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Vent alignments in San Francisco volcanic field, Arizona : statistical analysis and assessment of structural controls

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

VENT ALIGNMENTS IN SAN FRANCISCO VOLCANIC FIELD, ARIZONA:
STATISTICAL ANALYSIS AND ASSESSMENT OF STRUCTURAL CONTROLS

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

MASTER OF SCIENCE

IN

GEOLOGY

by

Zhuoning Chen

1994

To: Arthur W. Herriott
College of Arts and Sciences

This thesis, written by Zhuoning Chen, and entitled Vent Alignments In San Francisco Volcanic Field, Arizona: Statistical Analysis And Assessment Of Structural Controls, having been approved in respect to style and intellectual content, is referred to you for judgement.

We have read this thesis and recommend that it be approved.

Charles Connor

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The thesis of Zhuoning Chen is approved.

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Florida International University, 1994

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ABSTRACT OF THE THESIS

VENT ALIGNMENTS IN SAN FRANCISCO VOLCANIC FIELD, ARIZONA: STATISTICAL ANALYSIS AND ASSESSMENT OF STRUCTURAL CONTROLS

by

Zhuoning Chen

Florida International University, 1994

Miami, Florida

Dr. Grenville Draper, Major Professor

Using cluster analysis, a total of 605 vents in San Francisco Volcanic Field are studied over an area of approximately 5000km². Application of alignment analysis techniques, including the two-point azimuth analysis and Hough transform analysis, demonstrates that cinder cones are aligned along common orientations within larger clusters. These alignments consist of 9-10 cinder cones, are 20-38 km long, and are regional features. The vent alignments indicate the presence of geological features along which magma ascended more readily than elsewhere. The NE-trending Mesa Butte and Oak Creek Canyon-Doney fault systems seem to control the intermediate to silicic centers which are on the intersection of these fault systems with Cataract Creek fault system and affect the development of cinder cone alignments. Geological maps and geophysical surveys indicate that most vent alignments are parallel or subparallel to these large scale fault systems. This suggests that vent alignment patterns are controlled by regional structures.

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CHAPTER ONE

INTRODUCTION

DISTRIBUTION OF VOLCANIC CENTERS IN CINDER CONE FIELDS

Although cinder cone fields are a common volcanic feature, the reasons why they form, instead of a single large shield volcano, remains a controversial topic. There are two main hypotheses that explain the origin of cinder cone fields.

The first hypothesis suggests that cinder cone fields form because the areas in question have a relatively low magma supply rate (Fedotov, 1981; Hasenake and Carmichael, 1985). In this situation, it is claimed that magma conduits in the crust are not maintained and individual magma batches ascend along varied pathways to the surface, rather than in a single conduit. With decreasing magma supply rate, large shield volcanoes become intermediate size centers and then "areally" distributed small volcanic centers (Fedotov, 1981).

On the other hand, many authors think that the areally distributed volcanism of cinder cones fields may be the result of structural discontinuities of the crust, and that magma emplacement is controlled by pre-existing fractures and faults (Nakamura, 1977; Nakamura et al., 1979; Thompson and Zoback, 1979). Close association between regional structural features and vent alignments have been suggested for many

cinder cone fields within the Basin and Range Province and the Colorado Plateau (Kear, 1964; Settle, 1979; Delaney et al., 1986; Connor et al., 1992). In these regions, vents are apparently aligned along, or parallel to, fault trends. While the mechanics of the phenomena remains unknown, this behavior suggests that shallow crustal structural features are an important factor in the genesis of cinder cone fields.

In this study, statistical analysis of vent alignments and geophysical studies are employed to evaluate the importance of crustal structures in controlling the location of vents in the San Francisco Volcanic Field of northern Arizona. The SFVF was chosen because of the relatively simple structure of underlying geological substrate - a thick sequence of flat lying Paleozoic and Mesozoic rocks which overlie Pre-Cambrian metamorphic rocks.

INVESTIGATION OF VENT DISTRIBUTION IN THE SAN FRANCISCO VOLCANIC FIELD

Volcanism in the SFVF appears to be spatially associated with several major fault systems, but the dense vent distribution makes the recognition of specific alignments a difficult task.

This investigation explores some major problems in the SFVF, which include:

- (1). How are cinder cone alignments formed?

- (2). What percentage of the cones are part of the alignments?
- (3). How long are these alignments?
- (4). What is the role of major fault systems in forming the alignments? and
- (5). What is the precise relation between surface expressions of regional structures and vent alignments?

To answer these questions, and give insights into the relationship between regional structures and vent alignment, several statistical methods have been employed: cluster analysis, two-point azimuth analysis and Hough Transform analysis.

As in other cinder cone fields, volcanic centers in the SFVF, show a tendency to cluster (Carr, 1976; Heming, 1980; Walker, 1981; Connor et al., 1989). Using this analysis, it is possible to identify and map clusters in the distribution of cinder cones in the SFVF. Such maps provide quantitative information about the cinder cone distribution and may provide information on the processes governing magma ascent beneath the volcanic field.

Within the identified clusters, statistical analyses are used to classify vent alignments on the basis of their length, number of vents, orientation and their statistical significance. The results of this statistical analysis of vent distribution (Chapter 3) are compared to structural data and geophysical data collected in the field (Chapter 4). In

addition, geological, gravity and magnetic data are used to delineate specific structures associated with individual vents. Finally, the significance of the volcanic alignments and possible mechanisms of cinder cone emplacement within the field are discussed.

CHAPTER TWO

CHARACTERISTICS AND GEOLOGIC SETTING IN SAN FRANCISCO VOLCANIC FIELD

REGIONAL GEOLOGICAL SETTING

The Colorado Plateau is a broadly elevated region in the southern part of the Western Interior of the United States that has exceptional exposures of upper Paleozoic, Mesozoic, and Cenozoic rocks. The quality of exposures is a result of regional uplift in the middle and late Tertiary (Peterson et al., 1989) that caused rapid erosion and subsequent deep canyon incision in a semi-arid to arid climate. The structure of the plateau consists of broad basins, uplifts, and platforms locally bordered by monoclines. Although elevated in Tertiary time, the Plateau region was a distinct crustal block by the beginning of Mesozoic time (Raisz, 1939). Upper Paleozoic to Cenozoic strata contain a record of marine and continental deposition complicated in varying degrees by the interplay between sea-level changes and tectonism, both within the Plateau region and in bordering regions (Peterson et al., 1989).

Cinder cone volcanism was widespread in the southern part of the Colorado Plateau physiographic province during the late Tertiary and throughout much of the Quaternary (Wolfe et al., 1983). Almost all of this volcanism was

concentrated within seven volcanic fields located near the margins of the plateau (Fig. 2.1).

Geophysical models of the Colorado Plateau/Basin and Range transition show a significant decrease in depth to the mantle from approximately 40 km in the interior of the plateau to 22 km in the Basin and Range (Brumbaugh, 1987). The Mogollon Rim forms the physiographic boundary between the Colorado Plateau and the Transition Zone (the zone between the Colorado Plateau and the Basin and Range).

THE SAN FRANCISCO VOLCANIC FIELD

The San Francisco volcanic field is located in north-central Arizona (Fig. 2.1), just north of the Transition Zone and the Mogollon Rim. It is one of several (dominantly basaltic) volcanic fields of Late Cenozoic age situated near the southern Colorado Plateau (Tanaka et al., 1986). The field extends 120 km east-west and about 80 km north-south and consists of 605 vents distributed over an area of approximately 5000 km² (Fig. 2.2). Vents are predominantly basaltic cinder cones of Plio-Quaternary age. Three hundred and forty two of these vents are between 0.75-5 million years old, 263 vents are less than 750,000 years old and about 20 of these vents are less than 40,000 years old (Tanaka et al., 1986). Nearly all of the area has been mapped by the U.S. Geological Survey at a scale of 1:50,000 (Moore et al., 1987).

Fig. 2.1: Location of late Cenozoic basaltic volcanic fields in the Colorado Plateau and Transition Zone region. Shaded areas indicate volcanic fields less than 5 million years old and outlined areas show volcanic fields 5 to 16 million years old (from Wolfe et al., 1983).

Fig. 2.2: Map of the location of all 605 vents in the San Francisco Volcanic Field. Asterisk represents the location of cinder cone vents (from Wolfe and others, 1987).

The SFVF rests on Miocene volcanic rocks and erosional surfaces of low relief on Permian and Triassic sedimentary rocks (Wolfe and others, 1983). In contrast to other volcanic fields along the margin of the Colorado Plateau, such as the Springerville Volcanic Field (Fig. 2.1; Condit et al., 1989; Ulrich et al., 1989), large silicic centers are present in the SFVF (Wolfe et al., 1987a,b). Post-Miocene basaltic volcanism was broadly contemporaneous with the silicic and intermediate volcanism that formed Bill Williams Mountain, Sitgreaves Mountain, Kendrick Peak, San Francisco Mountain, O'Leary Peak and several isolated domes (Fig. 2.3; Tanaka et al., 1986).

The San Francisco Volcanic Field contains rocks which range from basalt to rhyolite in composition. All have erupted through Precambrian basement rocks and approximately one kilometer of overlying, nearly horizontal Paleozoic and Mesozoic sedimentary rocks (Wolfe et al., 1987). About 500 km³ volcanic rocks cover the 5000 km² of Paleozoic and Mesozoic rocks of the Colorado Plateau in Northern Arizona (Wolfe et al., 1987). Flows of basalt, basaltic andesite and a lesser amount of andesite, benmoreite and dacite were extruded from numerous individual vents, each of which erupted briefly and then became inactive (Wolfe et al., 1987). Such vents are widely distributed and their flows cover much of the area.

Fig. 2.3: San Francisco Volcanic Field, Arizona(after Tanaka and others,1986). Gray pattern, Pliocene and Pleistocene volcanic rocks; silicic centers within volcanic field are white. Numbers in parentheses indicate ages in millions of years. Faults dotted where concealed; bar and ball on downthrown side.

Previous investigators, (eg. Tanaka et al., 1986) identified a regional, west-to-east migration of volcanism in the field, and suggested that this was a result of the westward movement of the North American Plate relative to a sub-lithospheric mantle magma source. The K-Ar ages of the silicic centers in the field also suggest a northeastward, Pre-Matayama migration of volcanism, parallel to the Mesa Butte fault.

REGIONAL GEOLOGY AND FAULT SYSTEMS

Regional studies in the Flagstaff - Grand Canyon region (Ulrich et al., 1994; Breed et al., 1986), indicate that the study area is underlain by more than 1100 m (3500 ft) of essentially flat lying Paleozoic to Lower Mesozoic sedimentary rocks, which unconformably overlay tilted Pre-Cambrian sedimentary and metamorphic rocks. In the study area itself, the only units that crop out are the Lower Permian Kaibab Formation which is unconformably overlain by the lower to ?middle Triassic Moenkopi Formation. The Kaibab Formation consists of yellowish gray dolomitic limestones, sandstones and siltstones. The Moenkopi Formation on the other hand consists of red-brown colored mudstones, siltstones and sandstones.

Several regional fault systems cut the Paleozoic/ Mesozoic sedimentary rock sequence and locally affect volcanic rocks of the San Francisco volcanic field as well.

The Mesa-Butte, Oak Creek Canyon and Doney fault systems (Figs. 2.3 and 2.4) are the most prominent of these and have experienced normal slip in the Quaternary (Condit, 1978; Shoemaker et al., 1978).

The Mesa Butte fault system is a major structural feature trending northeast across the area. It is partly covered by volcanic rocks and entirely buried in the central part (Fig. 2.3). Several large silicic volcanic centers, including Bill Williams, Sitgreaves and Kendrick Peaks, are situated on or near the Mesa Butte system.

The faults recognized in the system can be grouped into a northeastern segment and a southwestern segment. The Mesa Butte fault is the principal member of the northeastern segment of the fault system and can be recognized at the surface for a distance of about 15 km. The maximum observed displacement in this segment is about 100 m (Shoemaker et al., 1978). A branch fault, the Cedar Ranch fault (Fig. 2.4), joins the Mesa-Butte fault near Mesa Butte and can be traced southwestward about 15 km where it disappears beneath younger lavas. Faults belonging to the southwestern segment of the Mesa Butte fault system can be traced for 16 km and the maximum displacement of the exposed rocks is about 150 m (Shoemaker et al., 1978). The fault disappears to the northeast beneath a field of Pleistocene age lava flows.

In the eastern part of the field, the Oak Creek Canyon system extends north from Oak Creek Canyon through Flagstaff

Fig. 2.4: Principal structural features (Wolfe et al., 1987) in the SFVF. Thick lines are major fault systems and thin lines are other faults. (asterisk represents the location of cinder cone vents)

(Fig. 2.4), dips east at a high angle and displays down-to-the-east displacement (Ulrich et al., 1984). To the north of Flagstaff, the Oak Creek Canyon fault system is concealed by Quaternary and Pliocene volcanic rocks of the San Francisco volcanic field and the large stratovolcano of San Francisco Mountain which lies astride the system. The Doney fault may be a northeastern extension of the Oak Creek Canyon fault system (Fig. 2.4). Similarly oriented structures exposed in the Grand Canyon have been interpreted as having originated during Precambrian time and subsequently reactivated during Mesozoic and Cenozoic time (Shoemaker and others, 1978).

Other systems of faults, such as the Cataract Creek and Kaibab systems, trend northwest through the field. Each system is a relatively broad zone in which the individual faults are short and tend to be parallel or subparallel with the overall trend of the zone (Shoemaker et al., 1978). Northwest-trending normal faults of small throw are conspicuous within the northwestern part and southeastern part of the field (Fig. 2.4).

CHAPTER THREE

STATISTICAL ANALYSIS OF CINDER CONE DISTRIBUTION AND ALIGNMENTS IN SAN FRANCISCO VOLCANIC FIELD

Six hundred and five separate and distinct volcanic centers were identified in the study area (Fig. 2.2). The majority are cinder cones with associated lava flows. In this Chapter, a statistical analysis of the cinder cone distribution is presented. I begin with a discussion of cinder cone density distribution, and then present a quantitative statistical analysis of vent clustering and vent alignment.

ANALYSIS OF VENT DENSITY DISTRIBUTION

A map of the density distribution of cinder cones in the SFVF was constructed by overlaying the study area with a grid whose spacing was 4000 m and then the number of cinder cones in search radius 8000 m were counted about each grid point. The grid point values were contoured with the commercially available MS-DOS application SURFER using a minimum curvature algorithm (Briggs, 1974) with a contour interval of 10 vents/100 km². The resulting contour map (Fig. 3.1) shows that vents are most densely concentrated in the western part of the field and the contours are elongate in a NE orientation, approximately parallel with the southern segment

Fig. 3.1: Map of the density distribution of cinder cones in the San Francisco Volcanic Field (grid spacing 4000m and search radius 8000m). Contour interval is 10 vents/100 km². Dark lines are major fault systems.

of the Mesa-Butte fault system. This distribution suggests that the Mesa-Butte fault zone may play an important role in controlling the regional vent distribution. The concentration of vents is also high in the eastern part of the field, adjacent to the Oak Creek Canyon - Doney fault system, also suggesting that a fault system may influence vent distribution.

