PHOTOGRAPHIC ANALYSIS OF LINEAMENTS IN THE SAN FRANCISCO VOLCANIC FIELD, COCONINO AND YAVAPAI COUNTIES, ARIZONA

by

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APPROVAL BY THESIS DIRECTOR

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Date

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ABSTRACT

The San Francisco volcanic field is located in the north-central part of Coconino County, Arizona. The rocks found in the area are the Permian Kaibab Limestone and Recent basalts.

Aerial photographs were studied and all natural linear features one quarter of a mile or longer were recorded. These data were transferred to a base map constructed by radial-line plotting and the data analyzed. A dominant trend at N. 60° W. occurs within the area. The maximum error in the study was estimated to be less than 5°.

The linear trends in the surrounding area show two maxima near N. 50° W. and N. 50° E. The dominant northwest trend within the thesis area is the result of the preferential opening of the northwest joint set to permit the eruption of the volcanic rocks.

INTRODUCTION

While taking concurrent courses in geotectonics and photogeology, the author became interested in the use of aerial photographs as a means of analyzing fracture patterns. It was thought that the study of a small area where this technique could be applied would prove to be valuable in future studies in this or similar areas.

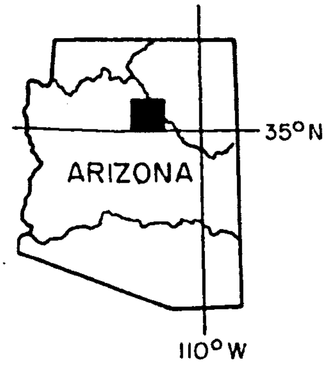
The San Francisco volcanic field was chosen for the study because there are interesting alignments present, good photographs are available (see appendix), and because it is readily accessible from Tucson.

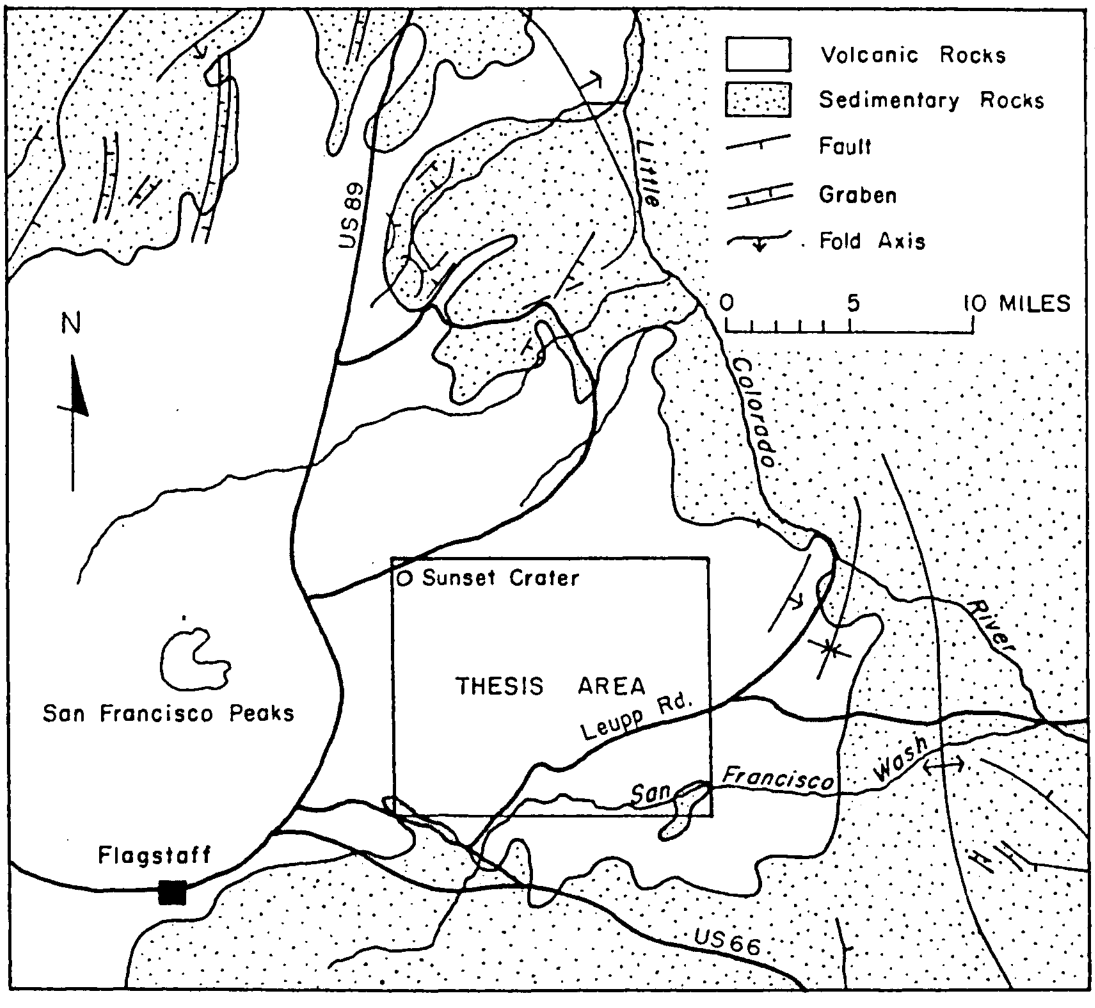
The specific problem was to determine the relationship between extrusive centers of volcanism and the basic fracture pattern by using photogeologic methods.

More than 100 hours were spent examining the photographs in the office and about eight days were spent checking various features in the field.

