PROGRESS REPORT

for

EVALUATION OF LINEAMENT ANALYSIS
AS AN EXPLORATION TECHNIQUE
FOR GEOTHERMAL ENERGY

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ABSTRACT

To evaluate lineament analysis as a technique for geothermal exploration an area of known geothermal activity and high regional heat flow was selected as a test area. An area of north-central Nevada coincident with the Winnemucca AMS sheet and encompassing four Known Geothermal Resource Areas was extensively studied. The primary study area consisting of approximately 7,420 sq. mi. (19,219 sq. km) was integrated into the regional lineament patterns by evaluation of Landsat (ERTS) mosaics of the western United States prepared by the Soil Conservation Service, Department of Agriculture. Previous analyses of lineaments in Nevada (Rowan and Wetlaufer, 1973 and 1975) were also used to complement this analysis.

Interpretation of Skylab S190-B photography at a scale of 1:250,000 provided intermediate scale structural analysis of approximately 75 percent of the Winnemucca AMS sheet. Low sun-angle aerial photography at scales of approximately 1:120,000 and 1:30,000 provided detailed structural analysis of the four Known Geothermal Resource Areas. Results of previous geologic mapping and geophysical investigations by Lawrence Berkeley Laboratories and others were used to supplement interpretations provided by this phase of the investigation.

Field studies supporting the image and photographic interpretation consisted of ground photographic documentation. The relationship of present geothermal activity with Cenozoic normal faulting and the areal distribution of recent volcanics was established. Northeast trending lineaments have played a major role in dictating the location of the four major hot spring areas studied. Cross-cutting relationships of the major structures tends to increase the intensity of geothermal activity and sites where similar intersections occur should be investigated in detail as potential sources of geothermal energy.

PRESENT STATUS

The present status of the investigation and preliminary results obtained are contained herein. The Principle Investigator has expended 75 percent of the allotted one-half time on the current investigation. The remaining one-eighth time will be used to determine the ages of faulting in the four geothermal areas using methods developed by Wallace (in press). The only phases of the proposed investigation that have not been completed, at the present time, are the determination of the ages of faulting, mentioned above, and the distribution of hydrothermally altered rocks. These endeavors are planned for the remaining months of the present contract when weather conditions will be favorable for field studies in north-central Nevada.

No problems are anticipated that would hinder completion of the two remaining tasks during the present contract period.

SCOPE OF INVESTIGATION

During the first nine months of this investigation, lineament analysis of multi-scale and format spacecraft and aircraft imagery and photographic products has been completed. Significant results from each of the data formats: Landsat, Skylab and U-2 low sun-angle photography will be discussed subsequently. Regional tectonic patterns have been mapped on Landsat imagery employing techniques used by numerous investigators (Rowan and Wetlaufer, 1973 and 1975, Levandowski and others, 1974, Hoppin, 1974, Abdel-Gawad and Tubbesing, 1974). To supplement the lineament analysis geophysical data including magnetics, gravity and seismicity along with previous work by numerous investigators employing one or more of the geophysical phenomena to geologic structure and regional tectonics were used (Levandowski and others, 1974, Stewart and others, 1975, Robinson, 1970, Koizumi and others, 1973, Thompson and Burke, 1974, Ryall, (in press), and Suppe and others, 1975). To evaluate the lineament analysis and the relation of lineaments to the Cenozoic tectonic framework of the basin-and-range previous work by

several investigators was tested (Wright, 1976, Hamilton and Myers, 1966, Sales, 1966, Wisc, 1963, and Shawe, 1965).

Intermediate scale (1:250,000) structural analysis was performed using Skylab S190-B photography over the Battle Mountain, Nevada area. The resolution of the Skylab photography which exceeds that of Landsat imagery by several orders of magnitude provided synoptic coverage of the area of investigation and delineated the relationship between Cenozoic basin-and-range faulting and geothermal areas.

Low sun-angle photography at scales of 1:120,000 and 1:30,000 provided site specific information of the structural setting of four geothermal areas within the Battle Mountain heat flow high (Sass and others, 1971).

Lineaments detected on the large scale Landsat imagery and intermediate scale Skylab imagery which could not be related to known geologic structures were visited in the field to determine the origin of their occurrence. Ground level photos of the anomalous linear features did not provide much information as to their causal relationship but did provide an understanding of their absence on existing geologic maps. In most cases the features are of regional extent exceeding tens of kilometers in length and several kilometers in width.

INTERPRETIVE TECHNIQUES AND LINEAMENT ANALYSIS

Interpretive techniques varied with the scale and resolution of the various data formats. Interpretation of a Landsat imagery mosaic at a scale of 1:1,000,000 of band 5 (Soil Conservation Service) was made by delineating tonal discontinuities, alignments or breaks in topographic features and vegetation alignments. The major lineaments can be traced through bedrock areas and in some instances across alluvial valleys.

Since the resolution of the Skylab S190-B Earth Terrain Camera (18 in. F.L.) is comparable to conventional aerial photography, airphoto interpretation techniques could be used. Faults and linear fractures were mapped on 1:250,000 scale

enlargements of the original 11.4 x 11.4 cm (4.5 x 4.5 in, in 1:950,000 scale) format. This scale of enlargement did not appreciably decrease the resolution of the photographs.

Conventional aerial photographic interpretive techniques were used to extract fault data from the U-2 low sun-angle photography (LASP). Various supplemental techniques such as the use of positive transparencies and magnification which are described in detail in Walker and Trexler (1977) were used.

Gravity and aeromagnetic data were used to supplement the lineament interpretation and to help define the genetic relationship between the surficial lineament expression and the subsurface mechanism or mechanisms which they reflect. A simple Bouguer gravity map of the Winnemucca AMS sheet (Erwin, 1974) was used to plot linear trends of contour closures. A generalized aeromagnetic map at 1:250,000 scale was prepared from U.S. Geologic Survey open-file maps (1:62,500 scale).

