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EXTENSIONAL FAULTING IN THE MINA REGION:
STUDY OF AN OLIGOGENE BASIN, WEST-CENTRAL NEVADA

by

JAVAN N. MEINWALD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
MASTER OF ARTS

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HOUSTON, TEXAS
FEBRUARY, 1982
ABSTRACT

EXTENSIONAL FAULTING IN THE MINA REGION:
STUDY OF AN OLIGOCENE BASIN, WEST-CENTRAL NEVADA

BY

JAVAN N. MEINWALD

Generally held ideas about Basin-Range faulting are incorrect in some areas. This paper presents the fault structure and history of the Upland Basin - a basin located in the Mina Region of the Basin-Range. Geologic mapping and two-dimensional gravity modelling of the Upland Basin indicate that the basin floor began subsiding more than 1.2 km along easterly-trending dip-slip faults about 27 Ma. Between 17 Ma. and 7 Ma., the basin was dissected by northerly-trending dip-slip faults in the west, and a northerly-trending strike-slip fault in the east. These fault motions reflect a history in which extension was northerly as early as 27 Ma. After 17 Ma. extension was westerly with an inhomogenous northerly-trending right-lateral shear. Mapped relations throughout the Mina Region are compatible with this kinematic history.

Fault kinematics of the Mina Region reflect a unique history with respect to the surrounding Basin-Range. Extension in the Mina Region existed earlier than elsewhere in the Basin-Range, where it is thought to have begun about 17 Ma., and was at first northerly not westerly as is generally believed.
ACKNOWLEDGEMENTS

For their assistance in surveying, I thank Mike Sidensticker, Scott Bowen, and Holly Dockery (all of Rice University).

For calculating terrain corrections by hand, I thank Betsy Julian, Karla Reverman, and Charles Haddock (all of Rice University).

Listings and maps of existing gravity data from the study area were provided by Allen Cogbill (Los Alamos Scientific Laboratory); and Peter Kirwin, Bob Whitman and Mr. Schempe (all of Conoco).

Discussion of the thesis and constructive criticism of the manuscript involved members of the Thesis Committee, Holly Dockery, Scott Bowen, Rick Coward, Bill Schmidt, Kate Pabst, and John Cuddihee (all of Rice University).

Finally I would like to thank all those people in the Geology Department who provided peripheral support.
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INTRODUCTION

In the Basin-Range (Fig. 1) faulting is generally considered to be the product of westerly extension because most Basin-Range faults trend north to north-northeast and have large dip-slip displacements. However, for that part of the Basin-Range within the western Great Basin (Fig. 1) faults strike in many directions and displacements are varied. Apparently a different and more complex model for faulting is necessary. Modifications have been made to the westerly extension model and another model has been proposed. However neither model adequately explains the faults.

This thesis deals with the structural development of a Cenozoic basin located in the Upland Valley. The valley is an easterly trending topographic depression between the Pilot Mountains and Gabbs Valley Range in Mineral County of west-central Nevada (Fig. 2). The structure of the Upland basin is ascertained from geologic maps and two-dimensional gravity models, all of which are presented in this study. Discussed are the kinematic history of faulting in the Upland Valley and its degree of compatibility with proposed models. A new model is proposed to account for faults of the Upland Valley and the surrounding Mina Region (Fig. 2).
Figure 1: The Basin-Range (hatchure), Great Basin (stipple), and Walker Lane of the western North America, after Proffett (1977).
Figure 2: Sketch map of Basin-Range faults showing the Mina Deflection, after Nielsen (1965), Wetterauer (1977), Oldow (unpub.), Oldow and Steuer (unpub.), Oldow and Speed (unpub.), and Oldow and others (unpub.). The dashed line encloses the Mina region and the dotted line encloses the study area.
THE WESTERN GREAT BASIN

FAULTS

The western Great Basin has two active fault types in addition to the northerly trending faults. These are, in order of abundance, NNW-trending faults with large right-lateral displacements and easterly trending faults with left-lateral displacements (Wright, 1979).

Most of the NNW-trending faults lie en echelon within the Walker Lane physiographic province (Fig. 1). The Walker Lane was originally defined by its low average elevations (Locke, 1940). More recently it has been considered a large shear zone with perhaps as much as 130 to 195 km of right lateral shear (see for example Albers, 1967; Stewart and others, 1968). Some of the shear is taken up by displacements along NNW-trending faults. The remainder is attributed to oroclinal bending (Albers, 1967).

Most easterly-trending faults in the western Great Basin are a part of the Mina Deflection, an easterly trending leg of a gigantic 'Z' defined by Mesozoic and Cenozoic contacts (Speed and Cogbill, 1979a). This 'Z' is shown in Figure 2 by the pattern of Cenozoic faults. What little is known about the displacements on easterly trending faults indicates that they are probably left-lateral strike-slip displacements (Speed and Cogbill, 1979a).

PROPOSED MODELS OF FAULT KINEMATICS

Two families of fault models, megashear and simple extension, have been proposed to explain the observed fault displacements in a wide zone of brittle failure in the western Great Basin. The inception of faulting
is generally considered to be about 17 Ma. (see for example McKee and Noble, 1974). Predicted fault motions for both models are discussed below and summarized in Table 1.

Atwater (1970) proposed a megashear model which postulates that displacements along Basin-Range faults are the product of a broad NNW-trending right-lateral shear. In her model the megashear results from the relative NNW-motion of the Pacific plate with respect to the North American plate and predicts certain fault motions: NNW-trending faults are right-lateral strike-slip faults; easterly trending faults are dip-slip faults; and N to NNE-trending faults are right oblique-slip faults with a small component of dip-slip. Thus, the megashear model can only account for the NNW-trending strike-slip faults. It can not account for the N to NNE-trending dip-slip faults or the strike-slip displacements on easterly trending faults.

The second family of models proposes that the Great Basin is undergoing simple extension in a westerly direction. Accordingly, N-trending faults are dip-slip faults; NNE and NNW-trending faults are left and right oblique-slip faults having only a small strike-slip component; easterly trending faults are strike-slip faults. Thus the westerly extension model can only account for the northerly trending faults with dip-slip displacements and the easterly trending faults with the strike-slip displacements. It can not account for observed NNW-trending faults with large strike-slip displacements (Hardyman and others, 1975); but these NNW-trending faults can be explained by the megashear model.
TABLE 1
Fault displacements and model-predicted fault motions

<table>
<thead>
<tr>
<th>Fault Trend</th>
<th>Displacement</th>
<th>Megashear</th>
<th>Simple Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-NNE</td>
<td>large dip-slip</td>
<td>largely strike-slip</td>
<td>largely dip-slip</td>
</tr>
<tr>
<td>ENE</td>
<td>strike-slip</td>
<td>dip-slip</td>
<td>largely strike-slip</td>
</tr>
<tr>
<td>NNNW</td>
<td>large strike-slip</td>
<td>strike-slip</td>
<td>largely dip-slip</td>
</tr>
</tbody>
</table>
GEOLOGY OF THE UPLAND VALLEY

BASINAL STRUCTURE

Field studies show that the Upland Valley is an asymmetric basin in which Cenozoic units overlie a depressed Mesozoic basement. The Cenozoic units dip toward an easterly-trending basin-axis. Exposed Cenozoic units are younger toward the axis. Geologic and gravity studies show that the northern basin limb dips gently to the south and the southern basin limb dips precipitously to the north.