Location and Accessibility

The San Francisco volcanic field is located in the south-central part of Coconino County and it extends into the northeastern part of Yavapai County, Arizona. That portion of the volcanic field considered in this report is east of the San Francisco Peaks (figs. 1 and 2) and includes all



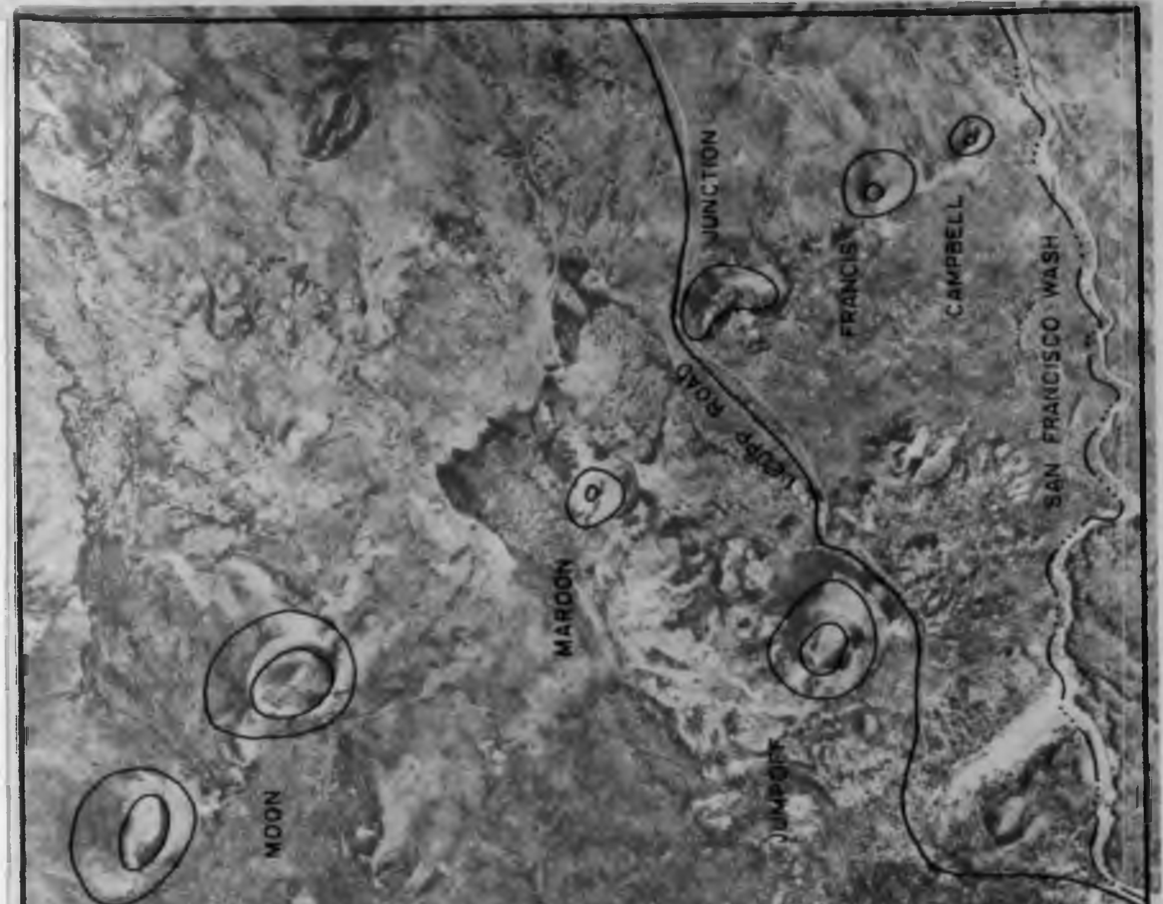


GENERALIZED GEOLOGIC MAP SHOWING THESIS AREA

FIGURE I INDEX MAP

FIGURE 2
AERIAL MOSAIC OF THESIS AREA

Approximate scale: 1 inch = 1.5 miles.
North at top of mosaic.


SUNSET
JANUS
MARCOU
MOON
MAROON
JUNCTION
FRANCIS
CAMPBELL
LEUPP ROAD
SAN FRANCISCO WASH

or parts of the following townships: T. 22 N., R. 8 E.; T. 22 N., R. 9 E.; T. 22 N., R. 10 E.; T. 23 N., R. 8 E.; T. 23 N., R. 9 E.; T. 23 N., R. 10 E. The area is easily reached from Flagstaff, the largest city in the northern part of the state, via highways US 66 east and US 89 north. The Leupp road and the Sunset Crater turnoff are the other paved roads in the area. The U. S. Forest Service and various ranches maintain unpaved roads that provide access to much of the area.

Regional Geology

The lavas of the San Francisco volcanic field were extruded upon the San Francisco Plateau. This plateau is a structural shelf which connects the Mogollon slope on the south with the Kaibab uplift on the north. The surface of the plateau is formed predominantly by the Permian Kaibab Limestone. Isolated remnants of the Triassic Moenkopi formation and Tertiary and Quaternary sands and gravels also occur. To the east, along the Little Colorado River, the Mesozoic section is exposed.

The East Kaibab Monocline is the major structural feature to the north of the volcanic field (Babenroth and Strahler, 1945). At its southern end, the monocline merges with various flexures which show large departures from its general northerly trend, north of the Grand Canyon. Associated with these flexures are many individual faults and grabens. The volcanic rocks partially cover some of these structures. To the east and southeast are the Grand Falls, Tolchaco, and Sunshine anticlines, as well as many small faults. There are two structural troughs trending northeast that break the surface of the plateau. One extends from Oak Creek Canyon to Wupatki Pueblo and the other extends from Sycamore Canyon to the vicinity of Cameron. These troughs were developed before the formation of the San Francisco Peaks. The Oak Creek fault and some of the other north-, northeast-, and northwest-trending faults have locally offset the older basalts and some of the younger basalts (Cooley, 1962). Today, these troughs are the sites of streams that flow eastward and northeastward to the Little Colorado River from the northern and eastern parts of the San Francisco Plateau.