The existence of a high-velocity lithospheric plate under northern Nevada has been established by teleseismic P wave arrivals (Koizumi and others, 1973). This high-velocity layer trends N60E and dips steeply to the southeast beneath Battle Mountain, Nevada. Koizumi and others (1973) interpret this high-velocity layer to be a paleosubduction zone. The relationship between the high-velocity layer and the northeast trending lineaments in north-central Nevada are not completely understood at the present time but this zone undoubtedly played a major role in the production of the major northeast trending lineaments.

LANDSAT, BAND 5 LINEAMENT ANALYSIS

Lineament analysis of northern Nevada was performed on a Band 5 mosaic prepared by the U.S. Dept. of Agriculture, Soil Conservation Service. To assure that the tonal contrasts on the mosaic were real and not matched seams of the mosaicing process, the mapped lineaments were checked on individual Landsat frames of the same Band obtained between October through March 1975. The inter-

pretation produced a lineament map which is reproduced at 1:2,000,000 scale and included as figure 1.

The interpretation includes some lineaments of Rowan and Wetlaufer, (1975) and for a detailed analysis of the techniques involved in production of an interpretive lineament analysis of Landsat imagery their excellent detailed report should be consulted.

The prominent trends delineated by this analysis are in three general directions: NW, NE and NNE-NNW. The geographic distribution of the major lineament directions is relatively uniform for northern Nevada. The NNE-NNW trends represent the expression of the Cenozoic basin-and-range faulting and may be correlated with mapped faults of the area (Stewart and Carlson, 1976 and Slemmons, 1967). The northwest trends which include from the west to east the Walker Lane (E-E'), Rye Patch Lineament (C-C') (Rowan and Wetlaufer, 1973) and the Oregon-Nevada Lineament (B-B') (Stewart and others, 1975) vary in azimuth from N40W to N20+W. The Walker Lane in northern Nevada has a general trend of N40W in the segment east of Walker Lake to Pyramid Lake. The trend of the Rye Patch Lineament is generally N30W for both segments (C-C') shown on figure 1. The offset in the Rye Patch Lineament may coincide with an extension of the Midas Trench (D-D') (Rowan and Wetlaufer, 1973). If this separation of the Rye Patch Lineament is associated with the Midas structure; then the Midas Lineament has a left sense of movement and the southern segment (now obscured) is younger than the Rye Patch Lineament. The sense of movement on the Rye Patch Lineament appears to be right-separation due to the pinching of the northern end of the Sweetwater Range.

The northwest-trending lineament extending from central Eureka County to western Humboldt County (B-B') has been termed the Oregon-Nevada Lineament (Stewart and others, 1975) and consists of closely spaced en echelon faults. The lineament appears as aligned canyons and escarpments on the Landsat-1 mosaic.

FIGURE 1. Landsat lineament interpretation of northern Nevada showing lineaments greater than 10 km. A-A' Ruby Mountain lineament, B-B' Oregon-Nevada lineament, C-C' Rye Patch lineament, D-D' Midas Trench, E-E' Walker Lane (mosaic prepared by Dept. of Agriculture, Soil Conservation Service, scale 1:2,000,000)

This lineament corresponds to a positive aeromagnetic anomaly which is probably due to dikes which supplied the late Tertiary silicic volcanics which mark the zone in northern Nevada. Stewart and others (1975) consider the Nevada portion of the lineament to have developed by a complex history of strike-slip and tensional movement during the Miocene. This timing corresponds with the accepted time of inception of basin-and-range faulting in north-central Nevada (Christiansen and Lipman, 1972). If the Miocene age for the Oregon-Nevada Lineament is valid then the northeast-trending Midas Lineament (D-D') is older since its trend is interrupted by the Oregon-Nevada Lineament north of Battle Mountain. The lack of topographic expression of the Midas Lineament southwest of the Oregon-Nevada Lineament may indicate a tensional history for this portion of the lineament and separation of the older Midas system.

The Midas "Trench" Lineament zone (D-D', fig. 1) extends from southern Washoe County in the southwest to the northern border of the state in central Elko County. The southern portion of this zone is expressed as a discontinuous alignment of canyons and ridges. In the southern Virginia Range Quaternary movement along a northeast trend has been mapped by Rogers (1975). In this area pervasive northeast trending structures in the pre-Mesozoic metamorphics (Zones, 1958) suggest the existence of an older tectonic setting predominated by northeast trends with a left-separation sense of offset (Trexler, 1977). In its northeast extension in central Nevada, the zone forms a depression in the vicinity of the town of Midas and forms the border between the Owyhee Desert and mountain ranges to the southeast in northwestern Elko County.

Other shorter, less distinct segments with similar NE trends can be seen in figure 1. These segments are believed to be genetically related to the larger pervasive zone referred to as the Midas Trench. The NNE trending lineament (A-A') has been termed the Ruby Mountains Lineament (Rowan and Wetlaufer, 1975). It is the least documented feature in Nevada and reflects the normal fault bounding the Ruby Mountains on the east. Its northern extension appears to

coincide with smaller faults (Rowan and Wetlaufer, 1975).

SKYLAB S190-B INTERPRETATION

Skylab S190-B photography was obtained over a portion of the Winnemucca AMS sheet on August 12, 1973. Time of acquisition on the SL-3 Track 20 Pass was 0745 local time which provided low sun-angle (28°) illumination. Figure 2 and accompanying overlay provide a synoptic view of approximately 75 percent of the study area. The quality of the S190-B photographic data is such that it can be enlarged to 1:250,000 and structural interpretations performed at this scale. The overlay on figure 2 includes only the major structural features mapped and is presented for purposes of this discussion.