GEOLOGIC UNITS

Basement

Basement consists of Mesozoic clastic, carbonate and intrusive rocks, exposed along the northern, eastern, and southern flanks of the Upland Valley (Fig. 3). The sedimentary rocks are composed of the Triassic Luning Formation and the Jurassic and Cretaceous Dunlap Formation (J. S. Oldow, oral comm. 1979). The intrusions are Cretaceous granitic rocks of probable Sierra Nevadan affinity (Nielsen, 1964). Outcrops of intrusive rock are small (<1.0 km²) and appear to be randomly distributed in the study area. The cumulative area of intrusive-rock outcrops is less than 2.0 km². Veining, fracturing, hydrothermal alteration and contact metamorphism of the sedimentary rocks are associated with aureoles around the intrusions. The aureoles are also minor in outcrop area.

Basin Fill/Cenozoic Units

A generalized Cenozoic stratigraphy of the Upland Valley is shown in a stratigraphic column, Figure 4. From the bottom to the top of the
Figure 3: Distribution of geologic units in the Upland Valley, shown in black from top to bottom and left to right are basement, older tuff, andesite, younger tuff, sedimentary rock, basalt, and gravels. Taken from Plate I.
GENERALIZED CENOZOIC STRATIGRAPHY OF THE UPLAND VALLEY

Major Units of the Upland Basin

<table>
<thead>
<tr>
<th>Exposed Thickness</th>
<th>Geologic Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5m</td>
<td>Gravel</td>
</tr>
<tr>
<td>0-20m</td>
<td>Basalt; flow</td>
</tr>
<tr>
<td>0-75m</td>
<td>Sedimentary Rock: conglomerate, sandstone, and mudstone</td>
</tr>
<tr>
<td>0-60m</td>
<td>Younger Ash Flow Tuff: two cooling units, having noncompacted sections (dotted) and compacted sections (other)</td>
</tr>
<tr>
<td>0-350m</td>
<td>Andesite: Brecia, flow and intrusive</td>
</tr>
<tr>
<td>0-150m</td>
<td>Older Ash Flow Tuff: four cooling units, having noncompacted sections (dotted) and compacted sections (other)</td>
</tr>
<tr>
<td></td>
<td>Basement</td>
</tr>
</tbody>
</table>

not to scale
column the units are older ash flow tuffs, andesite, younger ash flow
tuffs, sedimentary rock, basalt flow and gravels. Each unit is bound by
unconformities. Stratigraphic relations and gravity studies indicate that
only some of these units constitute a significant volume of fill in the
Upland Basin.

The older tuff is exposed around the perimeter of the valley (Fig.
3). Four ash flow units are exposed. Three units are a part of the
Benton Spring Group; the fourth is the Cedar Mountain Tuff (H. A.
Dockery, oral comm. 1980). Of the Benton Spring Group, the lowest unit
present may be the Gull Mine Member of the Mickey Pass Tuff (H. A.
Dockery, oral comm. 1980), dated elsewhere by K-Ar on minerals at about 27
My. old (Proffett, 1977 and Ekren and others, 1980). The two overlying
ash flows are part of the Singatse Formation (H. A. Dockery, oral comm.
1980), which is dated in the Upland Valley and elsewhere by K-Ar on
minerals at about 27 My. old (Proffett, 1977; Speed and Cogbill, 1979c;
Ekren and others, 1980). The stratigraphic position of the Cedar Mountain
Tuff with respect to ash flows of the Benton Spring Group is unknown but
the two successions are probably about the same age.

In the northern Upland Valley the older tuff onlaps the basement and
thickens depositionally to the south, from a feather edge to as much as
150 m of exposure. On the southern flank of the Upland Valley older tuffs
are juxtaposed with Mesozoic rocks by high-angle faults (Plate I).
The thickness of older tuff is probably 150 m or greater in the deepest
part of the basin.

Andesite of the Upland Valley is correlated with andesite of the
Candelaria Hills (J. S. Oldow and H. A. Dockery, oral comm. 1979), dated
at about 17 My. old by K-Ar on hornblend (Marvin and others, 1977). In the Upland Valley, andesite has the most extensive exposure of all rock units (Fig. 3). Like the older tuff, andesite onlaps to the north in the northern Upland Valley and thickens depositionally to the south. The preserved thickness of andesite also increases to the south, from a feather edge to as much as 350 m of exposure. Thus, the andesite is probably 350 m or thicker in the deepest part of the basin.

The younger tuff is exposed only in the west-central portion of the Upland Valley in two small outcrops totaling less than 1 km² (Fig. 3). The outcrops are preserved in a graben and a paleotopographic low. The unit is thin, less than 60 m, and displays no thickening trend. There is no indication that the younger tuff underlies younger units of the central valley or that it is a major component of basin fill.

Sedimentary rock of the Upland Valley is constrained as being 7.3 ± 0.2 My. old or younger based on K-Ar on biotites (Marvin and others, 1977). It is limited to central and west-central parts of the Upland Valley (Fig. 3) and is judged to be less than 75 m thick (J. S. Oldow, oral comm. 1981).

Basalt flows are limited to Table Mountain, north of the Upland Valley (Fig. 3). The basalt flows are less than 20 m thick and no thickening trend is recognized. There is no suggestion that the basalt underlies gravels of the central valley.

Gravels are limited to the central valley where they drape underlying rock and are dissected by arroyos (Fig. 3). The gravels are probably less than 5 m thick in the area of the the gravity study (J. S. Oldow, oral comm. 1981) and constitute an insignificant portion of the basin fill.
Stratigraphic relations show that there are only three geologic units which constitute a significant portion of fill in the basin. They are: older tuff, andesite, and sedimentary rock. Based on the sum of observed maximum thicknesses of Cenozoic units, basement is as deep as 575 m or more in the central Upland Valley.

Faulting

Geologic studies of the Upland Valley show that there are two major fault sets: one is northerly trending, superimposed on the other which is easterly trending (Oldow and others, 1979). Northerly trending faults have strikes that range from north-northeast to north-northwest, but the north-northwest trend dominates. As shown in Figure 5 the major northerly trending faults are the range-front faults, the Second Fault, Fault P, the Third Fault and the Battles Well Fault. From geologic and geophysical studies it is clear that these northerly trending faults are continuous from the southern Gabbs Valley Range to the northern Pilot Mountains, across the Upland Valley. Northerly trending faults with long trace lengths (>1 km) truncate and offset easterly trending faults, but are never truncated by easterly trending faults. The easterly trending set has a dogleg morphology with two populations of faults. The greater population has faults ranging in strike from east-northeast to east-southeast. The smaller population is north-northwest trending. As shown in Figure 5 the major easterly trending faults are the Old Fault, Fault E, and those faults which bound the northern edge of the Pilot Mountains.

