tahoe</td>
<td>Normal</td>
<td>40'</td>
</tr>
<tr>
<td>Sheperd Ck S1</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Normal</td>
<td>22'</td>
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<td>North Bairs Ck NB1</td>
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<td>Tahoe</td>
<td>Normal</td>
<td>16'</td>
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<tr>
<td>North Bairs Ck NB2</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Normal</td>
<td>27'</td>
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<tr>
<td>South Bairs Ck SB1</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Normal</td>
<td>26'</td>
</tr>
<tr>
<td>George Ck G1</td>
<td>Outwash</td>
<td>Tahoe</td>
<td>Normal</td>
<td>28'</td>
</tr>
</tbody>
</table>
Since the scarps are believed to be post-Tahoe, the youngest Tahoe age will be used for rate calculations (from Table 1). Therefore, 16 feet of displacement has occurred in 60,000 years or a rate of 0.27 feet per 1000 years. If this rate is compared to Wallace's (1977) graphs of scarp angle versus fault age, the same scarp would be dated $10^5$ to $10^6$ years in age. This far exceeds the maximum age possible for the fault scarps and will not be used for rate calculations. The age discrepancy probably results from Wallace's graphs having been constructed from faults located in different material types and having different climatic histories.

Fault displacements in the southern part of the study area show little height variance over a distance of six miles. At Independence Creek, 33 and 40 feet of vertical displacement has occurred in a Tahoe age moraine. These displacements, when related to the morainal age reflect 0.55 and 0.67 feet per 1000 years. The fault offsets at Sheperd Creek and farther south are less than those of Independence Creek. Sheperd Creek displays about 22 feet of normal displacement for a rate of 0.38 feet per 1000 years in post-Tahoe debris. The displacements at North and South Bairs and George Creeks were used to calculate rates ranging from 0.43 to 0.46 feet per 1000 years. The consistancy of these rates is very reasonable since the displacements were measured along the single fault trace (Fig. 21). It suggests that this southern portion of the fault zone has been more active in recent time than the region west of Big Pine (ie. 0.4 feet per 1000 years
versus 0.3 feet per 1000 years, respectively).

The average scarp height is 25 feet in the post-Tahoe outwash. This displacement calculates to a rate of 0.4 vertical feet per 1000 years. If Wallace's graphs are applied to this southern region, the scarps in this outwash debris are more recent than Tahoe age. In this case they would range from 500 to 5000 years old thus giving rates of displacement between 5 and 50 feet of vertical offset in 1000 years. The author questions these rates based upon the lack of fresh scarps along this fault zone as well as a lack of fault scarps in the younger stream terraces. Therefore the author's rates for the southern region are believed to be more accurate.

Assuming that these cumulative rates can be applied to the time since the formation of the present Sierra Nevada (the last 3 million years), a total displacement of 810 to 1200 feet would have been attained. The Sierra Nevada has undergone 19,000 feet of displacement in 3 million years, therefore a more rapid period of uplift has occurred in pre-Tahoe time.

This conclusion is also supported by calculating the cumulative rate of displacement of the Sierra Nevada over the last 3 million years. As mentioned above, 19,000 feet of displacement has occurred during this time thus giving a rate of 6.3 feet per 1000 years. Since the Tahoe moraines were deposited 60,000 to 75,000 years ago, they should exhibit 380 to 470 feet of fault offset. In actuality, no displacements of this size were located. Therefore, pre-Tahoe rates of
displacement were more rapid than those at present.

Following the principal uplift of the Sierra Nevada and formation of Owens Valley, processes of erosion and deposition began to play a major role in shaping the present topography. Two distinct areas of alluvial fans have developed on the frontal slopes along with colluvial accumulations.

During the more recent periods of time, glaciers advanced and carved their way down pre-existing access channels. These glaciers deposited lateral moraines in the valleys and terminal moraines at the upper reaches. Intermittent periods of melting offset these moraines that extended over the eastern valley fault zone. This produced a record of post-glacial displacements along this fault zone.

The Shaver and Tule stage glaciers extended into the valley far enough to intersect the fault zone. Only the lower terrane and associated deposits now have evidence of normal faulting. Both ages of glacial deposits show west-verging or anti-thetic faulting associated with the major front moraine. These anti-thetic faults do not record the actual vertical tectonic movements that have produced the present mountain relief.

Detailed mapping and measurements of the surface deposits in the alluvial deposits, combined with knowledge of the ages of the deposits allows for the calculation of uplift rates. The one given for the Owens terrane is believed correct by
CHAPTER 5

SUMMARY

Following the principal uplift of the Sierra Nevada and formation of Owens Valley, processes of erosion and deposition began to play a major role in forming the present topography. Two distinct ages of alluvial fans have developed on the frontal slopes along with volcanic extrusions.

During the more recent periods of time, glaciers advanced and carved their way down pre-existing stream channels. These glaciers deposited lateral moraines in the valleys and terminal moraines at the canyon mouths. Intermittent periods of faulting offset those moraines that extended over the western valley fault zone. This produced a record of post-glacial displacements along this fault zone.

The Sherwin and Tahoe stage glaciers extended into the valley far enough to intersect the fault zone. Only the Tahoe moraines and associated outwash now show evidence of normal faulting. Both ages of glacial deposits show west facing or antithetic faulting associated with the Sierra front warping. These antithetic faults do not record the actual vertical tectonic movements that have produced the present mountain relief.

Detailed mapping and measurements of the surface scarps in the glacial deposits, combined with knowledge of the ages of the deposits allows for the calculation of uplift rates. The age given for the Tahoe moraines is believed correct by
many researchers. From this, rates of displacement are calculated to be 0.27 to 0.4 feet per 1000 years in post-Tahoe time. These are quite small considering the total relief and age of the Sierra Nevada. Therefore, it can be concluded that faster rates of displacement existed in pre-Tahoe time and are responsible for the present topography.
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