The results of density mapping are strongly influenced by grid spacing and search radius. The appearance, therefore, of the density contour map will change if a different grid spacing and search radius are used. For a smaller grid spacing and search radius (2000 m and 4000 m respectively), the density map forms 4-5 distinct concentrations (Fig. 3.2), where locally, the cone density is as high as 6 vents/10 km². In Fig. 3.2, two of these density concentrations lie along an extension of the trend of the north segment of the Mesa Butte fault. There is also a concentration in the central-northeast part of the area, between the Mesa Butte and Oak Creek Canyon-Doney fault systems that is coincident with NE trending lineaments in the regional magnetic and gravity data (see Chapter 4).

In general, however, maps of vent density alone are difficult to relate to possible linear groupings, especially where vent distribution is dense as this makes alignment recognition difficult.

Fig. 3.2: Map of the density distribution of cinder cones in the San Francisco Volcanic Field (grid spacing 2000m and search radius 4000m). Contour interval is 5 vents/100 km². Dark lines are major fault systems.

Because of the dense vent concentration in the SFVF, the qualitative identification of vent alignments is of limited value. Instead, statistical methods are used which allow a more objective identification of vent alignments. The methods used include cluster analysis, two-point azimuth analysis, and Hough Transform analysis, all of which have been previously used to study point patterns in volcanic fields (Wadge and Cross, 1988; Connor et. al., 1990).

CLUSTER ANALYSIS

Cluster analysis is used to identify natural spatial groupings of vents. The method was chosen because the outcome depends on the variation in the spatial density of vents rather than on the distribution of individual cones. This is important because quantitative alignment recognition methods are adversely affected by inhomogeneities in vent distribution. By identifying clusters before making the alignment analysis, the effects of inhomogeneities are minimized (Connor, 1992).

A uniform kernel density fusion cluster algorithm (Wong and Lane, 1983; Sarle, 1985) was used, because it is less sensitive to cluster shape than other algorithms, which tend to search for compact or elongate clusters. In this algorithm, density linkage is used to refer to a class of clustering methods using nonparametric probability density estimates. If $f(X)$ is the number of vents within a circle of

radius r centered at vent X , then the dissimilarity matrix, $d^*(X_i, X_j)$, is computed as:

$$d^*(X_i, X_j) = 1/2 * (1/f(X_i) + 1/f(X_j)), \quad d(X_i, X_j) < r$$

$$d^*(X_i, X_j) = \text{infinity}, \quad \text{otherwise}$$

where $d(X_i, X_j)$ is the distance between the i th and j th vent. $f(X_i)$ and $f(X_j)$ are the number of vents within the circle of radius r centered at i th and j th vent respectively. Once this matrix is calculated, individual vents are linked using this matrix and a single linkage clustering algorithm. If the density fusion, d^* , between two clusters is less than the maximum d^* between any two vents within either cluster, the two clusters are not linked. This step makes the recognition of overlapping clusters possible by reducing the importance of individual vents. The single linkage clustering process continues repetitively until a stable number of clusters is found. A full listing of the computer program used can be found in Appendix A.

Maps are then constructed, showing the distribution of individual vents by cluster membership.

Clearly, changing the search radius r will change the number of clusters on this map. Therefore, one goal of the analysis is to find a range of search radii which produce relatively stable cluster groups. If clustering is a significant feature of the vent distribution, then the number of clusters will not change or change only slightly with changes in search radius (Connor, 1992).

According to this principle, maps of vent distribution by cluster membership are produced for different search radii. The change in the number of vent clusters with changing search radius (interval 250 m) is shown in Figure 3.3. For search radii greater than 8500 m, the change in the number of clusters is low, and cluster membership tends to form several extremely large clusters. For search radii less than 5000 m, small clusters separate out and the number of clusters increases rapidly with decreasing search radius. Between search radius 5500 m and 8000 m, the number of clusters change only slightly with changing search radius. Variation in total number of clusters usually is due to fragmentation of clusters comprising 10 or fewer cones.

Because these clusters do not change membership in a significant way over a search radii range of 5500 to 8000 m, clusters defined by search radii in this interval are viewed as significant features of cinder cone distribution in the SFVF. In addition, previous studies (Wadge and Cross, 1988; Connor, 1990) indicate that best number of clusters to investigate vent alignments in a given area is between five and ten. Hence, a search radius 6500 m and 7000 m to do cluster analysis seems reasonable (Fig. 3.3). Fig. 3.4 illustrates the results of a cluster analysis for a search radius 7000 m which is representative of the vent pattern in the field. Five large clusters (having between 78 and 151 cinder cones each) and four small clusters (between 5 to 22

Fig. 3.3: Diagram of the change in the number of vent clusters with changing search radius(interval 250m).

Fig. 3.4: Vents plotted by cluster memberships (search radius 7000m) using uniform kernel density fusion cluster analysis. The solid lines show the bounding polygon.

cinder cones each) persist over range of search radius with only slight changes in membership. The clusters shown are stable over the following search radii (Table 3.1). Here, approximately 93% of the cinder cones in the field are found within these 5 large clusters, and the remaining 7% of cones are distributed within the other small outlying clusters. A comparison of the results of the cluster analysis (Fig. 3.4) with a contour map of the cinder cone density distribution (Fig. 3.2) suggests that the large clusters correspond to concentrations in the cinder cone density distribution.

Table 3.1: Stable clusters over range of search radius

stable cluster	search radius	number of vents	average age
cluster1	4500-7750m	82	5.5±0.5M.Y.
cluster 2	4750-8250m	151	2.5±0.3M.Y.
cluster 3	6250-12000m	140	0.5±0.1M.Y.
cluster 4	5000-9500m	78	0.5±0.1M.Y.
cluster 5	6750-7750m	111	3.5±0.3M.Y.
cluster 6	5000-8250m	22	2.5±0.3M.Y.
cluster 7	5000-8250m	10	-
cluster 8	5000-8500m	8	-
cluster 9	5000-10000m	5	-

TWO-POINT AZIMUTH ANALYSIS

The two-point azimuth method, developed by Lutz (1986) and Zhang et al. (1989), provides a statistical means of identifying preferred orientations and anisotropy in vent distribution. The basis of the two-point method is a Monte Carlo simulation. "Monte Carlo simulations provide empirical

confidence values for azimuthal frequencies that can be used as guides to interpret azimuthal distributions. Here, Lutz's computer program was used (see Appendix A for listing).

Briefly, any two vents in the volcanic field can lie along a line. A line segment connecting two vents in an areal distribution defines an azimuth (Fig. 3.5). The frequency distribution of intersegment azimuths is drawn from all pairs of vents (Fig. 3.6A). The azimuthal distribution responds to both the presence of vent alignments and the shape of the boundary of the volcanic cluster, so vent pairs tend to align in a preferred orientation if the entire cluster is elongate. In order to account for the effect of cluster shape, the shape of the area is defined by a convex polygon (Fig. 3.4) that makes it possible to quantify the field shape effect by Monte Carlo simulations of random patterns. Only vents falling within the polygon selected are used in the analysis. For each simulation, n vents were randomly plotted within this polygon which included the vents at the margin of each cluster, the azimuth from each vent to every other vent within the polygon was found and the cumulative frequency was compared with the observed vent azimuth frequency distribution at 10° intervals (Fig. 3.6D).

Since the azimuthal frequency distribution is sensitive to the presence of geological inhomogeneities, it is possible to understand the underlying geological mechanisms which form the cinder cone area. If actual vents tend to align

Fig. 3.5: Two-point azimuth method. Intersegments are constructed between all pairs of vents; the angle of intersection of each segment or its extension with a N-S line defines its azimuth.

Fig. 3.6: Rose diagrams of two-point azimuth analysis showing preferred the azimuthal direction for cluster 3. A: observed data distribution (the line segment orientation in 10° interval). B: preferred azimuthal orientations (the 10° interval contains more observations which exceed the 90% confidence limit). C: the normalized distribution (the frequency per class of observed line segment orientations was normalized to take the shape of the study area into account). D: the upper confidence limit based on the Monte Carlo simulation (90% confidence limit).

preferentially in a given orientation, this vent alignment will emerge through comparison with the Monte Carlo results.

The two-point azimuth method was applied to the significant clusters in the field (Fig. 3.4). The outcome of the analysis indicates that significant alignment exists in the distribution of cinder cones within each cluster. Significant azimuthal orientations are found within each cluster at the 90% confidence level using a t test. Figure 3.6B shows the preferred azimuthal direction for cluster 3, that is, the observed azimuths (Fig. 3.6A) that exceed the 90% confidence limits (Fig. 3.6D). The direction is 140° - 150° or 320° - 330° which compares with the orientation in the diagram of the normalized distribution (Fig. 3.6C). The normalized azimuthal distribution can be calculated on the basis of the upper confidence limit distribution, D , and the mean distribution, $\bar{A}$. The normalized distribution, C , is defined as (Lutz, 1986):

$$C = (D / \bar{A}) * A$$

where A is the observed distribution. If the preferred azimuthal orientation is significant, then the preferred azimuthal orientation and the normalized azimuthal orientation should be consistent.

HOUGH TRANSFORM ANALYSIS

While the two-point azimuth method determines the trends of structures, it does not provide any other information

about their spatial distribution. Application of Hough Transform helps to determine the actual locations of alignment (Wadge and Cross, 1988). The Hough Transform method (see computer program in Appendix A) is a widely used computer method for detecting linear structures.

In the Hough transform method, each vent in a cluster is viewed to lie along an infinite number of lines, each line having a unique azimuth. In the case of a straight line, it can be represented in polar coordinates ρ and α , where ρ is the normal distance from that arbitrary origin point to the line, and α is the angle between the normal and the X axis (Fig. 3.7A). The equation of the line is thus $\rho = X \cos \alpha + Y \sin \alpha$, the axes of the new parameter plane corresponding to ρ and α . Each (x, y) point generates a sinusoidal curve in the parameter plane as ρ is calculated for successive values of α . Each point (ρ, α) on the sinusoidal curve represents a line containing the fixed point (x, y) . It follows that the curves in the (ρ, α) plane generated by two or more collinear points intersect at a common point. The values for ρ and α at this point define their alignments (Fig. 3.7B).

Approximate values for $d\rho$ and $d\alpha$ were determined by considering the likely dimension of an individual vent. Here, A value $d\alpha$ equal to 2° - 3° (which corresponds to vent dimension about 350-800 m diameter) and a corresponding value of $d\rho$ equal to 300-800 m, were taken because they represent a reasonable dimension of an individual vent as observed in the

Fig. 3.7: Hough transform method illustrate for three nearly collinear points (p). A: X and Y plane, w is length of cluster diameter. B: corresponding curve in ρ and α plane.

field. The behavior of this method was investigated with different parameter settings. Fig. 3.8, Fig. 3.9 and Fig. 3.10 show examples of alignment patterns obtained by considering different vent sizes (ie. different d_p and d_α) for cluster 3 with each alignment having 9 and more vents. Although the number of alignments changed slightly, the vent alignment pattern was remarkably stable.

Because inhomogeneities in vent distributions can adversely affect the results of the alignment analysis, the Hough transform method was applied on a cluster by cluster basis. Within each cluster, several alignments consisting of numerous vents were identified. Most of these alignments have orientations similar to those recognized as significant using the two-point azimuth method at the 90% confidence level. Figures 3.8, 3.9 and 3.10 show alignments which have almost the same orientation as that determined with the two-point azimuth method (Fig. 3.6).

The Hough transform is sensitive to both the number of cinder cones used in the analysis and the shape of the cinder cone cluster. The more cinder cones in a cluster, the more likely it is that several cinder cones will align. Alignments usually consist of 9-10 vents for large cluster and 4-5 for small clusters in the SFVF. If a cluster is elongate, alignments will likely be found in the direction of elongation. Therefore, care was taken in the final geological interpretation of the results of the Hough transform and a

Fig. 3.8: Hough transform alignments with minimum of 10 vents plotted on cluster 3 for parameters ($dp=450m$, $d\alpha=2^\circ$).

Fig. 3.9: Hough transform alignments with minimum of 10 vents plotted on cluster 3 for parameters ($dp=500m$, $d\alpha=2^\circ$).

Fig. 3.10: Hough transform alignments with minimum of 10 vents plotted on cluster 3 for parameters ($d_p=500\text{m}$, $d\alpha=3^\circ$).

comparison was made with the results of the two-point azimuth method, which does take cluster shape into account.

VENT ALIGNMENT PATTERNS IN THE SAN FRANCISCO VOLCANIC FIELD

The alignments derived from the Hough Transform analysis are shown in Figure 3.11 for $d\alpha=2^\circ$, $dp=500$ m, and a search radius of 7000 m, and are plotted along with the clusters in which they form and the major faults identified in the area. For clusters situated in the southwestern and northeastern part of the field (clusters 1, 4 and 5), alignments are generally oriented in a NE direction. These alignments (A-G, Fig. 3.11) extend approximately 20-38 km, consist of 9 to 10 vents, and generally coincide with the elongate area of highest vent density (Fig. 3.1). For these same clusters, the two-point azimuth method indicates that statistically significant (90% confidence level) alignments occur between 020° and 050° azimuth, which is comparable to the orientations identified using the Hough transform analysis (Table 3.2).

In clusters 2, 3 and 8 of Fig. 3.11 in the southeastern and west-central part of the field, a significant number of azimuths are oriented in NW to WNW directions.

The vent alignment patterns for search radius 6500 m (Fig. 3.12) are similar to those found for search radius of 7000 m. This indicates that this pattern is stable over a

Fig. 3.11: Vent alignment patterns in the San Francisco Volcanic Field (search radius 7000m). Solid lines (upper case letters) are alignments from large clusters and dashed lines (lower case letters) are alignments from small clusters. Thick lines are major fault systems.