The range-front fault of the northern Pilot Mountains is continuous with the Second Fault of the southern Gabbs Valley Range via Fault P in
Figure 5: Major faults of the Upland Valley. Taken from Plate I.
the Upland Valley (Fig. 5). Displacement along the range-front fault is predominantly dip-slip as determined by off-set on Mesozoic units. The throw on this fault system is about 300 m as seen in the northern Pilot Mountains and southern Gabbs Valley Range.

The Third Fault of the southern Gabbs Valley Range and the northern Pilot Mountains is continuous through the Upland Valley via a subsurface fault (see later). No significant strike-slip is recognized along the Third Fault. The throw along the subsurface segment of Third Fault is best defined by gravity studies which are presented later.

The Battles Well Fault is continuous from the northern Pilot Mountains, through the Upland Valley, to Table Mountain of the southern Gabbs Valley Range. North of Table Mountain the fault continues along strike at least another 18 km (Nielsen, 1965; Hardyman and others, 1979). South of the northern Pilot Mountains the fault continues at least another 10 km (Nielsen, 1965).

The Battles Well Fault truncates and offsets the ENE-trending Old Fault (Fig. 5). The offset is 2.0 km of right-lateral strike-slip. The 2.0 km displacement is also apparent on a pair of high-angle Mesozoic thrusts further south along the strike of the Battles Well Fault (Fig. 5). That the Old Fault is displaced the same distance as the thrusts shows that the Battles Well Fault post-dates the Old Fault. This age constraint and the continuity of northerly trending faults across easterly trending faults of the Upland Valley are the bases for the deduced superimposed relationship of fault sets.

Easterly trending faults which form the northern boundary of the Pilot Mountains appear to be complexly connected by short-trace faults,
forming a single dogleg fault (J. S. Oldow, oral comm. 1981). No large strike-slip displacements are recognized along the dogleg fault or the other easterly trending faults. However, from gravity studies, it is clear that some easterly trending faults have large dip-slip displacements, especially Fault E (see later).
GEOLOGY OF THE SODA SPRINGS VALLEY

The easterly-trending Upland Valley terminates to the west in the NNW-trending Soda Springs Valley. Exposed units in the Soda Springs Valley are Quaternary alluvial sediments. Faults which down-drop toward the basin are mapped along the east and west margins of the Soda Springs Valley (Fig. 2). On the east are the range-front faults of the southern Gabbs Valley Range and northern Pilot Mountains along with fault scarps at the mouth of the Upland Valley. Faults on the west side of the Soda Springs Valley are largely suballuvial. Recent work shows that strike-slip displacement along faults in the Soda Springs Valley is less than about 2.0 km and overall displacement is predominantly dip-slip (J. S. Oldow oral comm. 1979; also see later).
GRAVITY STUDY

PART I: BACKGROUND

Gravity Data

Gravity data for 366 stations were compiled for a detailed study of the Upland Valley and Soda Springs Valley (Appendix II). The stations cover an area of about 80 km². The data at each station are: location, elevation, observed gravity, referenced gravity base, and terrain correction. For the present study 177 stations were established along traverses across known and suspected fault traces, mostly in the southern Upland Valley. Conoco (unpub.) established 89 stations mostly along traverses trending northerly and easterly near the Copper Chief District, located in the eastern third of Upland Valley. Station spacing along traverses is about 200 m or less. Remaining stations were established in the western half of the study area by Cogbill (unpub.) and Healey (1976). All data were reduced to complete Bouguer anomaly values as summarized in Appendix I.

Bouguer anomaly values are accurate to within ± 0.6 mgals judging from the sum of the errors: referenced gravity base station, ± 0.3 mgals; station elevation, ± 0.06 mgals; instrument reading and drift plus tidal and latitude correction, ± 0.1 mgals; rounding error in reduction, ± 0.1 mgals.

The complete Bouguer anomaly values have an error contributed by terrain corrections. Terrain corrections for the Upland Valley were calculated out to about 21.9 km. Terrain corrections for six stations from Cogbill (unpub.) in the Upland Valley and all stations of this study were calculated by hand (Hammer, 1939) with an accuracy of ± 0.2
## TABLE 2

Comparison of Complete Bouguer Anomaly Values Reported for the Same Station by Different Surveyors

<table>
<thead>
<tr>
<th>Survey</th>
<th>CBA Difference (mgal)*</th>
<th>Stations in common**</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>0.14</td>
<td>6</td>
</tr>
<tr>
<td>Healey (1976)</td>
<td>0.34</td>
<td>8</td>
</tr>
<tr>
<td>Cogbill (unpub. data)</td>
<td>-0.40</td>
<td>12</td>
</tr>
</tbody>
</table>

* Complete Bouguer anomaly of the listed survey less the complete Bouguer anomaly from Conoco (unpub. data) for the same station.

**Number of stations in common between the listed survey and Conoco (unpub. data).
mgals or better. Terrain corrections of Conoco (unpub.) were calculated by machine (Plouff, 1976) with a reported accuracy of ± 0.1 mgals or better. Thus the sum of the errors in the complete Bouguer anomaly values for stations in the Upland Valley may be as great as ± 0.8 mgals. Data from the Soda Springs Valley includes that of Cogbill (unpub.) and Healey (1976), in addition to that of Meinwald (this study) and Conoco (unpub.) Where terrain corrections exist for stations of Cogbill (unpub.) and Healey (1976), they were calculated by hand (Hammer, 1939) to 2.2 km and by machine (Plouff, 1976) from 2.2 to 167 km. The accuracy of most of their terrain corrections is estimated at ± 0.3 mgals or better (Healey, 1976; Cogbill, 1979a). Although the sum of the errors for the complete Bouguer anomaly values of Cogbill (unpub.) and Healey (1976) from the Soda Springs Valley is ± 0.9 mgals (± 0.6 + ± 0.3 mgals), it should be noted that their values may be as much as 2.0 mgals too high relative to the values of the other surveyors because Cogbill (unpub.) and Healey (1976) use a greater terrain correction radius. Terrain corrections from Cogbill (unpub.) and Healey (1976) for stations in the Soda Springs Valley were not recalculated because they are typically only less than 1.0 mgal too high (see later) and they are from outside the principal area of interest.

As a check of the accuracies deduced above, there is a comparison of the complete Bouguer-anomaly values reported by different surveyors for the same stations (Table 2). The differences between the values reported by Conoco (unpub.) and the other surveyors are within the deduced accuracies. Conoco (unpub.) was chosen as the reference surveyor because it is the most accurate, having used the most accurate terrain
corrections and a gravimeter with the smallest dial constant.

Regional Gravity

The regional gravity was determined as a plane fit by the least-squares technique to six complete Bouguer anomaly values from stations located on basement in the southern Gabbs Valley Range and northern Pilot Mountains. The fit was accomplished by a general linear-modelling program of the Statistical Analysis System Institute, Inc. This method of regional calculation assumes that basement rocks do not contribute to gravity variations higher than first order in the study area. Work presented later shows this assumption is generally true.