It is apparent from inspection of figure 2 that every facet of the structural grain of the area can be discerned. Features which correspond to regional tectonic features are noted at 1 and 2. At location 1 and 1a the parallel northwest trending features are coincident with the trend of the Oregon-Nevada lineament. The northeast trending parallel structures at 2 and similar trending structures in the Beowawe Hot Springs (b) are probably related to the Midas Trench system. The structures at 2 are unique in that they are in bedrock and have a cross-cutting relationship to the general N-S trend of the Shoshone Range.

The northwest trending cross-fault near Beowawe (b) may extend southeastward to included hot spring activity at Hot Springs Point (T29N,R48E, plate 1). Further extension of the northwest-southeast trending structure and its intersection with the Crescent Valley Fault (1a and northeast) is also a site of hot spring activity (T28N,R49E, plate 1).

At the scale of figure 2 it is difficult to discern the minor faulting on the east side of Buffalo Valley (bv). It will be discussed, in the site specific structure section of this area, that northeast trends of basaltic cinder cones and faulting of alluvial valley fill with a similar trend occur in the vicinity

FIGURE 2. Skylab S190-B photograph of a portion of the Winnemucca AMS sheet acquired on August 12, 1973 at 0745 local time; 1 and 1a segments of Oregon—Nevada lineament, 2 = northeast trending bedrock lineaments, b = Beowawe Hot Springs, BM = town of Battle Mountain, bv = Buffalo Valley, fc = Fish Creek Mountains, ml = Mount Lewis, scale approximately 1:1,240,000.

of the hot spring area. The more regional view presented by the Skylab photography suggests that the well defined basin margin fault southwest of Battle Mountain (BM) and bounding the northwestern side of Buffalo Valley if projected southward, would intersect the northeast trends in the vicinity of Buffalo Valley Hot Springs at (bv).

It is apparent that most of the well defined structures present in figure 2 are basin and range faults and in many cases parallel to sub-parallel basin margin faults which offset unconsolidated valley fill deposits. The most difficult problem arising from analysis of such high quality synoptic data is to become overwhelmed by the majority of linear features. It is difficult to rationalize the existence of so many potential alignments of features on the scale presented in figure 2; that a data format such as Landsat imagery becomes useful in decreasing the "noise" provided to the interpreter using high resolution photographic data over such a large area.

The Skylab S190-B photographic data are of such good quality that they are most useful in site specific studies of smaller areas than that presented in figure 2. A detailed study of a portion of the frame encompassing one or two ranges and valleys would provide larger amounts of linearly continuous structural data than could be acquired from analysis of conventional aerial photography.

AEROMAGNETIC DATA INTERPRETATION

A generalized contour plot of total magnetic intensity was prepared from U. S. Geological Survey open-file aeromagnetic maps (1:62,500 scale). These data were reduced to 1:250,000 scale by means of Map-O-Graph optical enlarger. The baseline gamma setting for each of the 8 aeromagnetic surveys which cover the Winnemucca AMS sheet was different and therefore only the general magnetic intensity contour trends could be represented at the 1:250,000 scale.

The most prominent feature represented on the generalized aeromagnetic map (fig. 3, reduced from 1:250,000) is the expression of the NNW trending positive

FIGURE 3. Generalized total-intensity aeromagnetic map of the Winnemucca AMS sheet, prepared from U. S. Geological Survey open-file aeromagnetic maps at 1:62,500.

magnetic high which closely corresponds with the trend at the Oregon-Nevada lineament in this area. The close spacial association suggests that the magnetic anomaly is related to the feeder dikes which fed Miocene lava flows and domes (Stewart and others, 1975).

The anomaly is disrupted in several areas, most conspicuous at $116^{\circ}30'$ longitude and $40^{\circ}15'$ latitude (A in fig. 3). This disruption in the aeromagnetic trend corresponds to the northeast trending Crésent Valley fault. Another area of disruption of the anomaly occurs at $116^{\circ}40'$ longitude and $40^{\circ}40'$ latitude (B). Again the area coincides with northeast trending faults and a prominent Landsat lineament. The offset in the aeromagnetic anomaly in both areas is apparently the result of down-dropping of the highly magnetic rocks of the feeder dikes (Stewart and others, 1975). It may be due to localization of feeder dikes at intersections and aeromagnetic lows which represent areas where intrusive material is not near the surface.

The disruption of the aeromagnetic anomaly by cross-cutting northeast trending faults and close association with observed northeast trending Landsat lineaments suggests that the movement on the northeast trending structures is post-Miocene; if a Miocene age for the development of the Oregon-Nevada lineament is accepted as suggested by Stewart and others (1975). The fact that movement on the northeast trending structures appears to be normal faulting, as indicated by the apparent down-dropping of the feeder dikes, is important in that other regional associations of the northeast trending structures suggests a left offset sense of movement. As mentioned earlier, interpretation of the Landsat imagery suggests that the NW trending Oregon-Nevada lineament is younger than the Midas System since it obliterates the surface manifestation of the northeast trends north of Battle Mountain. The discrepancy in age between the apparent offset in the aeromagnetic anomaly and the age suggested by the lineament analysis exemplify the problems encountered in age interpretation of regional structures. Several hypotheses are presented which may explain the apparent disparity in relative age

of the features: 1) as suggested earlier the intrusion of igneous material causing the apparent linearity of the aeromagnetic anomaly may have occurred along zones which allowed near surface intrusion along areas which correspond to zones of weakness, 2) the northeast trends are younger and from Miocene time to the present (in this area) the predominant sense of movement has been vertical and not left lateral, and 3) the conjugate system of northeast and northwest trends had simultaneous movement during emplacement of the intrusive material and surface manifestation is predominated by the northwest trending Oregon-Nevada Lineament since mid-Cenozoic time. Further, more detailed studies beyond the scope of the present study would be necessary to determine the relationship between the disruption of the aeromagnetic anomaly and the Cenozoic history of the area.