Table 3.2. Summary of the alignment analysis

cluster	No. of Vents	Two-Point Azimuth	Hough Transform			
			Trend	No. of Vents	Length	Vents/km
1	82	040°-050°	046°(F)	9	22km	0.41
		-	172°(Q)	9	17km	0.55
		-	058°(G)	9	20km	0.45
2	151	080°-090°	-			
		090°-100°	100°(N)	10	38km	0.26
		100°-110°	102°(M)	10	34km	0.3
		-	132°(L)	10	34km	0.3
3	140	140°-150°	145°(J)	10	38km	0.26
			142°(I)	10	30km	0.33
		-	160°(H)	10	25km	0.4
		-	098°(K)	10	38km	0.26
4	78	100°-110°	-			
		030°-040°	030°(D)	9	37km	0.25
		-	015°(C)	9	33km	0.27
		-	050°(E)	9	22km	0.41
5	111	-	106°(O)	9	36km	0.25
		060°-070°	-			
		050°-060°	-			
		040°-050°	040°(B)	9	27km	0.33
		030°-040°	034°(A)	9	27km	0.33
		-	122°(P)	9	20km	0.45
6	22	140°-150°	-			
		100°-110°	-			
		020°-030°	022°(r)	5	-	-
7	10	140°-150°	150°(t)	4	-	-
		010°-020°	010°(u)	4	-	-
8	8	130°-140°	135°(s)	5	-	-
		030°-040°	-			
9	5	020°-030°	028°(v)	4	-	-

Notes: Upper case letters are alignments from large clusters and lower case letters are alignments from small clusters.

Fig. 3.12: Vent alignment patterns in the San Francisco Volcanic Field(search radius 6500m). Solid line is alignment from large clusters and dash line is alignment from small clusters.

range of search radii. One exception to this pattern is that the NW and WNW vent alignment orientations of cluster 2 in Fig. 3.11 (7000 m search radius) changes to the predominantly NE and NW directions of clusters 1 and 6 in Fig. 3.12 (6500 m search radius). Vent alignments determined at larger search radii may reflect deeper-seated features while alignments determined from small search radii may reflect relatively shallow features.

Figs. 3.11 and 3.12 also reveal some interesting relationships between regional fault structures and the Hough transform determined alignments. Some vents are aligned along the northern segment of the Mesa Butte fault, and in both figures, vent alignments appear to occur along a SW extension of this fault in the southwestern part of the field (alignment F in Fig 3.11). In Fig. 3.12 these trends cut across the center of the field (cluster 1). A similar pattern is observed for the southern segment of the Mesa Butte fault, where NE trending alignments appear as possible extensions of the fault, but are parallel, rather than coincident with the northern segment of the Mesa Butte fault. No clear alignment seems to connect the northern and southern segments of the Mesa Butte fault system.

The WNW trending alignments found in the clusters that cross the center of the field are also interesting, as this both the location of clusters and the orientation of the

alignments are consistent with the Cataract Creek fault zone that crosses the area in this location.

Two preliminary speculative conclusions can be drawn from these observations. The first is that the strong correlation of the cinder cone alignments with the older, and deep-seated fault structures suggests that the latter play an important role in controlling cinder cone alignment. A second speculation is that (if the first conclusion is correct) the northern and southern segments of the Mesa Butte fault are not the extremes of a single fault, as suggested previously (Shoemaker et al., 1978), but are really two separate and parallel fault systems whose southern and northern ends respectively have been buried by the volcanism in the San Francisco Volcanic field.

CHAPTER FOUR

PRELIMINARY GEOPHYSICAL STUDIES

This chapter presents an analysis of geophysical data available from regional databases and presents the results and analysis of local geophysical data collected in the field in the Summer of 1993. The aim of these preliminary geophysical studies is to investigate the geological setting of regional structures and to interpret the relationships between specific structures and vent alignments.

REGIONAL POTENTIAL FIELD DATA

Gravity and aeromagnetic data extending from latitude 35°03'N to 35°47'N, and from longitude 247°34'E to 248°53'E (Fig. 3.2) were utilized in the regional geophysical study. The data are from the Decade of North American Geology geophysical data base (National Geophysical Data Center, 1984). The regional data were interpolated to a 77 by 65 grids with a grid spacing of 1.6 km, which was contoured using a minimum curvature algorithm. This particular grid spacing was chosen because it gives the best anomaly map in the study area.

The wavelength filtering method is generally used to obtain separation of long wavelength regional anomalies associated with deep crustal or subcrustal features, from

short wavelength residual anomalies associated with shallow features. As an aid to the interpretation of gravity anomalies, a best fit plane was removed from the interpolated grid and the resulting residual anomalies are shown in Fig. 4.1. The most prominent features on this map are two 20mgal negative gravity anomalies surrounded by positive gravity anomalies. Qualitatively, it appears that these negative anomalies coincide with areas underlain by silicic volcanic rocks. Negative anomaly A (Fig. 4.1) is centered approximately with the silicic centers of San Francisco Mountain and O'Leary Peak and negative anomaly B is located exactly over the silicic centers of Bull Basin Mesa and Kendrick Peak. These negative anomalies probably reflect the lower densities of the underlying intermediate to silicic volcanic rocks.

Figure 4.2 shows the residual aeromagnetic anomalies in the San Francisco volcanic field. Several NE trending elements are present in the anomaly pattern. These are parallel to and coincide with the regional fault systems (see Chapter 2) and with some vent alignments identified in Chapter 3. For example, the anomaly patterns support the notion, presented in Chapter 3, that the North Mesa Butte (N.M.B. in Fig. 4.2) trend is a separate and parallel trend to the South Mesa Butte fault (S.M.B. in Fig. 4.2). Another NE trending pattern coincides with the Oak Creek Canyon - Doney Fault trend (O.C.C.-Doney in Fig. 4.2). As the

Fig. 4.1: Residual gravity anomalies (mgals) in SFVF overlain by vent alignment pattern (thin lines, search radius 7000m) and major fault systems (thick lines). A and B are two negative gravity anomalies associated with low density surface volcanics.

Fig. 4.2: Residual aeromagnetic anomalies (nT) in SFVF (Contour interval 100nT) overlain by vent alignment pattern (search radius 6500m) and major fault systems (thick lines).

anomalies indicate deep seated features, the coincidence of anomalies and the faults suggests that the fault systems are major basement structures. Another NE orientation anomaly pattern occurs in the northern part of map between the South Mesa Butte and Oak Creek Canyon - Doney Fault trends. Interestingly, this feature coincides with an elongate concentration (Fig. 3.2), clusters (4 and 5 in Figs. 3.11 and 3.12 respectively) and Hough transform alignment (D of Fig. 3.11) determined in the statistical studies.

In addition to the NE trending patterns, Figure 4.2 also shows a WNW trend that cuts through the center of the study area. This trend not only coincides with the diffuse Cataract Creek fault system that traverses the study area, but also coincides with several cinder cone lineaments identified in the alignment analysis presented earlier (alignments K, M and N in Fig.3.11).

In an attempt to obtain more information from the gravity anomalies, a NE directional filter (pass band 025° - 065°) was applied to the gravity data and the directional filtered gravity anomaly map is shown in Figure 4.3. The directional filtering produces several high gradient anomaly zones which correspond to density contrasts at depth. A strong high gradient anomaly zone coincides with the Oak Creek Canyon-Doney fault system, suggesting that the Oak Creek Canyon-Doney fault system is a continuous feature that penetrates basement beneath the surface volcanics. In

Fig. 4.3: Map of directionally filtered gravity anomalies (mgals) of pass band 025°-065°. Thick lines are Mesa Butte and Oak Creek Canyon-Doney fault systems. Straight lines are some NE-trending vent alignments.

contrast to the Oak Creek Canyon-Doney fault system, the Mesa Butte fault system does not coincide with a steep gravity gradient. Instead, the anomalies suggest, as do the the magnetic anomaly and vent alignment patterns (see Chapter 3), that the north and south segments of Mesa Butte fault system are probably two distinct faults (Fig. 4.3). Interestingly, between the South Mesa Butte and Oak Creek Canyon-Doney fault trends, there is a continuous, high gradient zone (Fig. 4.3). This high gradient zone coincides the magnetic trend mentioned above and with vent alignment D shown in Fig. 4.3. It is therefore suggested that this high gradient zone marks the presence of a major fault zone at depth, which has no direct surface manifestation, but that vent alignment D may be related to the same regional fault structure responsible for the gravity anomaly.

In summary, it is suggested that the analysis of the regional geophysical data, in combination with some of the results of the alignment analysis, indicates that there are four large scale, NE trending fault systems in the San Francisco Volcanic Field: (1) a northern segment of the Mesa Butte, (2) a southern segment of the Mesa Butte, (3) an unnamed fault system Between the Mesa Butte and Oak Creek Canyon-Doney, and (4) the Oak Creek Canyon-Doney Fault system.

In addition, NWW trending residual aeromagnetic anomalies shown in Figure 4.2 form a broad zone which is

coincident with Cataract Creek system and is also coincident with several cinder cone alignments (specifically, alignments K, M and N of Fig.3.11).

SPIDER WEB RANCH GEOPHYSICAL SURVEYS

A detailed gravity and magnetic survey was conducted in the Spider Web Ranch area (35°38'40''N, 35°39'32''N; 248°29'15''E, 248°30'E) in the northeastern portion of the study region. This area was chosen to investigate structures associated with a particular vent and vent alignment, such as feeder dikes and faults. This area was chosen because it is not covered by basaltic lava flows and because dikes and normal faults are exposed at the surface (Fig. 4.4). The trend of these features has the same orientation as alignment D identified from the alignment analysis (Fig. 3.11).

The local geological features in Spider Web Ranch area are shown in Fig. 4.4 (from Ulrich et al., 1987). A 10-40 meter thick sequence of shale, siltstone, and sandstone of the Moenkopi Formation underlies the area. Five to ten meter thick basalt flows and two cinder cone vents overlie these sediments. The lava flows are predominantly plagioclase-phyric basalts. A basaltic feeder dike to vent 6802 outcrops in the area and is approximately 0.5 m wide and 150 m long. This dike is composed of a plagioclase-phyric basalt that has abundant 1 to 3 mm plagioclase laths and contains baked sandstone xenoliths of the surrounding Moenkopi Formation

Fig. 4.4: Geological map of Spider Web Ranch area. Qmb: basalt flows erupted from vent V6802 and V6811A; Qmbi: basaltic dike near vent 6802; Trm: Moenkopi Formation. F1, F2 and F3 are local normal faults (bar and ball on downthrown side).

country rock. Several NE trending normal faults also can be seen in the given area (Fig. 4.4). Field measurements of the trend of these faults range from 018° to 025° .

Gravity and magnetic data were collected along profiles at 20-50 m and 2.5-20 m station spacing respectively. The total area surveyed was about one square kilometer. Gravity measurements were made using a Lacoste and Romberg gravimeter, which has a measured drift of less than 0.1mgals/month. Magnetic measurements were made using a proton precession magnetometer. Elevations were surveyed in using a precision automatic level. In total, the survey consisted of 10 profiles across the field (Fig. 4.4). A description of the reduction process and a listing of the gravity and magnetic data is shown in Appendix B.

Fig. 4.5 shows 8 Bouguer gravity anomaly profiles across vent 6802 and its associated dike. Because of the limited topography, the terrain correction was omitted. The tide correction was also omitted because the measurements were taken over a limited time interval. An assumption of a density of 2.67g/cc was made for the Bouguer correction. The absolute gravity value for our base station was tied to the Complete Bouguer Gravity Map of SP Mountain Quadrangle (Hendricks, 1975).

Results - Gravity

The most notable feature on the gravity profiles is an approximately 0.5 mgal low anomaly which is coincident with

Fig. 4.5: Bouguer anomaly of gravity survey profiles (Line #10000, Line #4000, Line #3000, and Line #5000). Location of lines is shown on Figure 4.4.

Fig. 4.5(continued): Bouguer anomaly of gravity survey profiles (Line #7000 and Line #2000).

Fig. 4.5(continued): Bouguer anomaly of gravity survey profiles (Line #1000 and Line #9000).

the dike and vent (Fig. 4.5, Line #3000, Line #5000 and Line #4000). Further away from the dike, the anomalies disappear. A contour map of the gravity data is shown in Fig. 4.6. In order to produce this map, point data were smoothed with a 3 point moving average and contoured with a minimum curvature contouring algorithm. The contour map clearly shows a small negative anomaly that is elongate with the orientation of the dike (Fig. 4.6).

Since the amplitude of the anomaly is relatively small, the assumed Bouguer reduction density may have a large relative effect on the anomaly, and an incorrect reduction density will result in a correlation between the Bouguer anomaly and topography. In order to test for this possibility, a plot of observed free air anomaly verses station elevation was made (Fig. 4.7). The slope of best fitting line is used to find the reduction density for Bouguer correction. This analysis resulted in a reduction density of 2.865g/cc. For this reduction density, the amplitude of the negative anomaly is actually slightly larger than that calculated using a density of 2.67g/cc. Therefore, the negative anomaly in this survey is not simply an artifact of the reduction process.

The density of cinder cone volcanic eruption materials and dike has a positive difference with the surrounding Moenkopi Formations. If so, the anomalies of profiles should be the reverse of that which is observed. Therefore, some

Fig. 4.6: Plane map of gravity anomalies (mgals) and geological features in vent 6802 area. Asterisk represents survey stations.

Fig. 4.7: Scatter plot showing the relationship between Free Air anomaly and elevation. The best fitting line corresponds to a Bouguer reduction density of 2.865g/cc. For comparison, a line corresponds to density of 2.67g/cc is shown.

geological processes might have occurred to make this area less dense when forming the dike. The anomaly in Fig. 4.6 is elongate exactly with the trend of the dike and this suggests that processes related to dike emplacement may be responsible for the small negative anomaly. One possibility may be that hydrothermal brecciation during dike intrusion has lowered the bulk density of the country rock immediately around the dike and beneath the anomaly.

Results - magnetism

The basaltic rocks in the field area show a strong magnetic signature (Fig. 4.8). This signature is the strongest on profiles which are situated on the basalt flows (Fig. 4.8, Line #5000 and Line #7000). These profiles are difficult to interpret because of the strong isothermal remnant magnetization due to frequent lightning strikes in this region. The magnetic anomaly of survey line #10000 which is situated on Moenkopi Formation area is much smaller than on the basalt flows (Line #5000 and Line #7000). In this survey line, the dike does not outcrop beneath the profile, but the magnetic anomaly has a remarkable dike signature (Fig. 4.9). This indicates that a dike must exist beneath the surface because a dike usually has a higher magnetite composition than Moenkopi Formation in this area.

In order to investigate the gravity and magnetic anomalies near other vents, two survey lines were conducted at vent 6811A which is aligned with vent 6802 and offset 800

Fig. 4.8: The anomaly of 3 magnetic profiles (Line #10000, Line #5000 and Line #7000) across the dike.

Fig. 4.9: The magnetic anomaly of Line #10000 in expanded scale.

meters to the south. Fig. 4.10 and Fig. 4.11 show the gravity and magnetic anomaly profiles. The gravity anomaly for the survey line #6000 has a low similar to those on lines #5000 and #3000, and survey line #8000 looks very similar to line #7000 (Fig. 4.5). Also, the survey line #8000 and line #6000 show the same magnetic anomaly shape as the line #10000 in Fig. 4.9. The only difference is that the amplitude of anomaly in line #8000 and line #6000 is much bigger than the one of line #10000. This may suggest that the size of a dike beneath line #8000 and line #6000 is bigger than the dike in vent 6802. The gravity and magnetic anomalies associated with vent 6811A have features similar to those near vent 6802. This suggests that similar to vent 6802, a dike must exist beneath the surface of vent 6811A (Fig. 4.4) like vent 6802. This suggests that many aligned vents may be associated with a dike beneath the surface.