The planar regional is inclined to the south-southeast with a gradient of 0.1483 mgals/km. Orthogonal components of the gradient are -0.1472 mgals/km north to south and -0.0012 mgals/km west to east. This amounts to a regional drop of about 1.8 mgals from north to south across the study area. The drop from west to east is less than 0.1 mgals and is insignificant.

As a check of the regional gravity trend, it is compared to that of a plane fit to the Bouguer anomaly field within 50 km of the central Upland Valley (Fig. 6). The field is approximated by 80 equally spaced values interpolated from a map sketched in Figure 6. The plane is inclined to the south-southeast as is the regional. The regional trend and the plane differ less than 0.01 mgals/km on each orthogonal component which is insignificant. Thus the choice of the regional gravity trend is good.

It is interesting to note that the trend of the regional gravity is also similar to the trend of a long-wavelength Bouguer-anomaly field of
Figure 6: Sketch of the Bouguer anomaly map of the western Great Basin (Cogbill, 1979). The heavy line is the California - Nevada border. The contour interval is 10 mgals. A dashed line encloses an area in which a plane was fit to the field. An asterisk marks the central Upland Valley.
the central study area (Fig. 7). The long-wavelength field drops between 1.0 and 2.0 mgals from north to south across the study area. The drop from east to west averages less than 0.4 mgals and is insignificant. That the trend of the long-wavelength field is so close to the regional trend suggests that the regional trend reflects structures having spatial wave-lengths of about 150 km.

Residual Anomaly

The residual anomaly is the regional gravity less the observed gravity. If local density variations in the basement are negligible, then the residual anomaly reflects the mass per unit area (product of the density and thickness) of basinal or Cenozoic rock. Since the residual values associated with Cenozoic rock in the study area are negative (Fig. 8), Cenozoic rock has a lower density than basement. Gravity lows have been repeatedly associated with basins of the Basin-Range filled with low density Cenozoic rock (see for example Thompson, 1959).

The residual anomaly map of the study area, Figure 8 and Plate II, shows two major negative anomalies. A -21 mgal anomaly is centered on the Soda Springs Valley and a -14.5 mgal anomaly is centered in the south-central Upland Valley. The -14.5 mgal anomaly indicates the existence of a sizeable basin which was previously unrecognized. This basin is here named the Upland Basin.

Simple Model of the Upland Basin

Using Talwani's (1970) gravity modelling program for two-dimensional anomalous masses, a simple model of the deepest part of the Upland Basin
Figure 7: Long-wavelength Bouguer anomaly map of the Upland Valley and vicinity (Cogbill, unpub.). The heavy line encloses the area of the gravity study. The roll-off wavelength is 116 km. Wavelengths greater than 150 km are unaffected and less than 95 km are removed by filtering.
Figure 8: Sketch of the residual Bouguer-anomaly map (Plate II) with gravity profiles A to F.
(the Upland Basin-deep) was constructed assuming that basin-fill is all of one density and that density is the greatest permissible. The gravity profile modelled is profile D, which passes through the lowest part of the anomaly and trends perpendicular to the highest gradient contours (Fig. 8). The model is shown in Figure 9. The model indicates that the density contrast, or basement density less the basin-fill density, is at least 0.63 g/cm$^3$ and the depth of the basin-deep is 1275 m.

Normally, modelling with a minimum density contrast produces a maximum basin depth. However, this may not be true here because of problems related to the assumption that the density of basin-fill is constant and because the real basin structure is not two-dimensional. Problems related to the assumption of constant-density fill will be treated later. The problem related to two-dimensionality is treated below.

A two-dimensional model is accurate only if the modelled structure extends two or more times its depth in each direction perpendicular to the plane of the model (Nettleton, 1976). The fact that the residual anomaly of the Upland Basin-deep has a total third-dimensional length of 3500 m and a modelled depth of about 1275 m means that the geometry of the basin-deep does not meet the criterion for an accurate two-dimensional model. The third dimensional effect does not change the interpretation of the minimum density contrast, but it does make the 1275 m depth a conservative maximum. The error due to the third dimensional effect, or the difference between the determined depth and the maximum depth, is not known quantitatively, but it is probably not large.

It is important to note two things at this point. First, the basin depth determined by gravity modelling is far greater than that expected
Figure 9: Simple two-dimensional model of the Upland Basin from profile D: curve of R (residual Bouguer anomaly) versus X (horizontal distance) is calculated; dots are contour values; curve of X versus Z (depth below surface) is the modelled anomalous mass. Fill is shown as white and basement as pattern. The basement depth to the north of the model shown decreases at a constant rate to a depth of zero at the mapped outcrop.
solely from stratigraphic relations and that this is a new and more accurate definition of the structure of the Upland Basin. Second, the minimum density contrast of Upland Basin fill, also determined by gravity modelling, is slightly larger when compared to density contrasts used by other workers in gravity modelling (see for example Thompson, 1959 and Felch, 1980) and the densities of most of the units in the basin (see later). Thus only a few units are candidates for being significant components of basin fill.

Density of Basement

Density variations in basement are negligible as shown by the low variability of densities measured on unaltered basement rocks (Table 3). Mean grain densities and dry bulk densities of unaltered basement rocks vary from 2.69 g/cm$^3$ to 2.61 g/cm$^3$ with a mean of 2.67 g/cm$^3$. Thus 2.67 g/cm$^3$ is assigned as the basement density.

Some density variability is noted in altered basement rock (Table 3). In the Copper Chief District it is associated with small positive and negative residual anomalies in the west and east (Fig. 8). Both anomalies have a short-wavelength (≤ 1 km) and low amplitude (≤ 2 mgals). Samples of the altered basement from outcrop and subsurface mines in the western Copper Chief have a mean density of 2.83 g/cm$^3$ (Table 3). In the eastern Copper Chief District alteration increased porosity an additional 5% or more, as estimated by examination of hand samples. Abundant open fractures and open space in veins also contribute to increased void space. The grain density of sampled veins averages only 2.36 g/cm$^3$ (Table 3). On the bases of the increased porosity and void space and the low density of
<table>
<thead>
<tr>
<th>Unit</th>
<th>No. of samples</th>
<th>Density, g/cm³</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
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<tr>
<td>Grain density</td>
<td></td>
<td></td>
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<tr>
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<td>unaltered</td>
<td>6</td>
<td>2.69</td>
<td></td>
<td>2.59-2.75</td>
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<tr>
<td>altered</td>
<td>3</td>
<td>2.83</td>
<td></td>
<td>2.62-2.99</td>
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<tr>
<td>vein**</td>
<td>2</td>
<td>2.36</td>
<td></td>
<td>2.31-2.42</td>
</tr>
<tr>
<td>Dunlap Frm.</td>
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<td>2.65</td>
<td></td>
<td>2.64-2.65</td>
</tr>
<tr>
<td>Dry-bulk density</td>
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<tr>
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<tr>
<td>Dunlap Frm.</td>
<td>6</td>
<td>2.61</td>
<td></td>
<td>2.57-2.64</td>
</tr>
</tbody>
</table>

* Altered rock is metamorphosed limestone from the western Copper Chief.
** Vein rock is from the eastern Copper Chief.
veins it is judged that altered basement rock of the eastern Copper Chief District is less dense than the assigned basement density. The random distribution of intrusions and their associated narrow aureoles in the Upland Valley shows they bear no relation to the -14.5 mgal anomaly of the Upland Basin.