The first period of volcanic activity in the area was the eruption of basalt, which has been dated by Robinson (1913) as late Pliocene and by Cooley (1962) as middle Pliocene. The second period of activity was during the late Pliocene or early Pleistocene. The major peaks in the volcanic field were formed during this period by the extrusion of intermediate and acidic rocks. This second period of activity was followed closely by the third period, which continued into very recent times. Sabels (1960) agrees with these ages. However, he states that the earliest basalts erupted 14 million years ago, during the late Miocene.

Previous Work

The San Francisco volcanic field has been mentioned by many authors, but Robinson (1913) was the first to study the area in detail. His main interest was the petrology of the intermediate and acidic volcanic rocks and their structural relations. He also established the age relations of the various units within the field.

In 1937 (revised 1950) Colton studied the basalt flows and cinder cones. He differentiated five periods of eruption which he termed Stages I through V. Stage I is the oldest stage in his scheme. His study was based on geomorphic and weathering criteria. Sabels (1960), using geochemical techniques, gave precise dates for some of the basalt flows. He also studied the chemistry of the various basalts and concluded that the basalts of Robinson's third period were contaminated by other material. Hodges (1962) studied the comparative geomorphology and petrology of the two most recent cones; namely, S. P. Crater and Sunset Crater and their associated flows. Cooley (1962), using geomorphic criteria on a regional scale, also dated the various volcanic rocks of northeastern Arizona as middle Pliocene to Recent. In 1964 Breed classified the cones on the basis of form and alignment.

There has been no systematic study of the lineament pattern within the San Francisco volcanic field except by

Kelley and Clinton (1960) as part of their analysis of the fracture patterns of the Colorado Plateau. Because their work was of a regional nature, this author thought that an investigation of a small area of the San Francisco volcanic field might reveal more evidence of the tectonic pattern in this part of the Colorado Plateau.

DESCRIPTION OF UNITS

There are three basic units in the area: (1) the Kaibab Limestone, (2) the volcanic rocks, both pyroclastic and flow material, and (3) soil, including alluvial material. The soils appear in the larger valleys, in stream beds, and as a thin cover on the surfaces of the older flows. The rock units will be described here briefly for purposes of identification on the photographs.

Kaibab Limestone

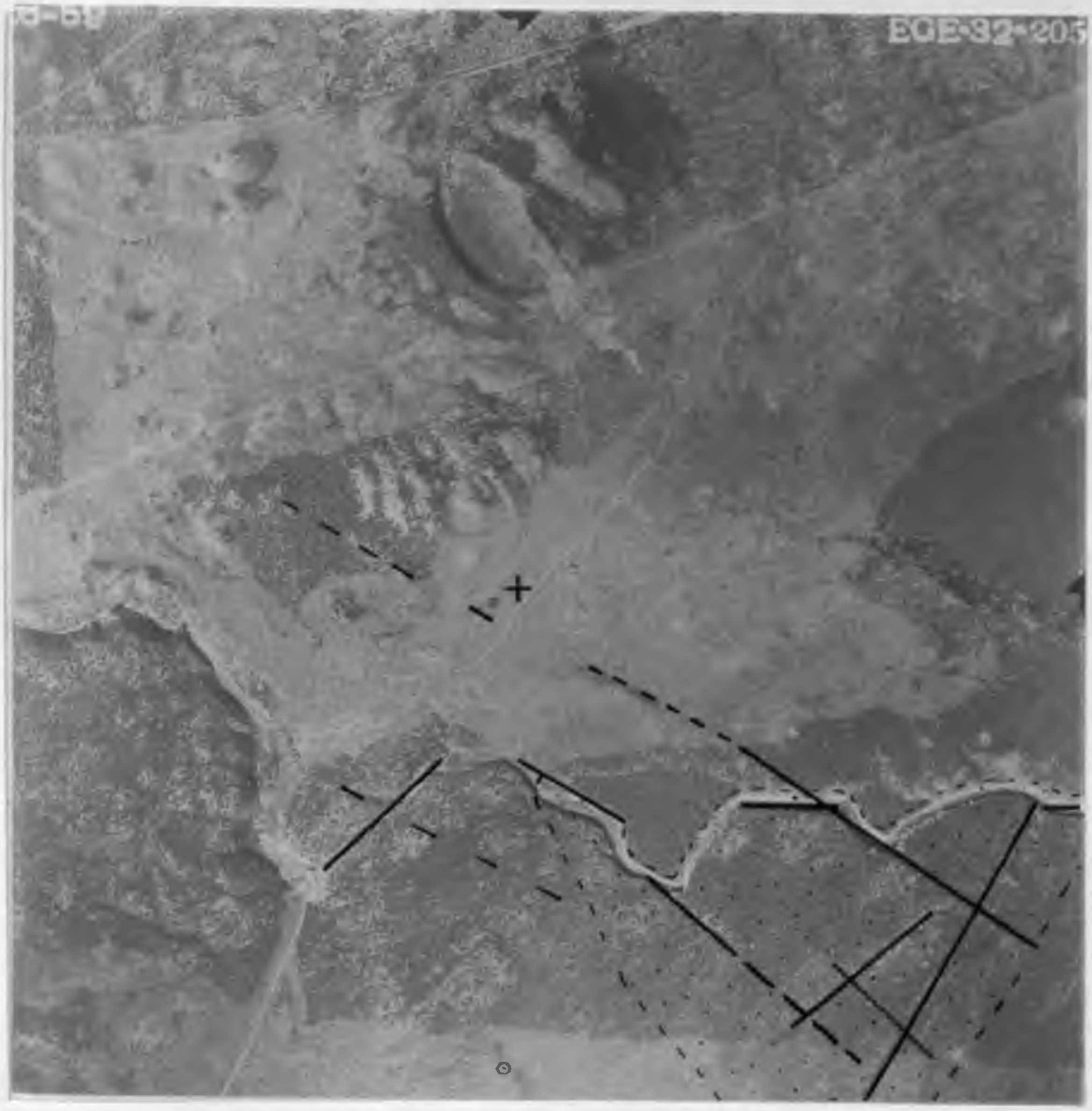
The only exposure of the Kaibab Limestone in the thesis area covers a few acres in and near the San Francisco Wash (fig. 3). South of the wash it appears, on the photographs, as small white patches under a thin cover of cinders. The wash penetrates the Kaibab Limestone to a maximum depth of about 30 feet at the eastern end of the area and surfaces on basalt about a mile to the west. Appearing in the walls of the wash, are many joints and small high-angle faults, some of which have been eroded and have become drainages into the wash.