In the western portion of figure 3(c) a north-northeast trending positive magnetic anomaly is disrupted by an east-west trending negative anomaly. The circular positive high to the south of the low is associated with granitic intrusive rock of Granite Mountain. The intrusive contact is spatially associated with a northeast trending Landsat lineament which coincides with the interruption of this magnetic anomaly.

An intense positive anomaly on the south side of Battle Mountain (D) appears to be associated with young basalt flows which trend northeast-southwest along the west side of Buffalo Valley. There is a discrepancy in the age of the basalts 3.05 ± 0.6 m.y. (McKee, U. S. Geological Survey) and 1.35 ± 0.15 m.y. (M. L. Silberman, personal communication). From the morphology of the cinder cones it is believed that the younger age is more realistic.

Interpretation of the total intensity magnetic anomalies indicates a direct correlation between the segments of the through-going positive anomaly which appears to be associated with the Oregon-Nevada lineament and the northeast trends associated with the Midas Trench system. The major Landsat lineaments which Rowan and Wetlaufer (1975) named the Midas are located north of the Winnemucca AMS sheet and surface expression of en echelon structures in the Winnemucca AMS

sheet are: 1) the Crescent Valley fault, 2) the Whirlwind Valley fault, 3) faults associated with the southern edge of the Sheep Creek Range, and 4) the Argenta Rim.

GRAVITY DATA INTERPRETATION

Comparison of regional gravity with Landsat lineaments on a statewide scale (figure 4) does not show any distinct correlation. This is probably because of the influence of the basin and range structure obscuring the crustal configuration of older lineaments. There is an increase (less negative) in the Bouguer gravity from the center portion of the state to the northwest. Typically values less than -200 milligals are found southeast of a line which extends from the northwest corner of the state to longitude 118.5° , latitude 39.5° . To better show this decrease in gravity, a residual gravity map (figure 5) was prepared from Wollard and Joesting (1964) Bouguer Gravity Anomaly Map of the United States (West Half, 1:2,500,000). A 20 mile (34 km) grid was superimposed on the Bouguer gravity anomaly map and average values were measured for each grid. This was contoured and the resulting map (figure 5) shows the regional gravity without the complications of basin and range structure. The marked increase in gravity to the northwest can be more clearly discerned.

A marked increase in gravity can also be seen in southern Nevada across an east-west zone where the average Bouguer-gravity increases from -190 to -120. The significance of this as a crustal boundary is discussed by Eaton (1975).

The strike and dip of the high-velocity lithospheric plate interpreted by Koizumi and others (1973) as being a paleosubduction zone under northern Nevada are shown on figure 4. The high-velocity layer has a northeast strike at Battle Mountain and Elko (N60E and N54E, respectively). The strike of the plate is altered to a more northerly direction (N32E), but maintains a similar dip. The variation in azimuth of the high-velocity layer in the Lovelock area may be due to disruption and rotation of the layer between the Walker Lane and Rye Patch lineaments. Since no further information is available at the present time, this

FIGURE 4. Bouguer gravity map of Nevada showing strike and dip of high-velocity layer (from Wollard and Joesting, 1964; Koizumi and others, 1973; LVK = Lovelock, BMN = Battle Mountain).

FIGURE 5. Residual Bouguer gravity map of Nevada prepared from figure 4 by averaging values on 20 miles (34 km) centers.

hypothesis as to the variation in azimuth of the high-velocity layer can only be conjecture.

An analysis of gravity linears was prepared by using Erwin's (1974) Bouguer Gravity Map of Nevada, Winnemucca Sheet. A reduction of Erwin's (1974) map is shown in figure 6. The variation in trends appear at first to be many; however using the method of Robinson (1970) and placing lines through contour closures, both high and lows, the resulting gravity linears fall within three well marked trends.

Figure 7 is a frequency plot of gravity linears produced from the gravity map (Winnemucca AMS sheet). Most of the northeast trends have correspondence with lineaments mapped from other data bases (Landsat and Skylab). The N20-25W trend of figure 7 does not correspond directly with any northwest trends in frequency plots of other lineaments. It may, however, be associated with the N30-25W maximum of Landsat lineaments of northern Nevada. One would not expect a one-to-one correlation between surface features (Landsat lineaments) and crustal or subsurface features which are represented by the gravity contours. Still in all the diversity that is initially apparent in a gravity contour map may provide significant information on the structural trends when treated as other linearly oriented data. For example compare figures 7 and 8. The majority of Landsat frequency maxima are represented in the frequency plot of the gravity linears. Minor disparities between exact maxima orientations of $5^{\circ} \pm$ does not change the overall correspondence between the plots of both types of data.

COMPARISON OF LINEAMENT TRENDS

Frequency plots were used to compare lineament trends from the various photographic products and geophysical data. The frequency plots were produced to represent the percent cumulative length of lineaments. This method, it was felt, represented the lineament trends better than the percent of the number of lineaments. For example, a through going, well marked continuous lineament would

FIGURE 6. Bouguer gravity map of the Winnemucca AMS sheet, after Erwin, 1974.

FIGURE 7. Frequency plot of gravity linears prepared from Bouguer Gravity Map of Nevada, Winnemucca Sheet, Erwin, 1974.

FIGURE 8. Frequency plot of Landsat lineaments from northern Nevada.

have a lesser value if plotted as percent on total number of lineaments than a lineament which is composed of segments with similar trends.