Densities of Major Basin-Filling Units

The density of rock that fills the Upland Basin is an important parameter in determining the depth of the basin. Measured densities of the major basin-filling units vary widely (Table 4). Some rock units even have two or more facies of different densities.

The older tuff consists of noncompacted and compacted facies. The noncompacted facies is present in the upper and lower parts of cooling units and has a low mean density (1.82 g/cm³, dry bulk). The compacted facies is present in the middle part of cooling units and has a moderate mean density (2.37 g/cm³, dry bulk). In the margins of the Upland Valley, where the older tuff is exposed, the upper sections are almost completely eroded away and the lower sections are not well developed. Exposed tuff is compacted facies. Noncompacted facies may contribute an additional few tens of meters to the 150 m thickness of older tuff in the valley margin and contributes far more in the Upland Basin-deep (see later).

Andesite has three facies of different densities, breccia, flow and intrusive; the breccia has a mean density that is low (2.12 g/cm³, dry bulk); the flow has a mean density that is moderate (2.44 g/cm³, dry bulk); the intrusive has a mean density that is high (2.51 g/cm³, dry bulk). The intrusives are not exposed in the area of the gravity survey.
### TABLE 4

Densities of Cenozoic Rocks in the Upland Valley

<table>
<thead>
<tr>
<th>Unit</th>
<th>No. of samples</th>
<th>Density, g/cm³</th>
<th>Mean density contrast, g/cm³*</th>
</tr>
</thead>
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<td><strong>Dry-bulk density</strong></td>
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<td>Andesite:</td>
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<td></td>
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</tr>
<tr>
<td>breccia</td>
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<td>2.12</td>
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<tr>
<td>flow</td>
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<td>2.27-2.46</td>
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<td>1.63-2.01</td>
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<td><strong>Grain density</strong></td>
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<tr>
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<td>2.42-2.51</td>
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<td>Older Tuff:†</td>
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<tr>
<td>compacted</td>
<td>3</td>
<td>2.46</td>
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<tr>
<td>noncompacted</td>
<td>2</td>
<td>2.24</td>
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*continued next page*
TABLE 4 (cont.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Mean Porosity, %</th>
<th>Mean wet-bulk Density, g/cm³</th>
<th>Mean density contrast, g/cm³*</th>
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<tr>
<td>Younger Tuff:+</td>
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<td></td>
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<tr>
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<td>0</td>
<td>2.37</td>
<td>0.30</td>
</tr>
<tr>
<td>Andesite:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>breccia</td>
<td>6</td>
<td>2.18</td>
<td>0.49</td>
</tr>
<tr>
<td>flow</td>
<td>1</td>
<td>2.45</td>
<td>0.22</td>
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<tr>
<td>intrusive</td>
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<td>2.52</td>
<td>0.15</td>
</tr>
<tr>
<td>Older Tuff:+</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>compacted</td>
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<td>2.40</td>
<td>0.27</td>
</tr>
<tr>
<td>noncompacted</td>
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<td>2.00</td>
<td>0.67</td>
</tr>
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</table>

+ ash flow unit
* assigned basement density of 2.67 g/cm³ less the mean unit density in g/cm³
The exposed andesite is about 75% breccia and 25% flow rock. Using this estimate the calculated andesite density is 2.21 g/cm$^3$ (dry bulk). If intrusives are present in the survey area their effect would be to raise the density of andesite above the calculated value.

The Tertiary sedimentary rock has three facies, conglomerate, sandstone, and mudstone. The conglomerate has a mean density that is low (2.00 g/cm$^3$, dry bulk). The sandstone and mudstone are more dense than the conglomerate as judged in the field by heft of dry samples. This agrees with the average dry bulk densities of Tertiary conglomerates, sandstones and mudstones elsewhere (Daly and others, 1966; Telford and others, 1976). Therefore the sedimentary rock averages at least 2.00 g/cm$^3$.

Maximum Density Contrast of Basin Fill

Further information on the density contrast of basin-fill can be obtained by analysis of the density contrasts of the major basin-filling units. The maximum density contrast can be no more than the greatest dry-bulk density contrast of the units present. Dry bulk densities are always less than or equal to wet bulk densities of the same rock. Thus increasing fluid content increases the density and decreases the density contrast.

Noncompacted tuff has the greatest density contrast (0.85 g/cm$^3$). More dense units present in the basin reduce the average density contrast of basin fill from a theoretical high of 0.85 g/cm$^3$ by amounts corresponding to their proportion of fill and their difference in density contrast with noncompacted tuff. Thus a maximum density contrast of
basin-fill would exist if: 1) the thicknesses of the more dense units (compacted older tuff, andesite, and sedimentary rock) are no greater than their maximum exposed thicknesses; and 2) the remainder of the basin fill is the lowest density unit (noncompacted older tuff). These conditions are simulated mathematically by using a principle stated earlier: the gravity anomaly is proportional to the mass/area of basin fill (thickness [1275 m] times density contrast [0.63 g/cm³]). Substituting the known thicknesses and density contrasts the maximum density contrast of basin-fill is calculated to be 0.67 g/cm³ and the minimum thickness or basin depth is 1200 m.

Model Density Contrast

The minimum and maximum density contrasts provide a narrow range of possible density contrasts that can be used to model basement depth in the Upland Basin. Two-dimensional models of basement depth in the following section use the maximum density contrast 0.67 g/cm³. Thus, the models indicate minimum depths to basement and minimum dips of the basement walls and floor.

Although little is known about the geology of the Soda Springs Valley it is assumed the model density contrast is applicable for modelling basement depth there. If the modelling density contrast is in error, it is likely to be too high (see earlier) and calculated depth thus too shallow.

PART II: INTERPRETATION OF CENOZOIC FAULTING

Easterly Trending Faults

The -14.5 mgal anomaly of the Upland Basin has high gradient contours trending east-southeast, north and south of the low or basin-deep, and
and north-northeast west of the low. Basin-deep margins presumably have the same trends. Gravity profiles B, C, and D are subperpendicular to the high-gradient contours of the basin-deep anomaly (Fig. 8 and Fig. 10). These profiles are most suitable for two-dimensional modelling of the basin-deep margins. Profiles C and D define the northern and southern margins; profile B defines the western and eastern margins.

The margins of the basin-deep are basement scarps on three sides: the north, south and west (see models B, C, and D). The eastern margin of the basin-deep may be a smooth low-angle basement surface (model B) or a basement scarp. Model B was not used in a basement depth determination because it has strong third-dimensional effects. Therefore model B is not inconsistent with the minimum depth of 1200 m. Gravity data along the eastern margin is too sparse for a clear definition of the margin. The basement scarps are high-angle and some are coplanar with, or on-strike extensions of, mapped faults. Thus the scarps are interpreted as the expressions of subsurface faults and the scarp heights as their throws on basement. Thus the northern, southern, and western margins of the basin-deep are formed by high-angle normal (extensional) faults; the eastern margin of the basin-deep may be a crustal flexure or a zone of diffuse faulting.