Volcanic Rocks

The basalt flows are usually recognized on aerial photographs by their outlines and surface features. Colton

FIGURE 3
AERIAL PHOTOGRAPH—FRACTURE TRACES IN KAIBAB LIMESTONE

Stippled area represents outcrop of the Kaibab Limestone with thin cover of cinders. Fracture traces shown by lines.
Approximate scale: 1 inch = 0.4 mile.
North at top of photograph.


EGE-32-205

(1950) has given criteria for the recognition of the relative ages of eruption. Most of the flows in the thesis area are classified as Stage III in his scheme, except for two flows which may be Stage IV. One of these occurs in the vicinity of Maroon Crater and the other extends from Janus Crater past Marcou Crater. The flows associated with Sunset Crater are Stage V. There are multiple flows in much of the area, but they often are buried under ash and cinders.

The pyroclastics cover the entire area with the exception of some valley bottoms where alluvium and soil cover can be found. The relief in the area is provided chiefly by cinder cones of different ages. Colton's Stage III cones seem to be the oldest in the area. There are many Stage IV cones near Sunset Crater, which is the only Stage V crater in the volcanic field. Where the ash and cinders do not form cones, they tend to blanket the irregularities of the older flows and the whole area appears dark gray to black in color.

In addition to the cinder cones and basalt flows, other minor features such as spatter cones, push-ups, pressure ridges, and small explosion craters or pits also occur.

All the volcanic material is basalt. The pyroclastics are scoriaceous, as are the tops of some flows. The flows, where examined in the field, are dense black basalt with occasional phenocrysts of olivine. All the flows are relatively fresh, but some alteration has occurred by surface weathering or emanating gases from vents.

THEORY OF FRACTURE TRACE AND LINEAMENT DEVELOPMENT

Most aerial photographs of good quality clearly reveal natural linear features appearing on the ground. Some of these are related to the outcrop pattern of tilted strata, foliation, and contacts between formations. Other linear features probably are caused by various types of fracturing. These linear features may range in length from a few feet to several miles.

There is no universal agreement on the terminology used to define these linear features. The terms fracture trace, linear, and lineament are used, regardless of length, by various authors to describe linear patterns. Basic references, such as Colwell (1960) and Lueder (1959), discuss the recognition and causes of these features, but make no distinction in their lengths.

Lattman (1958) has attempted to establish a standardized nomenclature in the usage of the terms fracture trace and lineament. He has classified those linear features observed on aerial photographs, and probably related to fractures in the bedrock, as fracture traces if they are less than one mile in length and lineaments if they are more than one mile in length. According to Lattman, this classification seems to be the consensus of many geologists. Although this is an arbitrary classification, based primarily on the length of a linear element, it is a useful one and has been adopted in this paper.

Fracture traces may be expressed in a variety of ways. Often they are visible to the unaided eye, but stereoscopic examination of high quality aerial photographs is necessary to observe others. The scale of photography should range from 1:10,000 to 1:40,000 for the mapping of fracture traces. There should be at least 50 percent overlap along the flight line and, if more than one flight line is studied, there should be a 20 to 30 percent overlap to either side.

The most obvious expression of fracture traces is that of joint sets in horizontal sedimentary strata and in some igneous terrains. Closely related to these are the short, straight segments of streams and rivers of all sizes. Joints and faults often provide a structural control that influences the direction of stream flow.

Vegetation alignments may be another evidence of fracture traces. These are produced by a concentration of trees, shrubs, or other vegetation along a zone of fracturing. A slightly higher concentration of moisture in these areas is presumed to be the basic cause. A more subtle expression of the same phenomenon is a line of slightly taller trees in a forested region.

Tonal changes in the soil, often subtle, are another indication of possible fracture traces. These may result from a higher moisture content, which darkens the soil, or possible leaching of certain elements from the soil by water. These effects are particularly useful in areas of cultivation where man has influenced the vegetation.

Very broad, shallow linear depressions that are not evident on the ground may be revealed by stereoscopic examination. These again may be attributed to the leaching of the soil by water percolating downward along a fracture zone. In limestone areas, surface fractures often are enlarged by solution. Underground solution cavities are also controlled by fractures and, if these approach the surface, some collapse may result, thus producing a linear feature.

Lineaments are best seen on aerial mosaics which permit the examination of a large area. They should be viewed at a low angle along their length. Often they consist of a large number of fracture traces. Large faults are also a cause of lineaments; the San Andreas Fault in California is a good example. Lineaments frequently are attributed to zones of weakness in the basement rocks, whereas fracture traces are thought to be the result of local jointing and faulting.

PROCEDURE

U. S. Forest Service photographs at a scale of 1:15,840 were studied individually and stereoscopically. Any alignment not obviously related to the works of man or produced by the edge of a basalt flow was recorded. Because some criterion had to be adopted, any alignment on the photographs longer than one inch was mapped. At the scale of the photography this represents one quarter of a mile. The only justification for choosing this particular length was convenience in mapping, although some fracture traces slightly shorter than one quarter of a mile also were mapped.