Fig. 4.10: Bouguer anomaly of gravity survey profiles (Line #8000 and Line #6000) near vent 6811A. refer to map figure which shows location of profiles (Fig. 4.4).

Fig. 4.11: The anomaly of magnetic profiles (Line #8000 and Line #6000) near vent 6811A. refer to map figure which shows location of profiles (Fig. 4.4).

CHAPTER FIVE

DISCUSSIONS AND CONCLUSIONS

SUMMARY AND DISCUSSION

The statistical studies described in Chapter 3 establish a strong correspondence between cinder cone, density, clustering and alignments with old fault structures in the substrate of the San Francisco Volcanic Field, especially in its western portion.

Density distribution maps (Figs. 3.1 and 3.2) show concentrations of vent density adjacent and collinear to the segments of the Mesa Butte fault. There is a high density of vents to the east of the Oak Creek Canyon - Doney trend, but it is not elongate and does not coincide directly with the OCC-Doney trend.

Cluster analysis defines several clusters of vents that are distributed broadly over the north, central and southern parts of the field. Vent alignment patterns, determined in each of these using the Hough Transform method, show well developed lineaments whose orientations are parallel to, and in some cases correspond exactly to the major fault systems that cut the Pre-Cambrian to Mesozoic rocks that underlie the area. In the western part of the field, both in the north and the south, the vent alignments are predominantly oriented in a NE direction. These vent alignments are usually 20-38 km in

length and include 9-10 vents. Some of these alignments are collinear with and appear to be an extension of the northern segment of the Mesa Butte fault system. Similarly, alignments in the northern part of the field are collinear with the southern segment of the Mesa Butte fault system. These relationships suggest that the volcanic alignments are strongly controlled by the old, deep seated faults such as the Mesa Butte fault system.

Furthermore, as no alignments (or geophysical data) link the southern and northern segments of the Mesa Butte fault "system", it is suggested that these two fault segments are not connected, but are separate and parallel fault systems. The regional geophysical data also support this view. Gravity anomaly maps (Fig. 4.1), and particularly the aeromagnetic anomaly maps (Fig. 4.2), show patterns that suggest that these two trends are separate and parallel.

Cinder cone concentration, alignment analysis and regional geophysics indicate another strong NE trend in the north-central part of the field, between the Mesa Butte systems and the OCC-Doney systems (Figs. 3.2, 3.11, 3.12 and 4.2). It is suggested that these features indicate another major NE trending fault in the basement.

In contrast, cinder cone concentration, alignment analysis and regional geophysics do not show a particularly strong correlation with the OCC-Doney fault in the eastern part of the field. This poor correlation suggests that this

particular NE trending fault system does not seem to have heavily influenced vent alignment patterns.

Clusters in the center of the SFVF form a WNW trend as do the Hough transform determined alignments. This trend is both parallel and coincident with the trend of the diffuse WNW Cataract Creek fault system. A similar trend can be seen crossing the study area in the regional geophysical patterns (Figs. 4.1 and 4.2). These patterns again suggest that old fault trends in the substrate of the field are an important influence in cinder cone alignment.

In summary, it is suggested that the correspondence of statistically defined alignments, regional geophysical anomalies and mapped older faults indicate that vent alignments in the SFVF are strongly controlled by major regional fault structures. In addition, almost all the intermediate to silicic centers in the SFVF occur over buried extensions of the two Mesa Butte and Oak Creek Canyon-Doney fault systems, which suggests that these fault systems play an important role in determining the location of the intermediate to silicic volcanic centers.

If this hypothesis is correct, then this suggests a reinterpretation of the regional structure of the area. It is suggested that the San Francisco Volcanic Field is underlain by four major NW trending fault systems: (1) a northern segment of the Mesa Butte, (2) a southern segment of the Mesa Butte, (3) an unnamed fault system Between the Mesa Butte and

Oak Creek Canyon-Doney, and (4) the Oak Creek Canyon-Doney Fault system. In addition, the central part of the field is crossed by the more diffuse Cataract Creek fault system. This new interpretation is compared with the older interpretation (Shoemaker et al, 1978; Tanaka and others, 1979) in Fig. 5.1.

The major intermediate to silicic centers are located adjacent to and along the two Mesa Butte and Oak Creek Canyon-Doney fault systems, and also lie within the Cataract Creek fault system. This coincidence strongly suggests that the intersection of these older fault systems are important in controlling the pathways for silicic magma ascent, although the precise mechanism is unclear.

Field observations and the geophysical studies indicate that dikes underlie and extend into several vents, including those examined in detail at Spider Web Ranch area. At Spider Web Ranch area, at least, the trend of the dikes and the elongation of the volcanic edifice are parallel to the alignment in which they are found.

In the following section, I try to discuss the geological significance of vent alignments and possible mechanism of cinder cone emplacement.

MAGMA EMPLACEMENT IN THE SAN FRANCISCO VOLCANIC FIELD

Many volcanic vents in the study area are aligned with major regional structures. Intermediate to silicic centers in particular seem to be associated with major fault systems.

Fig. 5.1: Structural features in the SFVF. (A). previous suggested structural features; (B). new interpretation of structural features suggested in this study.

Vent locations, are not entirely controlled by structural features however, as examination of vent alignment patterns (Figs. 3.11 and 3.12) indicates that only 30% of the vents belong to alignments. Most vents in the SFVF are, therefore, not part of the identified alignments. Moreover, vent clusters close to the OCC-Doney Fault show no NE trending alignment.

Density distribution analysis and cluster analysis demonstrate that vents occur in clusters, rather than having an uniform random distribution. These observations suggest that through time there is a tendency for successive pulses of magma injection to occur near one another, rather than randomly over the entire area of the field.

The following simple model is proposed to describe the process of magma emplacement in the SFVF. Magma in a particular pulse rises through the lower crust. When it reaches the upper crust where brittle structural features such as faults are encountered, the faults may act as pathways for the magma, especially if they are large fault systems that penetrate deeply into the crust. If no large faults are encountered then the magma pulse rises up more complex pathways and produces a random pattern of distribution in the cluster it produces. This might explain why only about one third of vents are found in alignments. Final dike orientation and edifice alignment are probably controlled by near surface brittle features such as faults

and joints (G. Draper personal communication, 1994), but this aspect needs further study.

The role of active (neotectonic) stresses in the SFVF is difficult to evaluate. If active tension were oblique to alignments, then this would indicate that the old, large crustal structures are the main controlling factor in alignment formation. In other words, magma does not rise up a newly formed fracture, but up an older fracture. Tensional stress axes as derived from earthquake data as shown on the Stress Map of North America (Zoback and others, 1991) trend NW in the study area, perpendicular the old NW trending structures (Fig. 5.2). It is therefore impossible to evaluate the influence of the neotectonic stress orientation on the vent alignment orientation. The presence of the WNW trending vent alignments in the Cataract Creek fault system suggests, however, that the role of neotectonic stress orientation is minimal.

CONCLUSIONS

1. Correspondence of vent alignments, major faults and geophysical trends in the San Francisco Volcanic Field suggests that regional structural fault systems are a major control on vent alignment. Cinder cone alignments which are generally more than 20 km in length and consist of 9-10 cinder cones in the SFVF also indicates that vent alignments are controlled by regional scale features. Only about one

Fig. 5.2: Neotectonic stress orientations derived from fault slip and earthquake focal mechanisms (after Zoback et al., 1991). Shaded areas indicate volcanic fields less than 5 million years old and outlined areas show volcanic fields 5 to 16 million years old. Arrows represent an azimuth of maximum horizontal stress.

third of the vents in the field are contained in alignments, so these structures do not influence the location of all magma conduits.

2. The Mesa Butte and Oak Creek Canyon-Doney fault systems may serve as pathways for the intermediate to silicic magma to ascend. Large silicic centers form close the intersection of the Cataract Creek fault system with the segments of Mesa Butte, Oak Creek Canyon-Doney fault systems respectively.

3. Statistical alignment and geophysical studies suggest that Mesa Butte fault is not a single continuous system as originally suggested by Shoemaker (1978). It is suggested instead that is two separate, but parallel fault systems. Geophysical and alignment studies suggest that a buried NE trending fault may lie between the Mesa Butte and Oak Creek Canyon-Doney faults. Geophysics confirms that the Oak Creek Canyon-Doney fault is indeed a single continuous structure. Vent alignment patterns indicate that the WNW-trending Cataract Creek fault system (Shoemaker, 1978) transects the field.

4. The orientation of neotectonic stresses is probably not an important factor in controlling vent alignment.

REFERENCES

- Baker, M.C.W., 1974, Volcanoes, spacing, fractures and the thickness of the lithosphere--A discussion, *Earth Planet. Sci. Lett.*, V.23, p.161-162.
- Brumbaugh, D.S., 1987, A tectonic boundary for the southern Colorado Plateau, *Tectonophysics*, V.136, p.125-136.
- Breed, W.J., Stefanic, and Billingsley, G.H., 1986, *Geologic guide to the Bright Angel trail, Grand Canyon, Arizona*:
- Carr, M.J, 1976, Underthrusting and Quaternary faulting in northern Central America, *Geol. Soc. Am. Bull.*, V.87, p.825-829.
- Condit, C.D., L.S. Crumpler, J.C. Aubele and W.E. Elston, 1989, Patterns of volcanism along the southern margin of the Colorado Plateau: The Springerville Field, *J. Geophys. Res.*, V.94, p.7975-7986.
- Connor, C.B., 1987, Cluster analysis and two-dimensional Fourier analysis of cinder cone distribution: Central Mexico and SE Guatemala (abstract), *EOS Trans. AGU*, V.68, p.1526.
- Connor, C.B., and C.D. Condit, 1989, Evidence of structural controls on vent distribution: Springerville volcanic field, Arizona, *Geol. Soc. Am. Abstr. program*, V.21, A15.
- Connor, C.B., and C.D. Condit, and L.S. Crumpler, 1992, Evidence of regional structure controls on vent

- distribution: Springerville volcanic field, Arizona,
Journal of Geophysical Research, V.97, p.12349-12359.
- Connor, C.B., 1990, Cinder cone clustering in the
TransMexican volcanic belt: implications for structural
and petrologic models, Journal of Geophysical Research,
V.95(B12): p.19395-19405.
- Decade of North American Geology geophysical data base,
National Geophysical Data Center, 1984.
- Delaney, P.T., D.D. Pollard, J.I. Ziony and E.H. Mchee, 1986,
Field relations between dikes and joints: Emplacement
processes and paleostress analysis, J. Geophys. Res.,
V.91, p.4920-4938.
- Fedotov, S.A., 1981, Magma rates in feeding conduits of
different volcanic centers, Jour. Volcan. Geotherm.
Res., V.9, p.379-394.
- Hasenaka, T., and Carmichael, I.S.E., 1985, The cinder cones
of the Michoacan-Guanajuato, Central Mexico, their age,
volume, distribution and magma discharge rate, J.
Volcan, Geotherm.Res., V.25, p.105-204.
- Heming, R.F., 1980, Patterns of Quaternary basaltic volcanism
in the northern North Island, New Zealand, N.Z.J. Geol.
Geophys., V.23, p.335-344.
- Hendricks, John D., 1975, Complete Bouguer gravity map of SP
mountain quadrangle, Coconino county, Arizona.

- Kear, D., 1964, Volcanic alignments north and west of New Zealand's central volcanic region, N.Z. J. Geol. Geophys., V.7, p.24-44.
- Lutz, T.M., 1986, An analysis of the orientations of large scale crustal structures: A statistical approach based on areal distributions of pointlike features, J. Geophys. Res., V.91, p.421-434.
- Moore, R.B., and Wolfe, E.W., 1987, Geologic map of the east part of the San Francisco volcanic field, north-central Arizona, U.S. Geological Survey Map MF-1960.
- Nakamura, K., 1977, Volcanoes as possible indicators of tectonic stress orientation-Principles and proposal, J. Volcanol. Geotherm. Res., V.2, p.1-6.
- Nakamura, K., Plafker, G., Jacob, K.H., and Davies, J.N., 1979, A tectonic stress trajectory map using information from volcanoes and faults: Bulletin of the Earthquake Institute, Tokyo, V.55, p.89-100.
- Newhall, C.G., Ulrich, G.E. and Wolfe, E.W., 1987, Geologic map of the southwest part of the San Francisco volcanic field, north-central Arizona, U.S. Geological Survey Map MF-1958.
- Perry, F.V., W.S. Baldrige, D.J. DePaolo and M. Shafiqullah, 1990, Evolution of a magmatic system during continental extension: the Mount Taylor volcanic field, New Mexico, J. Geol. Geophys., V.95, p.19327-19348.

- Peterson, F., and Turner-Peterson, C., 1989, Geology of the Colorado Plateau: Grand Junction to Denver, Colorado. Field Trip Guidebook T130, 28th International Geological Congress.
- Raisz, E., 1939, Physiographic map of the Colorado Plateau: Landforms of the United States, 1:1,000,000 scale.
- Sarle, W.S., 1985, The cluster procedure in SAS User's Guide: Statistics, 956pp., SAS Institute Inc., Cary, N.C.
- Settle, M., 1979, The structure and emplacement of cinder cone fields, American Journal of Science, V.279, p.1089-1107.
- Shoemaker, E.M., R.I. Squires and M.J. Abrams, 1978, Bright Angel and Mesa Butte fault systems in northern Arizona, Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Geological Society of America, Memoir 152, p.341-368.
- Tanaka, K.L., E.M. Shoemaker, G.E. Ulrich, and E.W. Wolfe, 1986, Migration of volcanism in the San Francisco volcanic field, Arizona, Geological Society of America Bulletin, V.97, p.129-141.
- Tanaka, K.L., T.C. Onstott, and E.M. Shoemaker, 1989, Magnetostratigraphy of the San Francisco volcanic field, Arizona. U.S.Geological Survey Bulletin 1929, p.35.
- Thompson, G.A., and Zoback, M.L., 1979, Regional geophysics of the Colorado Plateau, in T.R. McGetchin and R.B.