A comparison of the lineaments mapped from the same source (Landsat) at two different scales and areas of coverage show some variation in trend. As shown in figure 8 predominant trends for northern Nevada are N37E, N35W and N52E with minor trends at N15E and N03W. Within the area of the 1:250,000 scale map figure 9, the predominant trends are N67E and N52E. The N52E trend is consistent with a similar trend within the large scale northern Nevada Landsat analysis. All other trends within the area of the Winnemucca AMS sheet are represented to some degree on the frequency plot for the entire northern Nevada area with the exception of the N35W trend (figure 8) which represents the Walker Lane zone and the N67E trend (figure 9) which is not apparent in the northern Nevada analysis. The N67E trend is related to the structures in the area of Beowawe. Figure 10 is a frequency plot of the Beowawe area from a generalized geologic map of the Whirlwind Valley area (figure 5, Wollenberg and others, 1975). It is apparent that the N67E trend is associated with faulting in the Beowawe area. There is a strong ENE trend in figure 10 which culminates with a N72E orientation. The similarities in trends ($\pm 05^\circ$) between figures 9 and 10 at approximately N70E are probably due to the same structures which are represented by more detailed mapping in figure 10.

Interpretation of Skylab S190-B photography produced a lineament map which is generalized in figure 2. By inspection of figure 11 it is apparent that strong NW trends are absent within the area of figure 2. The N15W trend is related to the Oregon-Nevada lineament which even at this scale and area of coverage (1:712,500 and 4,225 sq. miles, respectively) can be discerned. All trends are almost equally distributed between N15W and N80E with a slight increase in the northerly components.

To determine the number of lineaments which are not related to basin-and-range faulting, all frontal faults were plotted on figure 12. Frontal faults were

FIGURE 9. Frequency plot of Landsat lineaments within the Winnemucca AMS sheet.

FIGURE 10. Frequency plot of Beowawe area (from Wollenberg and others, 1975; fig. 5).

FIGURE 11. Frequency plot of all lineaments and known faults in figure 2.

FIGURE 12. Frequency plot of identified basin and range faults in figure 2.

determined by visual inspection of those faults or fault-line scarps which juxtapose bedrock and alluvium at the range and basin margin. The orientations of frontal faults in figure 12 have variable azimuths from NNW through NE (N17W through N62E). There is a decrease in the northerly component of total faults and lineaments (i.e. N03W and N07E). Most of the other trends of major amplitude are found in both figures 11 and 12. There is a conspicuous exception in the range N70-75W which is not related to frontal faulting. The maximum amplitude of the N70-75E trend can be seen in figure 13 which is a plot of lineaments mapped, but which are not related to basin-and-range faulting. It is also apparent in figure 13 that the northerly trends (N03W and N07E) are in part frontal faults that transgress bedrock areas. This suggests that the northerly trends are more pervasive than other trends or that they are older and have been rejuvenated. Those portions in bedrock areas may have had movement contemporaneous with basin-and-range faulting but this is not apparent from inspection of the Skylab photography.

ANALYSIS OF PLATE 1

The spatial relationships between interpreted Landsat lineaments, Cenozoic normal faulting, sinter deposits, hot springs, opaline type cinnabar deposits and recent volcanics is shown on plate 1 (in pocket).

One of the most striking relationships is the alignment of recent volcanics in the west-central portion of the map area. This alignment has a preferred northeast trend, southwest along strike of a Landsat lineament which bounds the Sheep Creek Range on the southeast. There appears to be an association between the areal distribution of recent volcanics in the northwestern portion of the map and Landsat lineaments. Two areas of recent volcanism occur along the projected strike of the Landsat lineament which has been interpreted to cut the East and Sonoma Ranges. The second exposure of recent basalts protruding through valley fill deposits in the Humboldt River floodplain are not far off the projected trend of the Landsat lineament which coincides with the frontal faults on the south side of Buffalo Mountain.

FIGURE 13. Frequency plot of all structures in figure 2, which are not identified as basin and range faults.

Sinter deposits representing ancient hot spring activity are associated with basin-and-range normal faults. Two sinter terraces in T35N,R36E occur along the frontal fault along the westside of the East Range. Two other sinter deposits in T36N,R45E are aligned and closely associated with a mapped fault. To the south of these sinter deposits in T35N is a warm spring which occurs in valley fill material along the projected strike of a mapped fault.

At the boundary between T35 and 36N, R40E another isolated sinter deposit exists. Its location suggests that hydrothermal solutions which formed the deposit were percolated upwards along the extension of a basin bounding fault which has been mapped to the southeast.

The only other known occurrence of sinter representing previous hot spring activity is located along strike of a northeast trending fault which is now the site of Kyle Hot Springs. The association and location of the sinter deposit is fully described in the section on structure of the Kyle Hot Springs area.

The spatial relationship between probable older hot springs or hydrothermal systems as evidenced by opaline type cinnabar deposits and structural setting is negative. Two opaline type cinnabar deposits located in T30N,R37E are not associated with any mapped basin-and-range faults and they are not aligned along any interpreted Landsat lineaments. An interbedded type of cinnabar deposit located in T29N,R39E has fractures which are oriented N60E. The development of mercury mineralization along a fracture set that has a northeast-southeast trend would tend to indicate that fracturing may have been developed by tectonic activity associated with the Midas System.

Evaluation of Landsat lineaments shows that 55 percent of those within the Winnemucca AMS sheet correspond to faults shown on the geologic map of north-central Nevada (Stewart and Carlson, 1976). The remaining 45 percent of the lineaments fell into four categories. Those that corresponded to topographic features represented 13.5 percent, 9 percent represented lithologic contacts and

9 percent corresponded with known faults less than 25 percent of their length. Thirteen percent of 3 lineaments have no apparent topographic or geologic affiliations and must represent tonal variations on the Landsat imagery which are other than geologic or topographic.

The spatial relationship between hot springs and faults mapped at 1:250,000 scale shows that of the 7 hot springs with temperatures greater than 150°F, 4 are associated with faults and 2 of these are along faults of considerable linear extent and were interpreted as lineaments on the Landsat data. The Beowawe Hot Springs is one that occurs along a lineament which corresponds to mapped faults. The other hot springs are located along the Cortez fault in T28N,R49E. Both lineaments as interpreted have similar trends (N55E[±]5).