The surface projection of the basement scarp along the southern margin is approximately coincident with Fault E (Fig. 8). The surface projection of the western basement scarp is approximately on strike with Fault O (Plate II). Both faults have the same sense of displacement as their associated basement scarps. The suggestion is that these basement scarps are the subsurface expressions of the mapped faults.
Figure 10: Gravity profiles A-F of the Upland Valley and adjacent Soda Springs Valley as located on the sketch map (Fig. 8) and Plate II. See caption for Figure 6. Abbreviations: SSV - Soda Springs Valley; UB - Upland Basin deep; T-Third Fault; BW - Battles Well Fault; G - Fault G; I - Fault I; C - Fault C; D - Dogleg Fault.
No fault is mapped near the basement scarp of the northern margin or the gently dipping basement of the eastern margin. However the basement scarp of the northern margin is thought to be fault-related because of its high angle (models C and D).

It was previously shown that the depth of the Upland Basin is at least 1200 m. Basement depths along the uplifted sides of the basin-deep within the Upland Valley are about: 500 m on the north; 100 to 200 m on the south; about 500 m on the east; and 350 m on the west (see models A, B, C, and D). The difference between these depths and the depth of the basin-deep is the approximate throw on basement. The throw along the northern margin is about 700 m. The throw along the southern margin (Fault E) is 1000 to 1100 m. The throw along the eastern margin is about 700 m, of which some may be flexure. The throw along the western margins is about 850 m.

Along the southern margin of the Upland Valley basement is shallow (models C and D) and is exposed within a couple of kilometers of the basin-deep (Fig. 8). Basement shallows smoothly and no basement scarps are present. Indeed no faults are mapped except the ENE-trending Fault G which bounds the southern edge of basin-fill (Fig. 8.) Throw along Fault G is indicated to be at most a couple of tens of meters (model C). However in model C there is a small basement depression south of the basin-deep. It has a depth of 400 m. The depression may be unrelated to faults such as topography developed on basement before deposition of Cenozoic rocks.

East of the Third Fault, the throw along the dogleg faults is small, as it is to the west. In the east the throw is about 200 m or less
Just north of the basin-deep the basement shallows smoothly from about 500 m to 150 m (models C and D). Some of the shallowing is probably the result of crustal flexure associated with asymmetric faulting to the south. Some is probably the product of faulting even though the basement slope is low-angle. The spatial density of gravity data may be the cause of the shallow slope.

Northerly Trending Faults

The Third Fault of the southern Gabbs Valley Range and northern Pilot Mountains is continuous via a subsurface fault in the Upland Valley. The subsurface fault trends northerly and is shown as the basement scarp T in models A and E. The height of the scarp is 200 m in both profiles and approximates the throw along the Third Fault.

Throw along the Battles Well Fault is only about 200 m, downthrown to the west (model A). That the strike-slip displacement is 2.0 km (see earlier) means that the Battles Well Fault is a strike-slip fault.

The calculated and observed gravity values of profile A differ east of the Battles Well Fault, probably because of a strong third-dimensional effect. The effect results from the limited third dimensional length of basement outcrop east of the Battles Well Fault or perhaps locally low-density basement.

Soda Springs Valley

Profile A crosses the Soda Springs Valley (Fig. 8). The profile is subperpendicular to the strike of the valley and the range-front faults of the southern Gabbs Valley Range and northern Pilot Mountains. Model A
indicates that the Soda Springs Valley is underlain by a deep basin. The Soda Springs Basin is separated from the Upland Basin, to the east, by a basement high. West of the high basement deepens to about 1250 m in the central Soda Springs Valley, about 3 km north-northwest of Mina (Fig. 8). Thus the Soda Springs Basin is about as deep as the Upland Basin.

Modelled basement along the eastern margin of the Soda Springs Valley is smooth and dips gently west (model A). This gentle dip is interpreted to be the result of closely-spaced faults which trend north-northwest, have small throws and are downthrown to the west. A few such faults are exposed as surface scarps a few meters high. The scarps are located in the eastern-most Soda Springs Valley at the western extent of the Upland Valley.

Modelled basement along the western margin of the Soda Springs Valley is also smooth. However large throw faults may be present. Gravity stations are so sparse along the western margin that if faults with large throws are present they could not be detected.
CONCLUSIONS ON THE UPLAND VALLEY

SUBSIDENCE HISTORY

Tectono-Stratigraphic Relations

The stratigraphy of Cenozoic units in the Upland Valley is related to the subsidence of the Upland Basin along easterly-trending normal (extensional) faults as old as 27 M.y. Subsidence of the Upland Basin is unrelated to northerly-trending faults which are younger than 17 M.y.

The northerly onlapping and southerly thickening of the older tuff and the andesite indicate that these units filled an easterly trending basin, presumably the Upland Basin. Thus, the Upland Basin began subsiding about 27 Ma. and continued at least until about 17 Ma. There is no indication of continued subsidence during deposition of the Tertiary sedimentary rock (J. S. Oldow, oral comm. 1981).

About 27 Ma. some basin relief developed. It probably restricted the distribution of ash flows of the Singatse Formation and the Cedar Mountain Tuff. The Upland Valley is the southernmost extent of Singatse ash flows, which had a source to the north near the Gillis Range (Ekren and others, 1980). The Cedar Mountain Tuff is only found to the east of the Upland basin-deep. From the eastern Upland Valley, where it is as much as 90 m thick, the Cedar Mountain Tuff is continuous to the east as far as the Cedar Mountains (H. A. Dockery, oral comm. 1979) where it is about 150 m thick (Speed and Cogbill, 1979c). Apparently the source of the Cedar Mountain Tuff was to the east of the Upland Valley and its ash flows were trapped by the northern, southern, and western margins of the Upland Basin-deep.

By 17 Ma. the basin was bound by the dogleg fault on the south
(Faults G to D). The fault restricted deposition of andesite breccia to an area north of it. South of the dogleg fault in the northern Pilot Mountains there is no andesite breccia although there is andesite flow and intrusive.

Basin relief about 7.3 Ma. was only minor. Field relations and facies analysis of the Tertiary sedimentary rock indicate that the sedimentary rock is nothing more than a thin unit deposited in a shallow, inactive basin (J. S. Oldow, oral comm. 1981). The thinness of the sedimentary rock is supported by arguments on basin kinematics presented later.

The age of inception of northerly trending faults is younger than 17 My. and older than 7.3 My. Depositional patterns of the older tuff and andesite is not affected by the northerly trending faults. These faults only offset these units; no onlapping, thickening, or facies relations indicate that northerly trending faults existed before about 17 Ma. The disparity in displacements of preTertiary rocks and Tertiary sedimentary rock indicates that significant displacements along the Second Fault took place before 7.3 Ma., the maximum age of Tertiary sedimentary rock.

Inference from Gravity Models

The objective of this section is to determine by gravity modelling the thicknesses of units which fill the Upland Basin and thereby infer the subsidence history of the basin with more detail than is possible from stratigraphic constraints alone. The thicknesses of basin-filling units are determined by two-dimensional gravity modelling of the basin-deep along profile D. Profile D was chosen for modelling because this profile
has the highest gradient, providing a constraint on the minimum density
contrast and maximum depth of the thickest fill unit.