- Merrill, editors, Plateau uplift, mode and mechanism, Tectonophysics, V.61, p.149-181.
- Ulrich, G.E. and Bailey, N.G., 1987, Geologic map of the SP Mountain part of the San Francisco volcanic field, north-central Arizona, U.S. Geological Survey Map MF-1956.
- Ulrich, G.E. Billingsley, G.H., Hereford, R., Wolfe, E.W., Nealey, L.D. and Sutton, 1984, Map showing geology, structure and uranium deposits of the Flagstaff 10x20 quadrangle, Arizona:U.S. Geological Survey Miscellaneous investigation series, Mapn I-1446 (sheet 1).
- Wadge, G., and Cross, A., 1988, Quantitative methods for detecting aligned points: An application to the volcanic vents of the Michoacan-Guanajuato volcanic field, Mexico, Geology, V.16, p.815-818.
- Walker, J., 1981, Petrogenesis of lavas from cinder cone fields behind the volcanic front of Central America, J. Geol., V.89, p.721-739.
- Wolfe, E.W., G.E. Ulrich, and R.B. Moore, 1983, San Francisco Volcanic Field, Arizona, Volcano News, V.13, p.1-3.
- Wolfe, E.W., G.E. Ulrich, R.F. Holm, R.B. Moore and C.G. Newhall, 1987, Geologic map of the central part of the San Francisco volcanic field, north-central Arizona, U.S. Geological Survey Map MF-1959.
- Wolfe, E.W., G.E. Ulrich, C.G. Newhall, 1987, Geologic map of the northwest part of the San Francisco volcanic field,

north-central Arizona, U.S. Geological Survey Map MF-1957.

Wong, M.A., and T. Lane, 1983, A kth nearest neighbor clustering procedure, J. R. Stat. Soc., Ser. B, V.45, p.362-368.

Zhang, D., and T. Lutz, 1989, Structural controls on igneous complexes and kimberlites: A new statistical method, Tectonophys., V.159, p.137-148.

Zoback, M.L., Zoback, M.D., Abrams, J. Bell, S, Suter, M, Suarez, G. Jacob, K., Estabrook, C. and Magee, 1991, Stress map of North America: Geological Society of America, Decade of North American Geology, Continental Scale map 005, 4 sheets.

Appendix A

Computer Programs

Cluster Analysis Program

```
Option Linesize=66 nocenter;  
Filename vent 'vent.dat';  
Data spring;  
Infile vent;  
Input ventno east north;  
Proc cluster outtree=tree method=twostage r=2000-18000m  
Var east north;  
Run;
```

Two Point Azimuth Program

! PROGRAM: point azimuth
! Language: TrueBasic
! Author: Chuck Connor
! Dept. of geology
! Florida International University
! Miami, FL, 33199
!Date: Feb. 29, 1988
!
!Summary: This program looks for preferred orientations in
!point pattern data. The method used is developed from:
!
! Lutz, T.M., 1986, An Analysis of the orientations of
! Large-scale crustal structures: a statistical
! approach based on the analysis of pointlike features.
! Journal of Geophysical Research, 91:421-434.
!
! In this program, the coordinates of points are input from
! a file. The user then defines the area s/he wishes to
! analysis, inputting vertex coordinates using the mouse. Only
! data points falling within the area selected are used in
! the analysis. Several factors concerning this area are important:
!
! 1) the vertices must be input in a clockwise manner. If
! the vertices are input in a counter-clockwise manner,
! the program will use points only found OUTSIDE the
! polygon in the analysis.
!
! 2) the polygon will be rectilinear and concave inwards.
! This is because of the algorithm uses the orientation
! of line segments to discriminate between points within
! and outside the area selected.
!
! 3) the area selected will close automatically. For
! instance, if you select 5 vertices, 5 line segments
! will be drawn, connecting the vertices. The last line
! segment will be drawn connecting the first and last
! vertices.
!

! Once the area of analysis is selected, the program
! takes a minute to find the points within the area.
!
! Next select the frequency interval of the calculations
! for instance 10 gives 10 degree increments on the rose
! diagrams.
! Suggested loops for the monte carlo simulation are 50 or
! 100. Simulation with smaller runs are also possible.
! The program compares the observed number of line segments
! in each interval with the expected number, based on the \
! simulation results, using a t - test. The results are
! plotted on rose diagrams. The t-test is done with 90, 95,
! and 97.5 percent confidence (one-tailed).
!
! four rose diagrams appear at each level of confidence: the
! obs (observed data distribution), the enorm: the
! normalized distribution, based on the simulation results,
! uci: the upper confidence interval, based on the monte carlo
! results, and a histogram plotting the intervals which contain
! more observations than expected (that is which exceed the
! uci values).
!
! As each histogram appears: click the mouse at the spot
! you want a label for that rose diagram to appear.
!
! You can print the screen at any time by pressing the
! propeller-shift-four keys simultaneously.
!
! The screen can be saved as a MacPaint document at any
! time by pressing the propeller-shift-three keys simultaneously.

```
DIM pts(200,2), moncar(200,2), vert(30,2)
DIM obs(90), azm(90), ehat(90), ehat2(90), enorm(90)
DIM uci1(90), uci05(90), uci025(90)
DIM maxed1(90), maxed05(90), maxed025(90)
```

! mat pts is the matrix which holds point locations located
! within the selected area.
!
! mat moncar is the matrix that holds random points generated
! by the monte carlo subroutine. this matrix is scratched after
! each simulation

```

!
! mat vert holds the coordinated of the vertices selected by the user
while
! the program is running
!
! mat obs holds the frequency per class of line segment
! orientations in the input data set (matrix pts)
!
! mat azm holds the frequency per class of line segment
! orientations in the monte carlo data set (matrix moncar)
!
! mat ehat holds the empirical mean frequency of
! observations per class, based on the monte carlo simulation
!
! mat ehat2 holds the empirical mean frequency of
! observations per class squared, based on the monte carlo
!
! mat uci1,05,025 hold the upper confidence limits (90,95,97.5)
! percent, respectively of expected observations
! per class, based on the monte carlo simulation
!
! mat enorm contains the frequency per class of observed
! line segment orientations, normalized to take the shape
! of the study area into account
!
! mat maxed contain the intervals which exceed the
! confidence limit. (ie: obs - uci, if this is positive)
! these matrices are also for 90,95, 97.5 % confidence
! levels

```

```

PRINT " type the name of the file containing the observed"

```

```

PRINT " data points"

```

```

INPUT file$

```

```

OPEN #1: name file$

```

```

OPEN #10: screen .25,1,.25,1

```

```

OPEN #11: screen 0,1,0,.25

```

```

OPEN #12: screen 0,.24,.75,.8

```

```

OPEN #13: screen 0,.24,.6,.74

```

```

WINDOW #11

```

```

let yymin = 10000000
let xxmin = 10000000
let ymax = -1000000
let xmax = -1000000
DO while more #1
    INPUT #1: x,y
    if x < xxmin then let xxmin = x
    if x > xmax then let xmax = x
    if y < yymin then let yymin = y
    if y > ymax then let ymax = y

LOOP
reset #1:begin
!plot all the points
print "xmin = ";xxmin,"xmax = ";xmax
print "ymin = ";yymin,"ymax = ";ymax
PRINT "type in the dimensions of the area you want to see"
PRINT "xmin, xmax, ymin, ymax"
INPUT s1,s2,s3,s4

!dimension the window to be square
WINDOW #10
LET scrfix=s2-s1
SET window s1-(scrfix*28/128),s2+(scrfix*28/128),s3,s4
DO while more #1
    INPUT #1: x,y
    IF x<=s2 and x=>s1 and y=>s3 and y<=s4 then
        PLOT x,y
    END IF
LOOP

!plot the frame
PLOT s1,s3;s1,s4;s2,s4;s2,s3;s1,s3

RESET #1: begin

WINDOW #11
PRINT " how many vertices will you select"
INPUT numvts

PRINT "click in the vertex coordinates using the mouse"

```



```
MAT vert = zer(numvts, 2)
```

```
! the routine below locates the verticies when the  
! mouse is clicked, and plots the line segments  
! between verticies.
```

```
WINDOW #10
```

```
LET count = 0
```

```
DO
```

```
    LET count = count + 1
```

```
DO
```

```
    GET MOUSE vert(count,1), vert(count,2), state
```

```
    LOOP until state = 2
```

```
    PLOT vert(count,1),vert(count,2);
```

```
LOOP until count = numvts
```

```
PLOT vert(1,1),vert(1,2);
```

```
PLOT
```

```
!this routine now locates those observations within the  
! area selected (enclosed in the polygon just defined  
! by the verticies
```

```
!find the extreme x and y coordinates to speed the search
```

```
LET ymin2 = 1000000
```

```
LET xmin2 = 1000000
```

```
LET xmax2 = -1000000
```

```
LET ymax2 = -1000000
```

```
FOR look = 1 to numvts
```

```
    IF xmax2 < vert(look,1) then LET xmax2 = vert(look,1)
```

```
    IF xmin2 > vert(look,1) then LET xmin2 = vert(look,1)
```

```
    IF ymax2 < vert(look,2) then LET ymax2 = vert(look,2)
```

```
    IF ymin2 > vert(look,2) then LET ymin2 = vert(look,2)
```

```
NEXT look
```

```
! count the number of points in file$
```

```
DO while more #1
```

```
    INPUT #1: xpt, ypt
```

```

!the logical statement eliminates points located outside
! the smallest rectangle that completely encloses the
! polygon (this speeds the search)
IF ypt => ymin2 and ypt <= ymax2 and xpt => xmin2 and xpt <=
xmax2 then

```

```

!this curvt loop finds points inside the polygon by
!rejecting points found outside the polygon
FOR curvt = 1 to numvts

```

```

    IF curvt = numvts then

```

```

        LET x1 = vert(curvt,1)
        LET x2 = vert(1,1)
        LET y1 = vert(curvt,2)
        LET y2 = vert(1,2)

```

```

    ELSE

```

```

        LET x1 = vert(curvt,1)
        LET x2 = vert(curvt + 1,1)
        LET y1 = vert(curvt,2)
        LET y2 = vert(curvt + 1,2)

```

```

    END IF

```

```

    WHEN error in          ! error when x2-x1 = 0
        LET m = (y2-y1)/(x2-x1)    !slope of line bet. vertices
        LET b = y1 - m*x1    !intercept of line

```

```

    LET ytest = m*xpt + b    ! point on line

```

```

        ! don't want points outside line segments: use
        ! the following tests

```

```

        IF x1 > x2 and y1 > y2 and ytest > ypt then EXIT FOR
        IF x1 > x2 and y1 < y2 and ytest > ypt then EXIT FOR
        IF x1 < x2 and y1 > y2 and ytest < ypt then EXIT FOR
        IF x1 < x2 and y1 < y2 and ytest < ypt then EXIT FOR

```

```

    USE

```

```

        !use this test instead if vertical line

```

```
IF y2<y1 and xpt>x1 then EXIT FOR
IF y2>y1 and xpt<x1 then EXIT FOR
```

```
END WHEN
```

```
!if the random point has passed the above tests for
! every line segment, the point lines within
! the selected area
```

```
IF curvt = numvts then
```

```
LET totpts = totpts + 1
LET pts(totpts,1) = xpt
LET pts(totpts,2) = ypt
```

```
END IF
```

```
NEXT curvt
```

```
END IF
LOOP
```

```
!replot the area of interest
CLEAR
LET scrfix=xmax2-xmin2
SET window xmin2-
(scrfix*28/128),xmax2+(scrfix*28/128),ymin2,ymax2
```

```
FOR co = 1 to totpts
  PLOT pts(co,1), pts(co,2)
NEXT co
```

```
LET count = 0
DO
  LET count = count + 1
  PLOT vert(count,1),vert(count,2);
LOOP until count = numvts
PLOT vert(1,1),vert(1,2);
PLOT
```

```
!redimension the point matrices
MAT moncar = zer(totpts,2)
```

!lineseg is the total number of line segments

LET lineseg = totpts*(totpts-1)/2

LET count = 0

CLOSE #1

WINDOW #11

PRINT " what class interval do you want (180/interval = integer)"

INPUT interval

LET classnum = 180/interval + 1

!redimension all the rose diagram matrices

MAT obs = zer(classnum)

MAT azm = zer(classnum)

MAT ehat = zer(classnum)

MAT ehat2 = zer(classnum)

MAT enorm = zer(classnum)

MAT uci1 = zer(classnum)

MAT uci05 = zer(classnum)

MAT uci025 = zer(classnum)

MAT maxed1 = zer(classnum)

MAT maxed05 = zer(classnum)

MAT maxed025 = zer(classnum)

CALL azimuth(pts, totpts, interval, obs)

!now do the monte carlo

PRINT " How many loops do you want in the monte carlo simulation"

PAUSE 1

PRINT "ENTER one of the following numbers and the t-test"

PRINT "will be done automatically: 10,20,30,40,50,100"

PRINT "or enter any number (you'll need to know the T statistic)"

INPUT montesum

!look table for t-statitics, or enter your own
SELECT CASE montesum

CASE 10

LET ttest1 = 1.383
LET ttest05 = 1.833
LET ttest025 = 2.262

CASE 20

LET ttest1 = 1.328
LET ttest05 = 1.729
LET ttest025 = 2.093

CASE 30

LET ttest1 = 1.311
LET ttest05 = 1.699
LET ttest025 = 2.045

CASE 40

LET ttest1 = 1.304
LET ttest05 = 1.685
LET ttest025 = 2.023

CASE 50

LET ttest1 = 1.299
LET ttest05 = 1.676
LET ttest025 = 2.010

CASE 100

LET ttest1 = 1.290
LET ttest05 = 1.660
LET ttest025 = 1.984

CASE else

PRINT "degrees of freedom = ";montesum -1
PRINT "enter t-statistic, alpha = .1";
INPUT ttest1
PRINT "enter t-statistic, alpha = .05";

```

INPUT ttest05
PRINT "enter t-statistic, alpha = .025";
INPUT ttest025

END SELECT
LET count = 0
WINDOW #10
!clear the window
CLEAR
!replot the vertex coordinates
LET count = 0
DO
    LET count = count + 1
    PLOT vert(count,1),vert(count,2);
LOOP until count = numvts
PLOT vert(1,1),vert(1,2);
PLOT

WINDOW #11
PRINT "now plotting simulations";
WINDOW #12
PRINT "simulation:"

LET count = 0

DO
    LET count = count + 1

    WINDOW #13
    SET window -1,1,-1,1
    CLEAR
    LET cout$ = str$(count)
    PLOT TEXT, at 0,.2: cout$

    CALL findrnd(vert, moncar, numvts, totpts)
    MAT azm = zer(classnum)
    WINDOW #10

    !this loop plots the random points for each simulation,
    !and lets you make sure the random points are in the
    ! area selected