Often it was difficult to decide whether or not a given alignment really existed. This was especially true of vegetation alignments. Those alignments which remained in doubt after extensive study of the photographs were eliminated. This procedure of recording only definitely determined alignments is advocated by Lattman (1958).

Most of the area is covered by a blanket of cinders and ash, which makes it impossible to determine the cause of vegetation alignments. However, near the edges of some flows, there was a suggestion of fracture control. Some vegetation alignments were obviously controlled by topography. That is, they occurred along the crests of the elongate ridges of a cleft crater or at the change in slope between adjacent cinder cones, and thus were not mapped as fracture traces. Vegetation alignments often have a slight curve in them (fig. 4).

Another indication of fracture patterns is seen in cleft craters. Breed (1964) defines cleft craters as follows: "This type of cinder 'cone' is usually not conical as it is formed by the eruption of pyroclastic material through a fissure. The activity may be concentrated in the center of the cone or along the entire fissure. In either case the result is an elongated cinder cone with a cleft 'crater' parallel to the elongation rather than a true crater." Two examples of this are shown in figure 4. Multiple cones such as Janus Crater and cinder mounds, which are elongate piles of cinders without a visible crater, also may be closely related to this type of eruption.

Straight segments of the stream channel occur in San Francisco Wash. Field measurements showed that the trends of these segments are the same as the joint directions in the Kaibab Limestone, in which the wash is cut. These straight segments were therefore mapped as fracture traces (fig. 3).

Another criterion used in mapping both lineaments and fracture traces was the alignment of spatter cones, explosion pits, small cinder mounds, and zones of altered basalt along fissures (fig. 5).

FIGURE 4
AERIAL PHOTOGRAPH—CLEFT CRATERS AND VEGETATION ALIGNMENTS

Two cleft craters indicated by dashed lines. Two typical vegetation alignments shown by solid lines. Approximate scale: 1 inch = 0.4 mile. North at top of photograph.

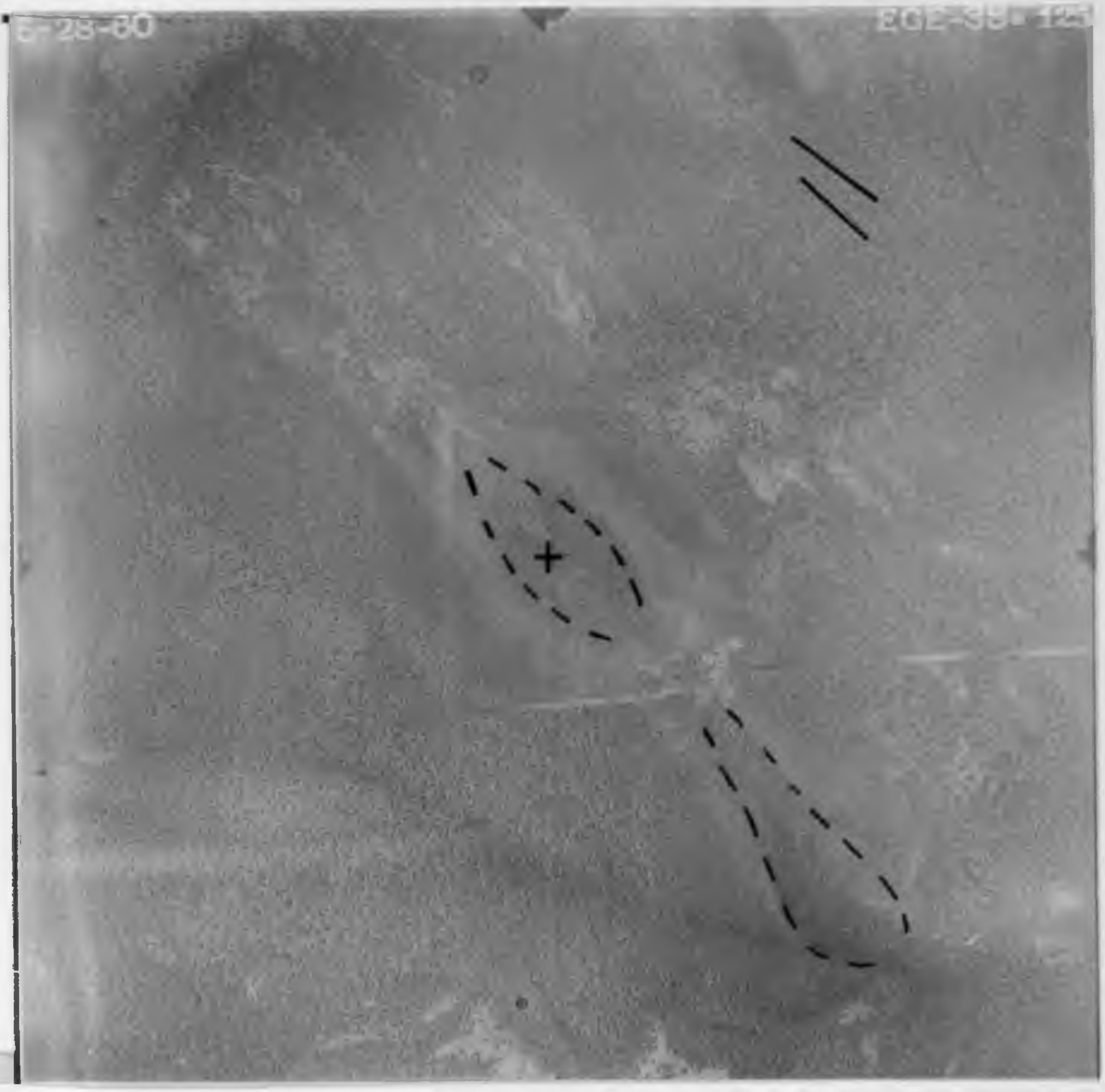

5-28-80
EGL-38-125

FIGURE 5
AERIAL PHOTOGRAPH—FISSURES EAST OF SUNSET CRATER

Part of the fissure system between Sunset and Janus Craters. Explosion pit and altered basalt visible.
Approximate scale: 1 inch = 0.4 mile.
North at top of photograph.