A four-layer model is used. Three layers represent Tertiary rocks:
older tuff, andesite and sedimentary rock. The fourth layer represents
basement. All models use the assigned basement density of 2.67 g/cm³.
All models use dry bulk density contrasts for the fill units, for reasons
as follows. Basin fill is dry near the surface because of very low
regional precipitation. Fill must be dry or impermeable at depth because
density contrasts of exposed [surface] fill units when saturated [wet
bulk] are too low to produce the observed gravity anomaly. The basin-deep
is approximated as having vertical walls for ease in modelling. This
approximation has little effect on the interpretation of the final models.
Two models are shown in Figure 11.

In model 1 the tuff alone is thickening basinward. In model 2 the
tuff and the andesite are thickening basinward. Both models assume that
the compacted tuff and andesite, have minimum basin-deep thicknesses of
150 m and 350 m respectively. Also assumed is that the sedimentary rock
is no thicker than 75 m.

Model 1 shows that the tuff, consisting mostly of noncompacted facies
can fill up to 60% of the basin-deep. On the other hand Model 2 indicates
that the andesite can fill up to 50% of the basin-deep if the sedimentary
rock is no thicker than 75 m. It is important that in both models the
tuff and the andesite are of nearly equal thickness. It is also important
that most of the basin-deep tuff is noncompacted facies, according to
arguments presented earlier on the minimum density contrast of basin fill.
Figure 11: Two four-body models of the Upland Basin, profile D. Fill units are tuff (heavy dot), andesite (intermediate dot) and sedimentary rock (light dot).
It is clear from modelling that the tuff thickens substantially in the basin-deep and the andesite may thicken substantially. The tuff thickens by increasing amounts of non-compacted facies. Basinward thickening of andesite alone can not account for all of the gravity anomaly because its density is too high.

KINEMATIC INTERPRETATION

Northerly-Trending Fault Set

Northerly trending faults of the Upland Valley are activated by westerly extension and inhomogenous NNW-trending right-lateral shear. Displacements along northerly trending faults of the western Upland Valley are compatible with simple westerly extension because the displacements are predominantly dip-slip. Examples of faults with dip-slip displacements are the range-front faults, Fault P, the Second Fault and the Third Fault. Displacement along the northerly trending fault in the eastern Upland Valley, the Battles Well Fault, is compatible with NNW-trending right-lateral shear because it exhibits significant right-lateral strike-slip displacement.

According to the displacement history of northerly trending faults, the current stress regime developed after 17 Ma. and probably before about 7 Ma.

Easterly-Trending Fault Set

Much evidence shows that the easterly trending faults were activated by north-northeasterly extension during their early history, 27 Ma. to 17 Ma.

Displacement along the easterly-trending Fault E indicates that the
extension direction before 17 Ma. could not have been westerly and must have been north-northeasterly. Displacement along Fault E is incompatible with the displacement predicted by the westerly extension model. In westerly extension the displacement along Fault E would be predominantly right-lateral strike-slip because the fault is subvertical and strikes subparallel to, but more west-northwesterly than, the westerly extension direction. Accordingly the strike-slip displacement would be on the order of ten times the 1200 m throw. There is however no evidence that a few kilometers of strike-slip exists. There is no sign of right-lateral shear along the fault or in basement outcrop 1 km east of the mapped termination of the fault. Indeed it would be impossible for the required strike-slip displacement to go to zero from the basin-deep to basement outcrop along the fault trace, a distance of less than 5 km. Thus the amount of strike-slip displacement required by the westerly extension model is not present. Therefore the basin could not have developed under right lateral shear and westerly extension. Since the strike-slip displacement along Fault E is apparently small the extension direction must have been more perpendicular to the fault and in a north-northeasterly direction. Subsidence of the Upland Basin between 27 Ma. and 17 Ma. or younger was a product of north-northeasterly extension.

This extension direction is supported by the existence of an andesite dike swarm in northwestern Upland Valley, exposed over a distance of 5 km and striking west-northwest (Fig. 12). In addition the geometry and displacement history of faults in the northwestern Upland Valley indicate the existence of north-northeasterly extension (Dockery, 1982). Apparently NNE-trending extension existed as late as 17 Ma. when the andesite
Figure 12: Outlined are WNW-trending dikes (heavy lines) of the southern Gabbs Valley Range.
dikes were intruded. The dikes intrude the uppermost andesite, indicating that the NNE-trending extension persisted until the close of andesite deposition.
INTERPRETATION OF THE MINA REGION

Speed and Cogbill (1979a) proposed that uniform westerly extension existed in the Mina Region since 25 Ma. or earlier. They did not recognize cross-cutting relationships of faults and proposed that faults of all strikes developed simultaneously. Recently-mapped relations indicate that northerly trending faults are superimposed on easterly trending faults in the Garfield Hills and Excellsior Mountains (Oldow, unpub.; Oldow and others, unpub.; Oldow and Speed, unpub.; Oldow and Steuer, unpub.).

These mapped relations and others (Hardyman, 1978; Hardyman and others, 1975) are compatible with: 1) north-northeasterly extension in the Mina Region about 27 Ma. to 17 Ma. or later, during which easterly trending faults developed and WNW-trending dikes were intruded 2) extension changing thereafter to west-northwesterly with an inhomogenous shear couple, at which time northerly trending faults were superimposed on the easterly trending faults. Some northerly trending faults are dip-slip whereas others are strike-slip.

Re-examination of work done by Speed and Cogbill (1979a) suggests that an easterly trending basin in the Candelaria Hills underwent a similar extensional history to that of the Upland Basin and described above.
APPENDIX I: REDUCTION OF THE GRAVITY DATA

Observed gravity values were reduced to free-air, simple and complete Bouguer anomalies on the IBM 360 at Rice University. All observed values are referenced to the International Ellipsoid of 1967 and converted to 1971 IGSN values by subtracting 13.90 mgals from the initial observed values (Healey, 1976). Bouguer anomalies assume a density of 2.67 g/cm³. Reductions were compiled in meters using the U.S. Geological Survey feet to meters conversion factor.

The free-air anomaly is given by:

\[ G_{FA} = G_o - G(e,Z). \]

\( G_o \) is the observed gravity in mgals and \( G(e,Z) \) is the reference gravity field in mgals at an elevation \( e \) and latitude \( Z \). \( G(e,Z) \) does not account for masses between sea level and \( e \). \( G(e,Z) \) is given by:

\[ G(e,Z) = G(Z) - (0.308768 - 0.43986 \times 10^4 \sin^2 Z) e + 7.212 \times 10^8 e^2 \]

(Cogbill, 1979).

\( G(Z) \) is given by:

\[ G(Z) = 978,031.85 \left( 1 + 0.005278895 \sin^2 Z + 0.000023462 \sin^4 Z \right) \]

(Cogbill, 1979).