```



```

FOR alp = 1 to totpts
  PLOT moncar(alp,1), moncar(alp,2)
NEXT alp

CALL azimuth(moncar, totpts, interval, azm)

!begin cumulating stats for each interval of each simulation
FOR i = 1 to classnum
  LET ehat(i) = ehat(i) + azm(i)
  LET ehat2(i) = ehat2(i) + (azm(i))^2
NEXT i
LET i = 0
LOOP until count = montesum

LET i = 0
LET count = 0

WHEN error in !an error if class is 0
  FOR i = 1 to classnum
    LET chat = (lineseg)/classnum
    LET ehat(i) = ehat(i)/montesum
    LET std = ((ehat2(i)-(ehat(i))^2)/(montesum-1))^.5
    LET enorm(i) = chat/ehat(i) * obs(i)

    !for alpha = .1
    LET uci1(i) = ehat(i) + ttest1*std/(montesum^.5)
    LET unic1 = chat/ehat(i) * uci1(i)
    IF enorm(i) => unic1 then
      LET maxed1(i) = enorm(i) - unic1
    ELSE
      LET maxed1(i) = 0
    END IF

    !for alpha = .05
    LET uci05(i) = ehat(i) + ttest05*std/(montesum^.5)
    LET unic05 = chat/ehat(i) * uci05(i)
    IF enorm(i) => unic05 then
      LET maxed05(i) = enorm(i) - unic05
    ELSE
      LET maxed05(i) = 0

```

END IF

```
!for alpha = .025
  LET uci025(i) = ehat(i) + ttest025*std/(montesum^.5)
  LET unic025 = chat/ehat(i) * uci025(i)
  IF enorm(i) => unic025 then
    LET maxed025(i) = enorm(i) - unic025
  ELSE
    LET maxed025(i) = 0
  END IF
```

NEXT i

USE

```
  LET enorm(i) = 0
END WHEN
```

!signal that the simulation is done

WINDOW #11

DO until signal = 30

SOUND 600, .03

SOUND 1500, .03

LET signal = signal + 1

LOOP

PRINT

PRINT "done with simulation, click mouse to continue"

DO

GET MOUSE xx,yy,state

LOOP until state = 2

CLOSE #10

CLOSE #11

CLOSE #12

CLOSE #13

!now plot the results on rose diagrams

OPEN #20: screen 0,.5,0,.5

OPEN #30: screen 0,.5,.5,1

OPEN #40: screen .5,1,.5,1

OPEN #50: screen .5,1,0,.5

```

FOR loop = 1 to 3                                !there are three
    !screens of results
    WINDOW #20

    CALL rosy(interval,enorm)

DO
    GET MOUSE u,v, state
    LOOP until state = 2
    PLOT TEXT, at u,v: "enorm"

WINDOW #30
    !observed frequencies don't change
    CALL rosy(interval,obs)
DO
    GET MOUSE u,v, state
    LOOP until state = 2
    PLOT TEXT, at u,v: "obs"

WINDOW #40

    IF loop = 1 then
        CALL rosy(interval,maxed1)
    ELSEIF loop = 2 then
        CALL rosy(interval,maxed05)
    ELSE
        CALL rosy(interval,maxed025)
    END IF

DO
    GET MOUSE u,v, state
    LOOP until state = 2

    IF loop = 1 then
        PLOT TEXT, at u,v: "intervals > alpha = .1"
    ELSEIF loop = 2 then
        PLOT TEXT, at u,v: "intervals > alpha = .05"
    ELSE
        PLOT TEXT, at u,v: "intervals > alpha = .025"
    END IF

WINDOW #50

```

```

IF loop = 1 then
  CALL rosy(interval,uci1)
ELSEIF loop = 2 then
  CALL rosy(interval,uci05)
ELSE
  CALL rosy(interval,uci025)
END IF

```

```

DO
  GET MOUSE u,v, state
  LOOP until state = 2
  PLOT TEXT, at u,v: "uci"

  !now loop until you are ready to continue

```

```

DO
  GET MOUSE m,p, state
  LOOP until state = 2
  !after the click, clear all the windows
CLEAR
WINDOW #40
CLEAR
WINDOW #30
CLEAR
WINDOW #20
CLEAR

```

```

NEXT loop
END

```

EXTERNAL

SUB AZIMUTH(pt(.), numpts, interval, azm())

```

!azimuth looks at each line segment, calculates its orientation
! and puts it into a class interval, to be plotted
! on the rose diagram
! pt() is the input matrix containing points
! numpts is the total number of points in pt(), input

```

```

! interval is the degree interval (class frequency), input
! azm() is the returned matrix containing the number of
! observations per class

LET counter = 0

FOR i = 1 to numpts-1
  FOR j = i+1 to numpts
    WHEN error in      !error when line segment in N-S
      LET theta = atn((pt(j,2)-pt(i,2))/(pt(j,1)-
pt(i,1)))*180/3.1416
    USE
      LET theta = 90  !theta is 90 if segment is N-S
    END WHEN

    ! this statement lets results be plotted on
    ! standard structural rose diagram
    IF theta < 0 then LET theta = theta+180

    FOR peg = interval to 180 step interval
      LET keeper = keeper + 1

      !criterion for the classification of orientations
      IF theta < peg then
        LET azm(keeper) = azm(keeper) + 1
      EXIT FOR
    END IF

  NEXT peg

  LET keeper = 0

NEXT j
NEXT i

END SUB

SUB FINDRND(vertr(), moncar(), numvts, rndtot)
  RANDOMIZE
  !this subroutine finds random points within a known
  !area defined by a definite number of vertices

```

```

!vert() is the input matrix of vertex coordinates
!moncar() is the output matrix of random points found
! by the subroutine, which lie within the area defined by
! vert()
! numvts is the number of vertices (input)
!rndtot is the number of random points to be found
! with in the area (input)

LET curvt = 0
LET rndct = 0
  MAT moncar = zer(rndtot, 2)  ! make sure this mtx is empty
LET x1 = 0
LET x2 = 0
LET y1 = 0
LET y2 = 0

  !find the extreme x and y coordinates to speed the search
  LET ymin2 = 1000000
  LET xmin2 = 1000000
  LET xmax2 = -1000000
  LET ymax2 = -1000000

  FOR look = 1 to numvts

    IF xmax2 < vert(look,1) then LET xmax2 = vert(look,1)
    IF xmin2 > vert(look,1) then LET xmin2 = vert(look,1)
    IF ymax2 < vert(look,2) then LET ymax2 = vert(look,2)
    IF ymin2 > vert(look,2) then LET ymin2 = vert(look,2)

  NEXT look

  !now select random points within this range
DO
  LET xrndpt = (xmax2-xmin2)*rnd + xmin2
  LET yrndpt = (ymax2-ymin2)*rnd + ymin2
  !now that we have found likely random points,
  ! check to see if they are in the specified area

  FOR curvt = 1 to numvts

    IF curvt = numvts then

```



```

    LET x1 = vert(curvt,1)
    LET x2 = vert(1,1)
    LET y1 = vert(curvt,2)
    LET y2 = vert(1,2)

ELSE

    LET x1 = vert(curvt,1)
    LET x2 = vert(curvt + 1,1)
    LET y1 = vert(curvt,2)
    LET y2 = vert(curvt + 1,2)

END IF

WHEN ERROR IN      !X2-X1 =0
    LET m = (y2-y1)/(x2-x1)    !slope of line bet. vertices
    LET b = y1 - m*x1        !intercept of line

    LET ytest = m*xrndpt + b    ! point on line

    ! don't want points outside line segments: use
    ! the following tests

    IF x1 > x2 and y1 > y2 and ytest > yrndpt then EXIT FOR
    IF x1 > x2 and y1 < y2 and ytest > yrndpt then EXIT FOR
    IF x1 < x2 and y1 > y2 and ytest < yrndpt then EXIT FOR
    IF x1 < x2 and y1 < y2 and ytest < yrndpt then EXIT FOR

USE
    IF y1<y2 and yrndpt < y2 then EXIT FOR
    IF y1>y2 and yrndpt > y2 then EXIT FOR
END WHEN
    !if the random point has passed the above tests for
    ! every line segment, the point lines within
    ! the selected area

    IF curvt = numvts then

        LET rndct = rndct + 1
        LET moncar(rndct,1) = xrndpt
        LET moncar(rndct,2) = yrndpt

    END IF

```

```

NEXT curvt

LOOP UNTIL rndct = rndtot

END SUB

SUB rosy(interval,total())

!this subroutine plots rose diagrams
!interval: the class interval for the rose diagram (eg: 10
!           means 10 degrees per class
! total: is a one dimensional matrix containing the number
!           of observations per class.
OPTION ANGLE degrees
SET color "black"

!find the maximum value in the intervals
!this value is used to dimension the rose diagram
FOR q = interval to 180 step interval
    LET counter = counter + 1
    IF maxin < total(counter) then LET maxin = total(counter)
NEXT q
IF maxin = 0 then LET maxin = 1

!set the window and correct the aspect ratio
SET window (-maxin-(28/64*maxin)),(maxin+(28/64*maxin)),-
maxin,maxin

!plot the E-W and N-S axes
PLOT 0,0; 0,maxin
PLOT -maxin,0; maxin,0

!decide about the frequency of
! tic marks on your rose diagram
IF maxin < 1 then
    LET lab = .1
ELSEIF maxin < 10 then
    LET lab = 1

```

```

ELSEIF maxin<50 then
  LET lab = 5
ELSEIF maxin< 100 then
  LET lab = 10
ELSEIF maxin <200 then
  LET lab = 20
ELSEIF maxin < 1000 then
  LET lab = 100
ELSE
  LET lab = 500
END IF

FOR tic = 0 to maxin step lab      !make tics on the
  PLOT tic,0;tic, -maxin/10      ! positive axis
NEXT tic
LET maxtic = tic

FOR tic = 0 to -maxin step lab    !make tics on the
  PLOT tic,0;tic, -maxin/50      !negative axis
NEXT tic

FOR tic = 0 to maxtic-1 step lab * 2  !label every other tic
  PLOT TEXT, at tic,-maxin/4: str$(tic)
NEXT tic

LET counter = 0
FOR q = interval to 180 step interval
  LET counter = 1 + counter

  LET r = total(counter)

  LET x1 = r*cos(q)
  LET y1 = r*sin(q)
  LET x2= r*cos(q-interval)
  LET y2 = r*sin(q-interval)

  PLOT 0,0; x1,y1; x2,y2; 0,0
  PLOT

NEXT q
END SUB

```

Hough Transform Analysis Program

```
dim x(155,2), pmtx(155,90)

print "type in file name"
input file$
open #1: name file$

open #10: screen .25,1,.25,1
open #11:screen 0,1,0,.25

window #11
let ymin = 100000000
let ymax = -100000000
let xmin = 100000000
let xmax = -100000000

Do while more #1
input #1: xxx,yyy
if xxx > xmax then let xmax = xxx
if xxx < xmin then let xmin = xxx
if yyy > ymax then let ymax = yyy
if yyy < ymin then let ymin = yyy
loop
close # 1

let s1 = xmin
let s2 = xmax
let s3 = ymin
let s4 = ymax
print s1,s2,s3,s4
window #10
let scrfix = s2-s1

set window s1-(scrfix*28/128),s2+(scrfix*28/128),s3,s4
!set window xmin,xmax,ymin,ymax
let kount = 0
library "pictlib*"
call copy_printer (1)
set color "red"
```

```

open #1: name file$
do while more #1

    let kount = kount + 1
    input #1: x(kount,1),x(kount,2)
    box circle x(kount,1)-200,x(kount,1)+200,x(kount,2)-
200,x(kount,2)+200

    let sumx = sumx + x(kount,1)
    let sumy = sumy + x(kount,2)
loop
close #1
let numpts = kount
let xmean = sumx/numpts
let ymean = sumy/numpts

plot s1,s3;s1,s4;s2,s4;s2,s3;s1,s3

let pmax = 0
for kount = 1 to numpts
    let dist = ((xmean-x(kount,1))^2 + (ymean-x(kount,2))^2)^.5
    if dist > pmax then let pmax = dist
next kount

let pmax = pmax + 500

window #11
print "xmean =";xmean,"ymean=";ymean; "kount=";kount
print "pmax = ";pmax
print "what rank?"
input rank
print "what thet range"
input lowrang,hirang
let lowrang = lowrang*pi/180
let hirang = hirang*pi/180
for kount = 1 to numpts
    let x11 = x(kount,1)-xmean
    let y11 = x(kount,2)-ymean
    let ele2 = 0
    for theta = 0 to pi step pi/90
        let ele2 = ele2 + 1
        let p = x11*cos(theta) + y11*sin(theta)

```

```

!****set delp****
  let delp = 400
  let ele1 = 0
  for k2 = -pmax to pmax step delp
    let ele1 = ele1+1

    if p>k2 and p<= k2+delp then
      let pmtx(ele1,ele2) = pmtx(ele1,ele2) + 1

    end if
  next k2
next theta
next kount
window #10
do
for xdir = 1 to 100
  for ydir = 1 to 90

    if pmtx(xdir,ydir) => rank then
      let thet = ydir*pi/90
      if thet=>lowrang and thet <= hirang then
        let p = xdir*delp - pmax
        let x1 = p*cos(thet) + xmean
        let y1 = p*sin(thet) + ymean

        let s11 = x1-xmean
        let s22 = y1-ymean
        if s11 = 0 then
          plot x1,s3;x1,s4
          print slop*180/pi
          print file$

        end if

        if s22 = 0 then
          plot s1,y1;s2,y1
          print slop*180/pi
          print file$
        end if

        if s22<>0 and s11<>0 then
          let slop = -s11/s22

```



```

    let y22 = slop*(s1-x1)+y1
    let y33 = slop*(s2-x1)+y1
    plot s1,y22;s2,y33
    print slop*180/pi
    print file$
!find the slope intercept, b1
let b1 = slop*s1 + y22
open #1: name file$
    open #2: name "outdum", create newold

reset #2:end
print #2: "slope (from East) = ", slop*180/pi
do while more #1
input #1: x2,y2
let b2 = -1/slop * x2 - y2
    let xint = (b2-b1)/(slop + 1/slop)
let yint = slop *xint + b1
let dist = ((x2-xint)^2 + (y2-yint)^2)^.5

    if dist <= delp/2 then
        let ct = ct + 1
        print #2: ct, x2,y2
    end if
loop
close #1
close #2
let ct = 0
end if
end if
end if
next ydir
next xdir
call copy_done
window #11

print "new rank?"
input rank
window #10
loop

end

```

Appendix B

Geophysical Survey Data

Reduction Formula of Bouguer Anomaly

The formula from Hendricks (1975) used for the reduction to the Complete Bouguer anomaly is:

$$CBG = G_{obs} + FAC + BC + ECC + TC - G_{theor}$$

The terms being:

CBG Complete Bouguer anomaly

G_{obs} Observed gravity (after drift correction)

FAC Free air correction = $h(0.30877 - 0.0013398\sigma + 0.0013553\sigma^2 - 0.0005329\sigma^3 + 0.0000911\sigma^4) - h^2(0.072 \times 10^{-6})$