9-4-59
EGE-7-4

Lineaments were mapped using the Army Map Service photographs and the aerial mosaic, supplemented by the Forest Service photographs. These features were usually represented by a series of cinder cones that form alignments such as those illustrated in figures 2 and 6. These cones usually form a straight line, but occasionally a slight offset of some of the craters occurs. This is true of the series formed by Marcou, Moon, Maroon, Junction, Francis, and Campbell Craters.

Because a good topographic map of this area was unavailable, a base map was constructed by the method of radial-line plotting (Mofitt, 1959). The Army Map Service photographs were used to construct a base map. This base map includes a larger region than the map of the thesis area (fig. 7), in order to have control points for orientation. The lineaments and fracture traces recorded on the photographs then were transferred to the base map. This was done in two steps. First, the data were transferred to transparent overlays on the Army Map Service photographs. Second, these were traced onto the base map, aligning the overlays along the flight lines.

Once the data were transferred to the base map, the azimuths of the various lineaments and fracture traces could be measured and analyzed.

There are several possible sources of error in the procedure used. First, and most obvious, is the lack of a good topographic map, which necessitated the construction

FIGURE 6
AERIAL PHOTOGRAPH—ALIGNMENT OF CINDER CONES

Cleft craters can be seen in southeast; double cone is Janus Crater; Sunset Crater is in northwest corner.
Approximate scale: 1 inch = 1.2 miles
North at top of photograph.


2449

the base map by radial-line plotting. Without ground control, some error in scale is unavoidable, but angular error is at a minimum unless there is excessive tilt. In all recent photography, the tilt is rarely greater than one degree and this has no measurable effect. In this study, the angular relations were the important factors to be considered.

Another source of error involves the location of true north. Compass bearings recorded in the field are unreliable because of the magnetic effect of the volcanic terrain. North was determined by reference to azimuths between road intersections that appeared on the base map and published maps. As another method of verification, the bearings of certain features that appear on the aerial mosaic were compared with those on the base map. The agreement was within one degree in most instances. The greatest divergences occurred when the precise alignments of features, such as cinder cones in series, could not be determined. Such errors probably are less than 5°; that is, repetitive measurements of the same alignment would vary within a range of $\pm 2.5^{\circ}$.

The transfer of data between the two series of photographs would affect the azimuth $\pm 1^{\circ}$. However, in transferring the data to the base map, an important source of error must be considered. This is relief displacement. All aerial photographs of areas of substantial relief do not have a constant horizontal scale. This results in planimetric error in the location of points in relation to a given datum.

Fortunately, the points are displaced radially from the center of the photograph, thus permitting calculation of the magnitude of the displacements. The greater the elevation above the datum, the greater is the displacement outward. Thus, between any two points that differ in elevation, the true azimuth and the azimuth measured on the photograph will vary.

To determine the significance of this error, several calculations were made based on the following formula from Mofitt (1959):

$$d = \frac{rh}{H}$$

where d = relief displacement in inches;

r = radial distance from the principal point to the ground image point in inches;

h = elevation of the point above the datum in feet;

H = flying height above the datum in feet.

In order to determine the maximum error, an extreme set of conditions that might be encountered in practice was chosen. Because the relief displacement for a given elevation increases with distance from the center of the photograph, r was chosen as 4.5 inches, which is about the maximum value. The maximum elevation difference along a short fracture trace might be as much as 500 feet. Flying height was determined from the scale of the photographs and an assumed 6-inch focal-length lens. This focal length was chosen because it will produce a greater relief displacement than will other commonly used aerial camera lenses.

Calculations based on these extreme conditions show that an elevation difference of 500 feet would result in a maximum error of azimuth that is less than 6°. Most of the fracture traces mapped would have a change in altitude of less than 200 feet, which would reduce the error to slightly more than 2°. The longer lineaments would produce even less error because of the geometric relations among the base, altitude, and angles of a triangle.

Considering the various sources of error discussed above, it seems clear that the error of any given azimuth is 5° or less.

ANALYSIS OF DATA AND CONCLUSIONS

The aerial mosaic and Army Map Service photographs reveal a dominant northwest-southeast trend in the area of study. This is not as obvious on the Forest Service photographs until the data are transferred to a map (fig. 7). This undoubtedly results from differences in scale; the Forest Service photographs show a small area and local trends may deviate considerably from the regional trend.

In order to test the apparent alignment, rose diagrams were constructed in the following manner. The compass bearing of each linear element plotted on the map was measured. These were then grouped by 10° intervals. This interval was chosen for two reasons; namely, for ease of treatment of data and to reduce the effect of the errors mentioned in the preceding section.

The rose diagram in figure 8a represents all the trends that were mapped. The dominant direction is N. 60° W. and an almost equal submaximum direction trends N. 40° W. Three minor trends of nearly equal magnitude correspond to bearings of N. 10° W., N. 40° E., and east-west. The N. 40° E. trend is only slightly more prominent than the other two minor trends.