Three hot spring areas (> 150°F) apparently are not associated with either mapped faults or lineaments. Two are in Dixie Valley and the other is near Carlin (T33N,R52E). The two springs in Dixie Valley however, may be associated with a northeast trend which includes Buffalo Valley Hot Springs, areally associated recent volcanics and two warm springs northeast of the town of Battle Mountain which are coincident with the southeastern extent of a N45E Landsat lineament. There appears to be an ill-defined broad zone containing hot spring activity and recent volcanics in the central and southeastern portions of Plate 1 that may be the expression of the well marked Landsat lineament at the southeastern side of the Sheep Creek Range.

As described earlier the northwest trending Landsat lineament which intersects the northeast trending fault at Beowawe Hot Springs may be associated with hot springs at Hot Springs Point (T29R,R48E) and along the Cortez Fault (T28N,R49E). If this alignment is real it would correspond with the general trend of the Oregon-Nevada Lineament.

SITE SPECIFIC STUDIES

LEACH HOT SPRINGS

Leach Hot Springs are in Pershing County approximately 28 miles (45 km) south of Winnemucca, Nevada in Grass Valley. The spring area is easily accessible by gravel road. The springs are at the base of a NNE trending fault scarp near the east side of the valley in the SE/4 S36, T32S, R38E.

Lithologies exposed in the area range from consolidated rocks of Paleozoic age to unconsolidated alluvial and colluvial deposits of late Pleistocene age. Paleozoic rocks include the Pumpernickel Formation, the Havallah Formation, the Koipato Group and China Mountain Formation (Tatlock, 1969). These rocks range in age from Pennsylvanian to Triassic. The older units being eugeosynclinal sedimentary rocks while those of intermediate age are slightly metamorphosed intermediate to silicic volcanics and the youngest pre-Tertiary rocks are chert, limestone, dolomite and argillite of the China Mountain Formation. Paleozoic and Mesozoic rocks are exposed within the uplifted block of the Sonoma Range east of the hot spring area.

Tertiary consolidated rocks are represented by a small outcrop of Tertiary welded tuff approximately 2 miles (3 km) northeast of the spring. Basalt of unknown age crops out on the upthrown side of a fault .75 mile (1.2 km) southeast of the hot springs.

Unconsolidated to semi-consolidated sedimentary rocks ranging in age from late Tertiary to Holocene overlie the older more consolidated pre-Tertiary and Tertiary rocks. The oldest (late Tertiary) rocks include claystone, mudstone, marl, tuffaceous sand, silicic ash and tuff. They have undergone moderate deformation as indicated by dips of as much as 30°.

Mid-Pleistocene to Holocene units are old gravel deposits, alluvium and sinter deposits. The old gravel deposits form hilly exposures on the west flank of the Sonoma Range immediately east of the hot springs and possibly underlie the

alluvium in the center part of the valley (Olmstead and others, 1975). The deposits consist of poorly consolidated boulders, gravels, sand silts and clays in various admixtures. They have been only mildly deformed with gentle easterly dips in various localities.

The youngest sedimentary units included alluvium and main-stream channel deposits. These units are contemporaneous and consist of gravel, sand silt and clay. They are generally unsorted and poorly bedded. East of the hot springs alluvial deposits overlie pediment surfaces and are only a few meters thick, however they thicken rapidly westward toward the axis of the valley.

Sinter deposits can be divided into old sinter and opaline sinter being deposited today. The old sinter is exposed on the eastern (upthrown) side of the fault along which the thermal waters emerge and is composed of dense chalcedony. It is commonly associated with silicified and kaolinized alluvium.

Faulting in the hot spring area does not appear to be more prevalent than in other portions of Grass Valley. However it is one of the few locations in which faulting along a NE trend breaks valley fill material. Through going NE trending faults in bedrock are common in the East Range northwest of Leach Hot Springs (Stewart and Carlson, 1976) and well marked lineaments are apparent on Landsat imagery (Reeves, personal communication). From regional analysis of lineaments it was mentioned previously that Leach Hot Springs appears to lie on an extension of the northeast trending Buffalo Mountain Fault. If this structure is related to a deep-seated tectonic pattern as suggested by the regional lineament analysis of Rowen and Wetlaufer (1975) and this work, then some correlation between hot springs and major structural lineaments can be inferred.

Faults which offset or juxtapose Quaternary deposits are shown on figure 14. The north-south range front fault which is relatively linear and separates bedrock from valley fill becomes segmented and transposed westward into valley fill deposits about 3 miles NNE of the hot spring, near the mouth of Sheep Ranch

FIGURE 14. Low sun-angle aerial photograph of the Leach Hot Springs area showing northeast trending faults in alluvium. The hot springs are located along scarp A. Another spring B is located along strike between the main hot springs A and a series of northeast trending fractures at C (scale 1:30,000).

Canyon. At this location the fault which now cuts older gravels and alluvium makes an arcuate SSE bend. At a point approximately 1.5 miles northeast of the hot spring the fault strike changes markedly to northeast-southwest and continues as a well marked scarp (A, figure 14) to the hot spring. Southwest of the hot spring the trace of the fault is obscured beneath alluvium. Along the projected strike approximately .4 miles (600 m) south a spring issues forth (B) and prominent cracks (C) in the young alluvium with a northeast trend may represent the southerly continuation of the fault. Other faults with a similar northeast trend can be seen in the vicinity of D. A north trending basin-and-range normal fault is apparent at E.

It is interesting to note that earlier interpretation of thermal infrared imagery of the Leach Hot Springs area by Quade and Trexler, (1975) indicated a thermal anomaly along the fault scarp near the mouth of Sheep Ranch Canyon. At that time the positive correlation between geothermal activity and northeast trending structure was not realized. A northeast trending fault intersects the northsouth trend of the range front fault at this location and may be responsible for the thermal anomaly.