BC Bouguer correction = $-0.1119h$

ECC Earth curvature correction = $-1.4639108 \times 10^{-3}h + 3.532715 \times 10^{-7}h^2 - 4.449648 \times 10^{-14}h^3$

TC Terrain correction (neglected in this study)

G_{theor} Theoretical Gravity = $978031.843 + 15727.66\sigma - 15762.337\sigma^2 + 6083.534\sigma^3 - 1089.748\sigma^4 + 69.43\sigma^5$

where: h = elevation (in meters)

$$\sigma = 0.0001\varphi^2$$

φ = latitude in degrees

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #1000		N120° from	base #26
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #26	0	1605.236	35.6551	0.1271286	2852.8285
1050	50	1603.846	35.654875	0.127127	2853.1055
1100	100	1602.866	35.65465	0.1271254	2853.1902
1150	150	1602.996	35.654424	0.1271238	2853.0762
1200	200	1601.336	35.654199	0.1271222	2853.2857
1225	225	1602.036	35.654087	0.1271214	2853.2647
1250	250	1605.436	35.653974	0.1271206	2852.7525
1275	275	1608.266	35.653861	0.1271198	2852.4629
1300	300	1612.936	35.653749	0.127119	2851.7985
1315	315	1614.586	35.653681	0.1271185	2850.8115
1330	330	1616.586	35.653614	0.127118	2850.345
1340	340	1617.806	35.653569	0.1271177	2850.5494
1350	350	1619.016	35.653523	0.1271174	2850.3508
1360	360	1620.296	35.653478	0.1271171	2849.8177
1370	370	1620.526	35.653433	0.1271167	2849.8016
1380	380	1621.171	35.653388	0.1271164	2849.6069
1390	390	1621.396	35.653343	0.1271161	2849.2117
1400	400	1621.326	35.653298	0.1271158	2849.3927
1410	410	1621.246	35.653253	0.1271155	2848.8115
1420	420	1621.596	35.653208	0.1271151	2849.1301
1430	430	1622.056	35.653163	0.1271148	2849.3698
1440	440	1622.686	35.653118	0.1271145	2848.914
1450	450	1623.641	35.653073	0.1271142	2848.954

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
495.22322	-179.6259	-1.439803	979788.75	-976621.8	-183.2637
494.79456	-179.4704	-1.439343	979788.73	-976621.7	-183.2401
494.49234	-179.3607	-1.439018	979788.71	-976621.8	-183.3283
494.53243	-179.3753	-1.439061	979788.69	-976621.9	-183.3975
494.02051	-179.1895	-1.43851	979788.67	-976622	-183.4944
494.23638	-179.2678	-1.438743	979788.66	-976621.9	-183.3684
495.28491	-179.6483	-1.439869	979788.65	-976621.7	-183.204
496.15765	-179.965	-1.440799	979788.64	-976621.4	-182.9288
497.59783	-180.4875	-1.442323	979788.63	-976621.2	-182.6676
498.10667	-180.6722	-1.442858	979788.63	-976621.8	-183.325
498.72345	-180.896	-1.443504	979788.62	-976621.9	-183.3935
499.09968	-181.0325	-1.443896	979788.62	-976621.5	-182.9459
499.47283	-181.1679	-1.444284	979788.62	-976621.4	-182.9033
499.86756	-181.3111	-1.444694	979788.61	-976621.7	-183.1814
499.93849	-181.3369	-1.444767	979788.61	-976621.7	-183.1485
500.1374	-181.409	-1.444973	979788.6	-976621.7	-183.2128
500.20679	-181.4342	-1.445045	979788.6	-976622.1	-183.5601
500.18521	-181.4264	-1.445022	979788.6	-976621.9	-183.3889
500.16054	-181.4174	-1.444997	979788.59	-976622.5	-183.982
500.26847	-181.4566	-1.445108	979788.59	-976622.1	-183.5908
500.41033	-181.5081	-1.445255	979788.58	-976621.8	-183.257
500.60461	-181.5786	-1.445455	979788.58	-976622.1	-183.5854
500.89912	-181.6854	-1.445758	979788.58	-976621.9	-183.3542

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #2000		N120° from	base #22
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #26		1605.236			2852.4246
base #22	0	1600.441	35.6564	0.1271379	2853.3168
2050	50	1599.531	35.656175	0.1271363	2853.8296
2100	100	1599.046	35.65595	0.1271347	2853.3533
2150	150	1599.436	35.655724	0.1271331	2853.4807
2175	175	1602.086	35.655612	0.1271323	2852.7638
2200	200	1611.216	35.655499	0.1271315	2850.353
2225	225	1615.016	35.655387	0.1271307	2850.4327
2240	240	1616.096	35.655319	0.1271302	2849.7421
2255	255	1617.336	35.655251	0.1271297	2849.8914
2265	265	1617.966	35.655206	0.1271294	2849.7418
2275	275	1618.621	35.655161	0.1271291	2849.5698
2285	285	1619.166	35.655116	0.1271287	2849.6189
2295	295	1619.943	35.655071	0.1271284	2849.8479
2300	300	1620.448	35.655049	0.1271283	2849.5342
2305	305	1620.733	35.655026	0.1271281	2849.1226
2310	310	1620.941	35.655004	0.1271279	2849.5188
2315	315	1621.009	35.654981	0.1271278	2849.6836
2320	320	1621.143	35.654959	0.1271276	2849.0385
2325	325	1621.128	35.654936	0.1271275	2849.5937
2335	335	1620.97	35.654891	0.1271271	2849.4027
2345	345	1620.873	35.654846	0.1271268	2849.5586
2355	355	1620.738	35.654801	0.1271265	2849.6272
2365	365	1620.61	35.654756	0.1271262	2849.4909
2375	375	1620.451	35.654711	0.1271258	2849.6426
2385	385	1620.158	35.654666	0.1271255	2849.3969
2400	400	1619.808	35.654598	0.127125	2850.1413
2420	420	1619.164	35.654508	0.1271244	2849.9687
2435	435	1618.446	35.654441	0.1271239	2850.3079

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
495.46319	-179.6259	-1.439803	978031.84	-974865	1573.4791
493.74447	-179.0894	-1.438212	979788.86	-976622.3	-183.8273
493.46384	-178.9875	-1.437908	979788.84	-976622	-183.4737
493.31428	-178.9333	-1.437746	979788.82	-976622.5	-184.0259
493.43455	-178.9769	-1.437876	979788.8	-976622.3	-183.8027
494.25179	-179.2734	-1.438759	979788.79	-976622.5	-183.9901
497.06738	-180.2951	-1.441764	979788.78	-976623.1	-184.6003
498.23926	-180.7203	-1.442997	979788.77	-976622.3	-183.7656
498.57232	-180.8411	-1.443346	979788.77	-976622.7	-184.2385
498.95472	-180.9799	-1.443745	979788.76	-976622.3	-183.8402
499.149	-181.0504	-1.443947	979788.76	-976622.4	-183.8623
499.351	-181.1237	-1.444158	979788.76	-976622.4	-183.902
499.51907	-181.1847	-1.444332	979788.75	-976622.2	-183.7421
499.75869	-181.2716	-1.444581	979788.75	-976621.9	-183.3568
499.91442	-181.3281	-1.444742	979788.75	-976622.1	-183.5696
500.00231	-181.36	-1.444833	979788.74	-976622.4	-183.9233
500.06646	-181.3833	-1.444899	979788.74	-976622	-183.4844
500.08743	-181.3909	-1.444921	979788.74	-976621.8	-183.3043
500.12875	-181.4059	-1.444964	979788.74	-976622.4	-183.9212
500.12413	-181.4042	-1.444959	979788.74	-976621.9	-183.367
500.0754	-181.3865	-1.444909	979788.73	-976622.1	-183.5852
500.04549	-181.3757	-1.444878	979788.73	-976621.9	-183.4444
500.00386	-181.3606	-1.444835	979788.72	-976621.9	-183.3985
499.96438	-181.3463	-1.444794	979788.72	-976622.1	-183.556
499.91535	-181.3285	-1.444743	979788.72	-976621.9	-183.4316
499.82499	-181.2957	-1.444649	979788.71	-976622.2	-183.7309
499.71706	-181.2565	-1.444538	979788.71	-976621.6	-183.0494
499.51846	-181.1845	-1.444332	979788.7	-976621.8	-183.3407
499.29704	-181.1041	-1.444101	979788.69	-976621.6	-183.1365

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE#3000		N105° from	base #2
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #2	0	1597.346	35.6589	0.1271557	2853.4078
3050	50	1596.296	35.658783	0.1271549	2854.3218
3100	100	1595.336	35.658667	0.1271541	2854.1825
3150	150	1594.379	35.65855	0.1271532	2854.2809
3200	200	1594.886	35.658434	0.1271524	2854.1544
3225	225	1595.941	35.658375	0.127152	2853.8278
3250	250	1597.991	35.658317	0.1271516	2853.5024
3275	275	1599.526	35.658259	0.1271511	2852.9785
3280	280	1600.201	35.658247	0.1271511	2852.4594
3285	285	1600.756	35.658236	0.127151	2852.5577
3290	290	1601.291	35.658224	0.1271509	2852.4491
3295	295	1602.261	35.658212	0.1271508	2852.3915
3310	310	1603.211	35.658177	0.1271506	2852.0439
3330	330	1603.011	35.658131	0.1271502	2852.2135
3345	345	1602.321	35.658096	0.12715	2852.5247
3370	370	1601.056	35.658037	0.1271496	2852.4974
3420	420	1599.372	35.657921	0.1271487	2853.2136
3470	470	1595.869	35.657804	0.1271479	2853.8319
3520	520	1593.881	35.657688	0.1271471	2854.3933
3570	570	1592.391	35.657571	0.1271462	2854.5862

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
492.78998	-178.743	-1.437176	979789.08	-976623.1	-184.5575
492.46617	-178.6255	-1.436823	979789.07	-976622.3	-183.8395
492.17012	-178.5181	-1.4365	979789.06	-976622.7	-184.157
491.87499	-178.411	-1.436177	979789.05	-976622.7	-184.2364
492.03134	-178.4677	-1.436348	979789.04	-976622.8	-184.2534
492.3567	-178.5858	-1.436704	979789.03	-976622.9	-184.3681
492.9889	-178.8152	-1.437393	979789.03	-976622.8	-184.2864
493.46228	-178.987	-1.437906	979789.02	-976623	-184.5043
493.67044	-179.0625	-1.438132	979789.02	-976623.4	-184.89
493.8416	-179.1246	-1.438317	979789.02	-976623.2	-184.6817
494.00659	-179.1845	-1.438495	979789.02	-976623.2	-184.6844
494.30572	-179.293	-1.438817	979789.02	-976623.1	-184.5508
494.59869	-179.3993	-1.439133	979789.01	-976623.2	-184.709
494.53702	-179.3769	-1.439066	979789.01	-976623.1	-184.5747
494.32423	-179.2997	-1.438837	979789.01	-976622.9	-184.3958
493.93412	-179.1582	-1.438417	979789	-976623.2	-184.6662
493.41479	-178.9697	-1.437855	979788.99	-976622.8	-184.2704
492.3345	-178.5777	-1.43668	979788.98	-976622.8	-184.3293
491.72142	-178.3553	-1.436009	979788.97	-976622.7	-184.1479
491.26192	-178.1886	-1.435504	979788.96	-976622.7	-184.2372

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #4000		N90° FROM	base #1
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	Gobs(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #1	0	1598.676	35.6589	0.1271557	2853.6862
4050	50	1598.101	35.6589	0.1271557	2853.9646
4100	100	1596.891	35.6589	0.1271557	2854.1992
4150	150	1595.636	35.6589	0.1271557	2854.6482
4200	200	1594.426	35.6589	0.1271557	2854.7002
4225	225	1593.821	35.6589	0.1271557	2854.7789
4250	250	1594.251	35.6589	0.1271557	2854.5474
4270	270	1594.081	35.6589	0.1271557	2854.7534
4295	295	1594.291	35.6589	0.1271557	2854.637
4310	310	1594.841	35.6589	0.1271557	2854.5563
4325	325	1594.806	35.6589	0.1271557	2854.5909
4340	340	1594.601	35.6589	0.1271557	2854.6193
4355	355	1594.481	35.6589	0.1271557	2854.7375
4370	370	1594.321	35.6589	0.1271557	2854.8607
4385	385	1594.026	35.6589	0.1271557	2854.9861
4400	400	1593.751	35.6589	0.1271557	2854.7648
4415	415	1593.511	35.6589	0.1271557	2855.0933
4440	440	1593.536	35.6589	0.1271557	2855.2077
4465	465	1593.806	35.6589	0.1271557	2855.3527
4515	515	1594.151	35.6589	0.1271557	2854.904
4565	565	1592.966	35.6589	0.1271557	2855.0133
4615	615	1591.801	35.6589	0.1271557	2855.3355
4665	665	1590.846	35.6589	0.1271557	2855.4387

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
493.20014	-178.8918	-1.437622	979789.08	-976622.5	-184.0182
493.02281	-178.8275	-1.437429	979789.08	-976622.4	-183.8526
492.64966	-178.6921	-1.437023	979789.08	-976622.4	-183.8554
492.26263	-178.5517	-1.436601	979789.08	-976622.2	-183.6525
491.88948	-178.4163	-1.436193	979789.08	-976622.3	-183.8378
491.7029	-178.3486	-1.435989	979789.08	-976622.4	-183.8778
491.83551	-178.3967	-1.436134	979789.08	-976622.5	-184.0249
491.78308	-178.3777	-1.436077	979789.08	-976622.4	-183.8523
491.84784	-178.4012	-1.436147	979789.08	-976622.4	-183.9275
492.01746	-178.4627	-1.436333	979789.08	-976622.4	-183.9004
492.00667	-178.4588	-1.436321	979789.08	-976622.4	-183.8725
491.94345	-178.4359	-1.436252	979789.08	-976622.4	-183.8844
491.90644	-178.4224	-1.436212	979789.08	-976622.3	-183.7898
491.8571	-178.4045	-1.436158	979789.08	-976622.2	-183.6979
491.76612	-178.3715	-1.436058	979789.08	-976622.1	-183.6304
491.68131	-178.3407	-1.435965	979789.08	-976622.4	-183.9056
491.6073	-178.3139	-1.435884	979789.08	-976622.1	-183.6242
491.61501	-178.3167	-1.435892	979789.08	-976622	-183.5049
491.69827	-178.3469	-1.435984	979789.08	-976621.8	-183.307
491.80467	-178.3855	-1.4361	979789.08	-976622.2	-183.6879
491.43923	-178.2529	-1.435699	979789.08	-976622.3	-183.8111
491.07995	-178.1225	-1.435304	979789.08	-976622.2	-183.7174
490.78544	-178.0157	-1.43498	979789.08	-976622.3	-183.8016