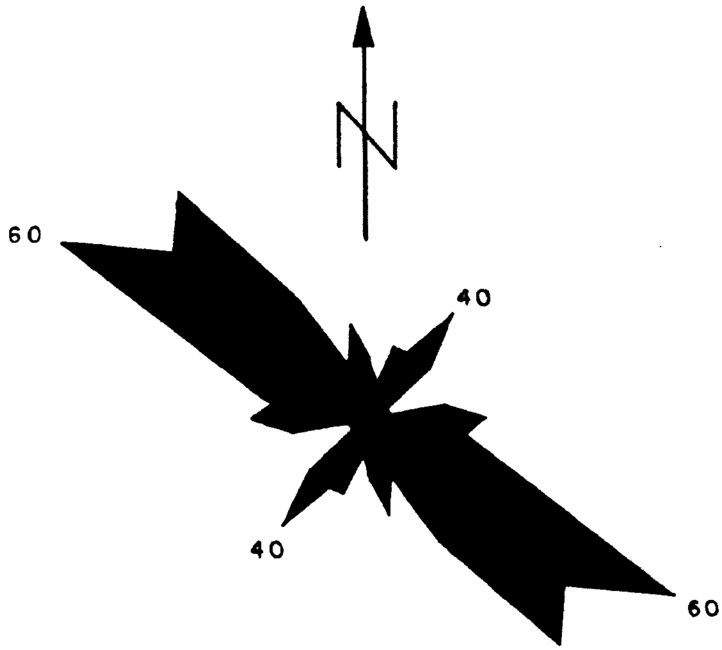
For purposes of comparison, a second rose diagram (fig. 8b) was constructed; this diagram shows the directions

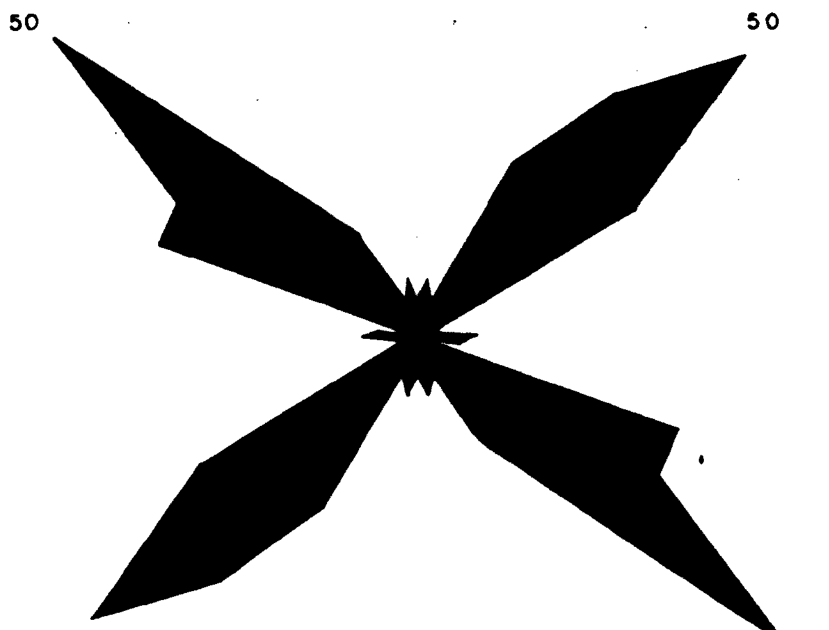
FIGURE 8a
ROSE DIAGRAM—THESIS AREA

Trends of all lineaments
and fracture traces.
Arrow indicates north.

FIGURE 8b
ROSE DIAGRAM—AERIAL MOSAIC
EXCLUSIVE OF THESIS AREA

Trends of all lineaments
and fracture traces.
Arrow indicates north.


N
60
40
40
60


50
50
50
50

of fracture traces and lineaments readily seen on that part of the aerial mosaic not included in the thesis area. There are two dominant directions present. That of N. 50° W. is slightly more pronounced than the one at N. 50° E. Again, there are three minor directions of equal magnitude; namely, N. 10° W., N. 10° E., and east-west.

The thesis area is in the southwestern portion of the aerial mosaic. The northern half of the mosaic is close to the region where the structural features associated with the southern part of the Kaibab Monocline disappear under the volcanic cover. Many of these structures have a strong northeasterly trend. The strong N. 50° E. trend observed in the second rose diagram (fig. 8b) may be a reflection of these structures.

In order to obtain the broader regional trends, the tectonic map of the Colorado Plateau (Kelley and Clinton, 1960) was studied. This shows a dominant N. 65° W. trend for the joint systems and a secondary direction of N. 30° E. Minor trends of N. 75° E. and N. 15° W. also occur. These joint systems are developed in Triassic and older rocks. In the immediate area of the thesis, the Permian Kaibab Limestone exhibits these trends. Joint directions measured on outcrops of the Kaibab Limestone in the area range from N. 45° W. to N. 75° W. Another joint set at N. 25° E. to N. 35° E. confirms the validity of the trends for this local region. These same azimuths occur on the photographs that show the Kaibab Limestone outcrops (fig. 4). Some of these joints are thought to control the drainages in the area.

North of the area studied, the various structures associated with the southern terminous of the Kaibab Monocline disappear beneath the volcanic cover. Most of these features have a northerly or northeasterly trend, but the dominant trend of the fractures in the Kaibab Limestone is still northwest.

Robinson (1913) states that the San Francisco volcanic field is located near the crest of a broad gentle anticline or dome. Mayo's study (1958) of the lineament tectonics of the southwestern United States suggests that the San Francisco volcanic field is located at the intersection of three, and possibly four, major structural trends. He terms these the northwest central Arizona belt, the northeast Front Range porphyry belt, the north-south Arizona-Utah belt, and a possible east-west San Franciscan belt.

It therefore appears that the volcanic activity occurred within a zone of weakness that resulted from forces which acted in different directions for a long period of time. The upbowing of the region may be the result of an intrusion at depth which opened the pre-existing joints to allow the extrusion of lavas.

This study has demonstrated the feasibility of using aerial photographs of a volcanic area to study the relationship between the underlying fracture pattern and the centers of volcanic eruption. The study has also been a small contribution to the understanding of the San Francisco volcanic field.