BUFFALO VALLEY

Buffalo Valley is an endorheic basin located southwest of the town of Battle Mountain. It is bounded on the west by the Tobin Range which is composed of siliceous clastic rocks of Paleozoic age. To the east the southern portion of the valley is bounded by the northern Fish Creek Mountains. These mountains are predominantly Paleozoic clastic and Tertiary carbonate rocks overlain by ash-flow tuffs of Miocene age (McKee, 1970).

Basalts extruded from vents along the southeast side of the valley form a chain of cinder cones. The distribution of the basalt, some located atop the Fish Creek Mountains, suggests that the volcanic event predated the uplifting of the range. The age of the basalts is in question. McKee (1970) suggests a

Pliocene or early Pleistocene age based on K-Ar dating (ca. 3 m.y.). However a more recent date (Silberman, 1976, personal communication) by K-Ar method provides an age of 1.35 ± 0.15 m.y.; considering the morphology of the cinder cones it is believed the 1.3 m.y. date is probably correct. This is further substantiated by the thin alluvial covering which overlays basalt penetrated in two test holes at depths of 29.9 and 21.0 m (Olmstead and others, 1975, p. 232). They suggested a slow rate of deposition along the east side of Buffalo Valley based on the 3 m.y. date. If the younger date (1.3 m.y.) is assumed correct then rates of deposition would probably be normal for this thickness of alluvial material.

The unconsolidated valley fill consists of alluvium, lacustrine deposits, playa deposits and spring deposits of early Pleistocene to Holocene age. Periodically during the late Pleistocene, lakes occupied the valley. Shorelines left from these lakes are conspicuous around the valley margin. Playa deposits overlie lake deposits and consist mainly of silt and clay. Abundant salts exist in the near-surface playa deposits due to evaporation of ground water. Spring deposits consist of clay, silt and sand. These deposits are predominantly calcareous, with siliceous sinter being absent.

Buffalo Valley is an asymmetrical graben closed at its southern end. North trending basin-and-range faults bound the valley on the west at the base of the Tobin Range. Several faults diverge from this northerly trend and become oriented northeasterly around the central playa area north of latitude $40^{\circ}25'$ (Wollenberg and others, 1975). Basin bounding normal faults are not as conspicuous on the east.

A northeast trending fault visible on figure 15 (B-B') cuts recent basalt. A tonal variation in the alluvium is apparent along the southwest extension of the fault. Wollenberg and others, (1975) mapped a concealed fault continuing from the surface manifested scarp through the Buffalo Valley Hot Springs. The northeast alignment of cinder cones (A-A') suggests that they were extruded

FIGURE 15. Low sun-angle aerial photograph of Buffalo Valley showing the distribution of Quaternary basaltic cinder cones. Trend A-A' is continuous with the regional northeast trend of the Midas Trench system. A fault cuts the basalts and alluvium between B-B' and has a similar trend to A-A'. The circumalluviated basalt outcrops at C and the location of Buffalo Valley Hot Springs appear to align along a similar northeast trend. (scale 1:120,000)

along a basin-and-range fault or fault zone (Olmstead and others, 1975). The location of the hot springs and a circumalluviated basalt cinder cone at C are also aligned along a similar northeast-southwest trend.

KYLE HOT SPRINGS

Kyle Hot Springs are located in Buena Vista Valley about 30 miles (50 km) south of Imlay, a small settlement on Interstate 80. The spring area is on the eastside of Buena Vista Valley in a similar position, relative to the valley axis, as Leach Hot Springs.

Basement rocks in the East Range are Paleozoic eugeosynclinal facies which are allochthonous. The oldest rocks are the Ordovician Valmy Formation which consists of chert, shale, quartzite, greenstone and minor amounts of limestone. Younger Paleozoic eugeosynclinal rocks of Mississippian through Permian in age have been thrust over the Valmy Formation above the Golconda thrust (Stewart and Carlson, 1976). These rocks include pillow lavas, coarse volcanic breccias, chert, argillite, shale, sandstone and minor limestone of the Havallah Sequence and undifferentiated rocks of Mississippian age.

Mesozoic rocks are represented by plutonic leucogranite and sedimentary rocks ranging from limestone to conglomerate in composition. Rocks of Tertiary age are intrusives of quartz monzonite to granodiorite in composition and extrusive rocks ranging from basalt to andesite.

Semiconsolidated and unconsolidated clastic material of Late Tertiary and Quaternary age cover the pre-Tertiary rocks in Buena Vista Valley. These rocks thicken from the base of the East Range westward and attain a maximum thickness of 6,500 to 8,200 feet (2-2 1/2 km) (Erwin, 1974).

Faulting in the Kyle Hot Springs area is shown in figure 16 where a northwest trending fault segment (A-B) parallels the range front. The fault becomes somewhat segmented at B and makes an arcuate bend to the southwest and continues through the hot spring to C. Along the projected strike of the northeast-

FIGURE 16. Low sun-angle aerial photograph of the Kyle Hot Springs area. Note fault A-B, trending north-northwest parallel to the range front. At B the fault bends southwest and continues to C (Kyle Hot Springs). Along the projected strike of this trend is an older, inactive spring mound. (scale 1:120,000)

southwest trending segment (B-C) is an old, inactive spring mound which appears geometrically similar to the present active spring in the distribution of sinter.

Here again as at Leach Hot Springs which is located in the valley immediately east of Buena Vista Valley, the hot springs occur along northeast oriented faults which cut older alluvium. The age of faulting in this area is apparently greater than 12,000 years B.P. since shorelines southwest of the spring area are not cut by the fault and manifestation of the fault in recent stream channel deposits is not apparent.