The simple Bouguer anomaly is the free-air anomaly less a correction for mass between sea level and \( e \). That mass is assumed to be an infinite slab of thickness \( e \) (the Bouguer slab). Assuming this slab has a density of 2.67 g/cm³, the simple Bouguer anomaly is given by:

\[ G_{SB} = G_{FA} - 0.10226e \] (Nettleton, 1971).

The later term is the simple Bouguer correction (\( G_{SB} \)).
The complete Bouguer anomaly is the simple Bouguer anomaly with corrections for local topography ($G_T$) and curvature of the earth. The curvature correction is the difference in the gravitational attraction of a Bouguer slab and a spherical cap of 1.50 angular radius. Using the Bouguer density, the curvature correction is given by:

$$G_{CC} = 1.464 \times 10^{-3} e - 3.53 \times 10^{-7}e^2 + 4.48 \times 10^{-14}e^3$$

(Oliver, 1974).

The complete Bouguer anomaly is given by:

$$G_{CB} = G_{FA} - (G_{SB} + G_{CC} + G_T).$$
**APPENDIX II: LIST OF THE GRAavity DATA AND REDUCTIONS**

Reductions are calculated as described in the previous appendix.

<table>
<thead>
<tr>
<th>Heading</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA.</td>
<td>Gravity station number</td>
</tr>
<tr>
<td>LATITUDE</td>
<td>Latitude of the gravity station in degrees, minutes and seconds (+2 seconds)</td>
</tr>
<tr>
<td>LONGITUDE</td>
<td>Longitude of the gravity station in degrees, minutes and seconds (+ seconds)</td>
</tr>
<tr>
<td>ELEV.</td>
<td>Elevation of the gravity station to the nearest foot</td>
</tr>
<tr>
<td>OBSERVED</td>
<td>Observed gravity in mgals less 979,000 mgals to the nearest tenth</td>
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<tr>
<td>FREE-AIR</td>
<td>Free-air anomaly in mgals</td>
</tr>
<tr>
<td>S. B. A.</td>
<td>Simple Bouguer anomaly in mgals</td>
</tr>
<tr>
<td>TCI</td>
<td>Terrain correction in mgals for the inner zones (see text for details)</td>
</tr>
<tr>
<td>TCO</td>
<td>Terrain correction in mgals for the outer zones (see text for details)</td>
</tr>
<tr>
<td>TCT</td>
<td>Total terrain correction in mgals (see text for details)</td>
</tr>
<tr>
<td>CC</td>
<td>Curvature correction in mgals</td>
</tr>
<tr>
<td>C. B. A.</td>
<td>Complete Bouguer anomaly (S.B.A plus TCT and CC)</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>C.B.A. Less planar regional (see text for details)</td>
</tr>
<tr>
<td>COUNT</td>
<td>Number of the station in its data source listing</td>
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</tbody>
</table>
BIBLIOGRAPHY


RANGE FRONT FAULTS

SODA SPRINGS
VALLEY
MINA

QUATERNARY

\[ Q_{al} \quad Q_t \quad Q_{is} \]

QUATERNARY AND/OR TERTIARY

TERTIARY

\[ T_{v_b} \quad T_s \quad T_{v_{13}} \quad T_{v_{11}} \quad T_{v_{10}} \quad T_{v_n} \quad T_{v_f} \]
PLATE I: GEOLOGY

LITHOLOGIC UNITS

\( Q_{ls} \) alluvium, talus and landslides

\( Q_{Ta} \) gravels

\( T_{vb} \) basalt flow; Miocene

\( T_{s} \) sedimentary rock; about 7.3 M.y.

\( T_{v13} \) plagioclase ash flow tuff; vitric plagioclase-biotite ash flow tuff

\( T_{v11} \) hornblend andesite: breccia, flow and intrusive; about 17 M.y.

\( T_{v10} \) Singatse Formation, Benton Spring Group; about 27 M.y.

\( T_{v8} \) Cedar Mountain Tuff; Oligocene

\( T_{v7} \) Guild Mine Member of the Mickey Pass
PLATE 1: GEOLOGY MAP

LITHOLOGIC UNITS

alluvium, talus and landslides

TERTIARY
AND/OR CRETACEOUS

gravels

CRETACEOUS
AND/OR JURASSIC

basalt flow; Miocene

JURASSIC
AND TRIASSIC

sedimentary rock; about 7.3 M.y.

TRIASSIC

plagioclase ash flow tuff;

MESOZOIC
vitric plagioclase-biotite ash flow tuff

MESOZOIC

hornblend andesite; breccia, flow and intrusive; about 17 M.y.

AND/OR PALEOGENIC

Singatse Formation, Benton Spring Group; about 27 M.y.

MESOZOIC

Cedar Mountain Tuff; Oligocene

AND/OR PALEOGENIC

Guild Mine Member of the Mickey Pass Tuff, Benton Spring Group; about 27 M.y.

intrusive
MAP OF THE UPLAND VA

CRETACEOUS

KJI  Dunlap Formation

TKE  intrusive felsite

JRS  Sunrise Gabbs Formation

PALEOZOIC

TRI  Luning Formation

Mzi  granitic intrusive

X    unnamed
VALLEY

STRUCTURAL SYMBOLS

/  contact: dashed where approximate

/./  strike and dip of bedding or foliation

/ .  high-angle fault, bell on downthrown side: dashed where approximate, dotted where suballuvial

/  thrust fault, teeth on upper plate: dashed where approximate

/  fold axis

/  andesite dike

Geology by: J.S. Oldow, H.A. Dockery and J.N. Meinwald
STRUCTURAL SYMBOLS

contact: dashed where approximate

strike and dip of bedding or foliation

high-angle fault, bell on downthrown side: dashed where approximate, dotted where suballuvial

thrust fault, teeth on upper plate: dashed where approximate

fold axis

andesite dike

Geology by: J.S. Oldow, H.A. Dockery and J.N. Meinwald
CONTOUR INTERVAL - 1 mgal

NEVADA

plate location

1 km

1" = 2,000'

GRAVITY SYMBOLS

contour

profile and two-dimensional anomalous - mass model (see text)

GEOLeGIC SYMBOLS

units

Cenozoic

Mesozoic

STATIONS

- Meinwald (this study)
- Conoco (unpub. data)
- Meinwald (this study) and Conoco (unpub. data)
- Healey (1976)
- Cogbill (1976)

Geology after: J. S. Oldow, H. A. Dockery, and J. N. Meinwald (Plate I)

STRUCTURE

high-angle fault
arrows show
where appro
contact, slash
western boundary
PLATE II: \[\text{Diagram of geological features}\]

**SYMBOLS**

- TN: Transect north-south
- MN: Transect east-west

**LITHOFACIES**

- Solid fill: solid fill
- Crossed-out: fill in cross-section

**STRUCTURE**

- Solid line: single fault
- Slashed line: double fault
- Dashed line: subparallel fault

**LEGEND**

- Solid line: subparallel fault
- Dashed line: fault in cross-section
- Slashed line: fault in cross-section

**NOTE**

- Slashed is approximate from Ferguson and Keller (1949)

- Boundaries of Soda Springs Valley

SODA SPRINGS VALLEY
UPLAND VALLEY
GARFIELD HILLS