RECOMMENDATIONS FOR FUTURE STUDY

Study of the tectonic map of the western United States reveals an interesting relationship between the Colorado Plateau province and the distribution of volcanic activity. There are large Tertiary to Recent volcanic fields around the border of the plateau but relatively little activity has occurred within the province. A detailed study of the San Francisco volcanic field would be one step toward understanding the reason for the distribution of volcanism about the periphery of the Colorado Plateau.

One of the first steps in such a study should be a thorough analysis of the fracture patterns in and around the San Francisco volcanic field. This should include detailed field mapping in addition to photogeologic studies because, however valuable, photogeologic studies only provide information on the effects rather than the causes of same.

APPENDIX

The photographs used in this study come from three different sources as follows:

1) U. S. Department of Agriculture
Forest Service, Region 3
Portion of Coconino County, Arizona
Scale: 1:25,840; Flying completed June 30, 1960
Index sheet 20

Symbol	Flight Line	Photograph Numbers
EGE	6	60-72
EGE	37	83-96
EGE	7	34-46
EGE	37	154-167
EGE	38	152-163
EGE	9	60-71
EGE	32	204-215
EGE	41	134-143

2) Army Map Service Photographs
Symbol: VV HU M17, 18, and 20
Approximate scale: 1:50,000; Flown in 1954

Photograph Numbers
2222-2225
2280-2284
2448-2452
2705-2710

3) Fairchild Aerial Surveys
Photomosaic
Area between $35^{\circ}15'$ and $35^{\circ}30'$ north latitude
$111^{\circ}15'$ and $111^{\circ}30'$ west longitude
Scale: 1 inch = 1 mile; Flown in 1936

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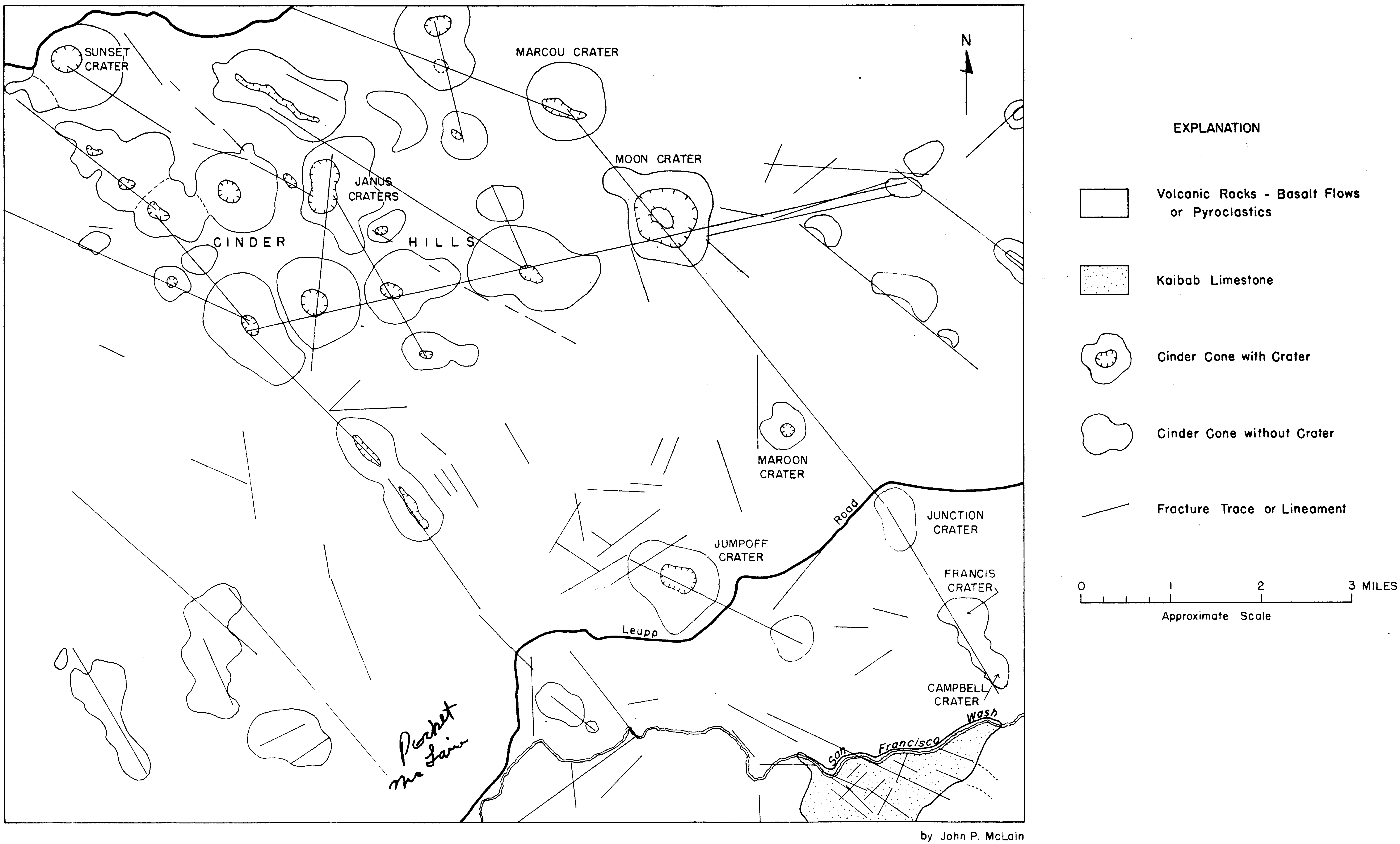

by John P. McLain

Figure 7--Fracture and Lineament Map of a Portion of the Eastern Part of the San Francisco Volcanic Field, Coconino County, Arizona