BEOWAVE GEOTHERMAL AREA

Located approximately 18 miles (30 km) east of Battle Mountain the Beowawe geyser area occupies the southeast side of Whirlwind Valley. It is evidenced by the conspicuous sinter terrace which is 2,800 feet (850 meters) long at the top, 4,000 feet (1,200 meters) long at the base and 100 feet (30 meters) wide at the crest. The terrace stands over 250 feet (75 meters) high and is backed by the ENE-trending Malpais scarp (Osterling, 1962).

The oldest rocks exposed in the area of hot spring activity or Paleozoic eugeosynclinal facies (Ordovician, Vinini fm.) which are allochthonous above the Roberts Mountains thrust. Outcrops of the rocks are of limited distribution. Tertiary volcanic rocks of basaltic andesite composition comprise most of the bedrock in the area. Minor later basalt caps the basaltic andesite to the southeast of the spring area atop the Malpais scarp (Osterling, 1960).

Quaternary deposits in the area consist of alluvial deposits, alluvial fan deposits, landslide deposits and sinter. The sinter of the terrace is entirely opal and varies widely in texture and color.

Basin-and-range normal faulting predominates in the area of Beowawe Hot Springs. Variable trends and intersecting trends occur near the spring terrace. Small scale mapping by Osterling (1960) best exemplifies the complexity of the

area. He mapped several cross-cutting faults trending northwesterly across the dominant ENE-trending Malpais scarp. Recurrent movement along the faults is suggested by a 50 ft. (17 m) scarp in the sinter terrace which has dropped a portion of the terrace this amount in Recent times.

At larger scales the complex and cross-cutting relationships between faults in the area can be identified. Figure 17 shows the Beowawe area at a scale of 1:120,000 the ENE-trending Malpais scarp (A-A') is sub-parallel to the Argenta Rim (B-B'). Both features can be readily identified on Landsat imagery. The structural grain parallel to these two features can be distinguished as short linear breaks in the Tertiary volcanics throughout the area of figure 17 east of C-C'. The ENE-trending grain is somewhat complicated and not readily apparent in Paleozoic rocks west of C-C'. A north-northwest trending lineament (D-D') crosses the Malpais scarp east of the spring area. The lineament coincides with en echelon north-northwest trending faults, one of which crosses the scarp in the vicinity of the landslide (E).

More northwesterly trending lineaments are apparent in the vicinity of F and Osterling (1960) inferred that two sets of faults with northwest trends extended from F to the spring area.

The existence of Beowawe Hot Springs is undoubtedly related to faulting. It is interesting that the majority of spring activity is associated with ENE-trending faults. The intersection of north-northwest trending cross faults in all probability lend to the fracturing of basement rocks but it appears that the majority of hydrothermal activity is concentrated along the ENE-trending faults. The structural complexity of the area is certainly related to the intensity of spring and geyser activity which is the largest in the study area.

PRELIMINARY CONCLUSIONS

Three of the four geothermal areas studied in detail occur along faults which have surface manifestations. The interesting finding is that the hot

FIGURE 17. Low sun-angle photograph of the Beowawe area, scale 1:120,000.

springs occur along faults or along segments of faults which have northeast or east-northeast trends. One hot spring area (Buffalo Valley Hot Springs) has no apparent surface faulting in the immediate spring area. The spring area does appear to align with a fault which offsets alluvium and basalts northeast of the spring. The geothermal area which exhibits the most activity, geysers and blowing wells, is located near the intersection of two structural trends which have affinities to regional scale trends. These two major trends are the Oregon-Nevada lineament and the Mida's Trench. The location of extensive hot spring activity and high subsurface temperatures (Garside, personal communication) in the Beowawe area indicates that other areas which occur at the intersection of faults which have trends similar to regional lineaments may provide sites for further more detailed investigations.

The areal distribution of recent volcanics in the Winnemucca AMS sheet tend to occur along the projected strike of major Landsat lineaments. The basalt cinder cones along the southeast side of Buffalo Valley have a northeast alignment which is probably related to the northeast trending lineament which bounds the southern side of the Sheep Creek Range. A small circumalluviated outcrop of recent basalt southwest of Buffalo Valley Hot Springs appears to align along a trend that is parallel to the trend of the cinder cones.

The distribution of sinter deposits which probably represent older now inactive hot springs occur along mapped faults or are aligned along buried faults. Opaline type cinnabar deposits do not appear to have any association with either mapped faults or Landsat lineaments.

The use of multi-scale, multi-format imagery and photography, along with all geophysical data should be utilized to provide a complete understanding of the temporal and spatial relationships between the surface expression of lineaments and their subsurface characteristics. To integrate the regional structural trends with site specific studies high quality low sun-angle aerial photography is invaluable.

In summary, preliminary conclusions pertaining to the relationship between geothermal areas in the Winnemucca AMS sheet suggest that the four hot spring areas studied in detail have northeast trending structures which apparently played a major role in the surficial manifestation of hot spring activity. Cross-cutting relationships of major regional structures tend to increase the intensity of geothermal activity and other sites where similar intersections of major northeast and northwest trends occur should be investigated in detail as potential sources of geothermal energy.

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Base from U.S. 1:250,000 series, Winnemucca sheet, 1962

LINEAMENT ANALYSIS WINNEMUCCA SHEET by D. TREXLER, 1977

- BASALT, LESS THAN 6 m.y.
- MAPPED FAULTS, from Stewart and Carlson, 1976
- LANDSAT LINEAMENTS

- SINTER DEPOSITS, UNRELATED TO PRESENT HOT SPRING ACTIVITY (source: Southern Pacific Mineral Survey Maps)
- OPALINE TYPE CINNABAR DEPOSITS (source: Quicksilver Deposits of Nevada)
- INTERBEDDED TYPE DEPOSITS, SHOWING TREND OF FRACTURES (source: Quicksilver Deposits of Nevada)

- SPRING WELL
- < 100
- 100-150
- 150-200
- > 200

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