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #5000		N124° from	base #1
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #1	0	1598.676	35.6589	0.1271557	2854.241
5050	50	1597.067	35.658648	0.1271539	2854.4967
5100	100	1595.082	35.658396	0.1271521	2854.8165
5150	150	1595.785	35.658144	0.1271503	2854.6253
5175	175	1595.202	35.658018	0.1271494	2854.8197
5200	200	1596.072	35.657892	0.1271485	2854.4888
5225	225	1598.584	35.657767	0.1271476	2853.8795
5250	250	1602.478	35.657641	0.1271467	2852.9805
5270	270	1609.373	35.65754	0.127146	2851.6722
5290	290	1614.408	35.657439	0.1271453	2850.5739
5305	305	1615.681	35.657364	0.1271448	2850.2874
5320	320	1617.458	35.657288	0.1271442	2849.9149
5327.5	327.5	1618.368	35.65725	0.127144	2849.5002
5335	335	1619.013	35.657212	0.1271437	2849.5153
5350	350	1618.906	35.657137	0.1271431	2849.703
5365	365	1618.793	35.657061	0.1271426	2850.0151
5380	380	1618.828	35.656986	0.1271421	2849.6302
5395	395	1618.496	35.65691	0.1271415	2849.8102
5420	420	1617.867	35.656784	0.1271406	2850.1486
5445	445	1616.893	35.656658	0.1271397	2850.3636
5470	470	1615.268	35.656532	0.1271388	2850.4621
5495	495	1607.857	35.656406	0.1271379	2852.126
5520	520	1599.445	35.65628	0.127137	2853.6464
5570	570	1597.615	35.656029	0.1271352	2854.0225
5620	620	1596.683	35.655777	0.1271334	2854.0822

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
493.20014	-178.8918	-1.437622	979789.08	-976622	-183.4634
492.70394	-178.7118	-1.437083	979789.05	-976622	-183.5017
492.09179	-178.4897	-1.436414	979789.03	-976622.1	-183.5497
492.30859	-178.5683	-1.436651	979789.01	-976622.1	-183.5814
492.1288	-178.5031	-1.436455	979789	-976622	-183.4906
492.3971	-178.6005	-1.436748	979788.99	-976622.1	-183.6401
493.17178	-178.8816	-1.437591	979788.98	-976622.3	-183.7459
494.37265	-179.3173	-1.438889	979788.97	-976622.4	-183.8702
496.499	-180.0888	-1.441162	979788.96	-976622.3	-183.8174
498.05173	-180.6523	-1.4428	979788.95	-976622.4	-183.9194
498.44431	-180.7947	-1.443212	979788.94	-976622.5	-183.9497
498.99232	-180.9936	-1.443784	979788.94	-976622.5	-183.9671
499.27295	-181.0954	-1.444076	979788.93	-976622.7	-184.2001
499.47186	-181.1676	-1.444283	979788.93	-976622.6	-184.0553
499.43886	-181.1556	-1.444249	979788.92	-976622.4	-183.8821
499.40402	-181.1429	-1.444213	979788.92	-976622.1	-183.5856
499.41481	-181.1469	-1.444224	979788.91	-976622.5	-183.9572
499.31243	-181.1097	-1.444117	979788.91	-976622.3	-183.8358
499.11845	-181.0393	-1.443916	979788.89	-976622.1	-183.61
498.81809	-180.9303	-1.443602	979788.88	-976622.1	-183.5753
498.31696	-180.7485	-1.443078	979788.87	-976622.3	-183.7849
496.03149	-179.9192	-1.440665	979788.86	-976622.1	-183.5639
493.43732	-178.9779	-1.437879	979788.85	-976622.2	-183.6828
492.87297	-178.7731	-1.437266	979788.83	-976622.1	-183.6441
492.58555	-178.6688	-1.436954	979788.81	-976622.3	-183.7456

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #6000		N105° from	#6100
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
#6100		1644.572			
6000	0	1641.7	35.6478	0.1270766	2844.4046
6050	50	1643.018	35.647683	0.1270757	2843.9764
6100	100	1644.572	35.647567	0.1270749	2843.6875
6125	125	1642.248	35.647509	0.1270745	2843.9249
6175	175	1633.018	35.647392	0.1270737	2846.1704
6225	225	1625.892	35.647275	0.1270728	2847.4663
6245	245	1625.182	35.647229	0.1270725	2847.2978
6265	265	1624.452	35.647182	0.1270722	2847.3571
6285	286	1623.762	35.647133	0.1270718	2846.9768
6305	305	1623.321	35.647089	0.1270715	2847.1365
6325	325	1622.949	35.647042	0.1270712	2847.2845
6345	345	1622.522	35.646996	0.1270708	2847.3835
6365	365	1621.969	35.646949	0.1270705	2847.4868
6385	385	1621.622	35.646902	0.1270702	2847.7561
6405	405	1621.812	35.646856	0.1270698	2848.4442
6425	425	1623.022	35.646809	0.1270695	2847.7508
6475	475	1626.087	35.646692	0.1270687	2847.7246
6525	525	1626.234	35.646576	0.1270678	2847.8666
6575	575	1622.078	35.646459	0.127067	2848.5606
6625	625	1620.103	35.646343	0.1270662	2848.9183

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
506.46832	-183.7062	-1.451369	979788.13	-976622.4	-183.9094
506.87477	-183.8537	-1.45177	979788.12	-976622.6	-184.0691
507.354	-184.0276	-1.452241	979788.11	-976622.5	-184.0431
506.63732	-183.7676	-1.451536	979788.1	-976622.8	-184.2566
503.79093	-182.7347	-1.448701	979788.09	-976622.3	-183.8119
501.59337	-181.9373	-1.44647	979788.08	-976622.4	-183.9039
501.37442	-181.8579	-1.446246	979788.08	-976622.7	-184.2077
501.1493	-181.7762	-1.446015	979788.07	-976622.8	-184.2877
500.93651	-181.699	-1.445797	979788.07	-976623.3	-184.7991
500.80051	-181.6496	-1.445657	979788.06	-976623.2	-184.7221
500.68579	-181.608	-1.445539	979788.06	-976623.1	-184.6431
500.55411	-181.5602	-1.445403	979788.06	-976623.1	-184.6239
500.38357	-181.4983	-1.445227	979788.05	-976623.1	-184.6251
500.27656	-181.4595	-1.445117	979788.05	-976622.9	-184.4199
500.33516	-181.4808	-1.445177	979788.04	-976622.2	-183.6904
500.70831	-181.6162	-1.445562	979788.04	-976622.6	-184.1425
501.65351	-181.9591	-1.446532	979788.03	-976622.1	-183.5574
501.69885	-181.9756	-1.446578	979788.02	-976621.9	-183.3766
500.41719	-181.5105	-1.445262	979788.01	-976622	-183.488
499.80813	-181.2895	-1.444632	979788	-976622	-183.5077

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #7000		N120° from	base #19
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
7000	0	1600.416	35.6581	0.12715	2854.2818
7050	50	1599.796	35.657875	0.1271484	2854.2005
b#19 7100	100	1599.076	35.65765	0.1271468	2854.3596
7150	150	1598.276	35.657424	0.1271452	2854.2632
7200	200	1597.714	35.657199	0.1271436	2854.3492
7252	252	1596.621	35.656965	0.1271419	2854.8105
7270	270	1599.576	35.656884	0.1271413	2854.4188
7295	295	1607.439	35.656771	0.1271405	2853.0258
7320	320	1617.776	35.656659	0.1271397	2850.8144
7345	345	1646.406	35.656546	0.1271389	2845.07
7375	375	1659.651	35.656411	0.127138	2841.5309
7400	400	1653.026	35.656298	0.1271372	2843.9821
7418	418	1648.876	35.656217	0.1271366	2844.8397
7443	443	1633.666	35.656105	0.1271358	2847.9665
7468	468	1629.426	35.655992	0.127135	2849.8037
7500	500	1627.646	35.655848	0.127134	2849.9026
7550	550	1624.878	35.655623	0.1271323	2850.6096
7600	600	1609.823	35.655397	0.1271307	2854.0905
7650	650	1609.353	35.655172	0.1271291	2854.252
7700	700	1611.778	35.654947	0.1271275	2853.4395
7750	750	1612.196	35.654722	0.1271259	2853.3798
7800	800	1612.091	35.654496	0.1271243	2853.5054

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
493.73675	-179.0866	-1.438203	979789.01	-976621.5	-183.0128
493.54555	-179.0172	-1.437996	979788.99	-976621.7	-183.1964
493.32351	-178.9366	-1.437756	979788.97	-976621.7	-183.1592
493.0768	-178.8471	-1.437488	979788.95	-976621.9	-183.3932
492.90349	-178.7842	-1.4373	979788.93	-976621.9	-183.3982
492.56642	-178.6619	-1.436933	979788.91	-976621.6	-183.1312
493.47771	-178.9926	-1.437923	979788.9	-976621.4	-182.9364
495.90258	-179.8724	-1.440528	979788.89	-976621.3	-182.7773
499.09039	-181.0291	-1.443886	979788.88	-976621.5	-182.9514
507.91947	-184.2328	-1.452794	979788.87	-976621.6	-183.0696
512.004	-185.715	-1.456719	979788.86	-976622.5	-183.9987
509.96097	-184.9736	-1.454771	979788.85	-976621.3	-182.8376
508.68118	-184.5092	-1.453535	979788.85	-976621.3	-182.7872
503.99066	-182.8072	-1.448902	979788.84	-976621.1	-182.6347
502.6831	-182.3328	-1.447581	979788.83	-976620.1	-181.6196
502.13418	-182.1336	-1.447022	979788.81	-976620.4	-181.8576
501.28057	-181.8239	-1.44615	979788.79	-976620.2	-181.6742
496.6378	-180.1392	-1.441309	979788.78	-976619.6	-181.1274
496.49286	-180.0866	-1.441156	979788.76	-976619.5	-181.0388
497.2407	-180.358	-1.441947	979788.74	-976619.9	-181.3563
497.36961	-180.4047	-1.442083	979788.72	-976619.8	-181.3147
497.33723	-180.393	-1.442049	979788.7	-976619.7	-181.1905

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #8000		N105° from	#8187
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
#6100		1644.572			
#6000	-187	1641.7	35.6478	0.1270766	2845.3694
8050	-137	1641.78	35.64803	0.1270782	2845.0252
8100	-87	1642.515	35.64825	0.1270798	2844.7234
8150	-37	1642.702	35.64845	0.1270812	2844.4929
8187	0	1642.412	35.6486	0.1270823	2844.5328
8237	50	1636.234	35.648483	0.1270814	2845.8933
8290	103	1627.487	35.64836	0.1270806	2847.5312
8340	153	1624.99	35.648243	0.1270797	2847.7321
8365	178	1624.497	35.648185	0.1270793	2847.7882
8390	203	1623.624	35.648127	0.1270789	2848.0045
8410	223	1623.227	35.64808	0.1270786	2848.1264
8430	243	1623.436	35.648033	0.1270782	2848.4049
8450	263	1623.86	35.647987	0.1270779	2848.4294
8470	283	1623.183	35.64794	0.1270776	2847.9164
8490	303	1621.152	35.647894	0.1270772	2849.5472
8510	323	1619.136	35.647847	0.1270769	2849.97
8530	343	1618.682	35.6478	0.1270766	2850.2321
8550	363	1618.483	35.647754	0.1270762	2850.1072
8570	383	1617.989	35.647707	0.1270759	2850.3245
8620	433	1617.538	35.64759	0.1270751	2850.4306
8670	483	1616.329	35.647474	0.1270742	2850.6897
8720	533	1615.14	35.647357	0.1270734	2850.782
8770	583	1613.62	35.647241	0.1270726	2851.2486

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
506.46832	-183.7062	-1.451369	979788.13	-976621.4	-182.9446
506.49299	-183.7152	-1.451394	979788.14	-976621.8	-183.2928
506.71965	-183.7974	-1.451617	979788.16	-976622	-183.4693
506.77731	-183.8184	-1.451674	979788.18	-976622.2	-183.6802
506.68788	-183.7859	-1.451586	979788.19	-976622.2	-183.7101
504.78268	-183.0946	-1.449695	979788.18	-976622.1	-183.5516
502.08523	-182.1158	-1.446973	979788.17	-976622.1	-183.619
501.31519	-181.8364	-1.446185	979788.16	-976622.4	-183.8979
501.16316	-181.7812	-1.446029	979788.16	-976622.4	-183.9335
500.89394	-181.6835	-1.445753	979788.15	-976622.4	-183.8835
500.77151	-181.6391	-1.445627	979788.15	-976622.3	-183.8355
500.83596	-181.6625	-1.445693	979788.15	-976622	-183.5121
500.96672	-181.7099	-1.445828	979788.14	-976621.9	-183.4004
500.75794	-181.6342	-1.445613	979788.14	-976622.5	-184.0421
500.13161	-181.4069	-1.444967	979788.13	-976621.3	-182.8058
499.5099	-181.1813	-1.444323	979788.13	-976621.3	-182.7745
499.36989	-181.1305	-1.444177	979788.13	-976621.1	-182.5974
499.30853	-181.1083	-1.444113	979788.12	-976621.3	-182.7574
499.15618	-181.053	-1.443955	979788.12	-976621.1	-182.633
499.0171	-181.0025	-1.44381	979788.11	-976621.1	-182.6054
498.64426	-180.8672	-1.443421	979788.1	-976621.1	-182.5735
498.27759	-180.7342	-1.443037	979788.09	-976621.2	-182.7044
497.80884	-180.5641	-1.442545	979788.08	-976621	-182.526

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE #9000		N120° from	base #27
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #26		1605.236			
base #27	0	1607.306	35.6544	0.1271236	2853.2476
9050	50	1605.186	35.654175	0.127122	2853.3016
9100	100	1604.681	35.65395	0.1271204	2853.5682
9150	150	1603.994	35.653724	0.1271188	2854.0964
9178	178	1602.062	35.653598	0.1271179	2854.2906
9200	200	1604.151	35.653499	0.1271172	2854.0911
9225	225	1606.26	35.653387	0.1271164	2854.2573
9250	250	1607.998	35.653274	0.1271156	2853.7193
9275	275	1609.16	35.653161	0.1271148	2853.3128
9300	300	1611.232	35.653049	0.127114	2852.8481
9320	320	1614.019	35.652959	0.1271134	2852.5166
9340	340	1616.173	35.652869	0.1271127	2852.1825
9360	360	1618.823	35.652778	0.1271121	2851.3023
9380	380	1622.261	35.652688	0.1271114	2850.8056
9400	400	1625.21	35.652598	0.1271108	2850.3981
9420	420	1626.988	35.652508	0.1271101	2849.7346
9440	440	1629.443	35.652418	0.1271095	2849.3113
9460	460	1632.263	35.652328	0.1271089	2848.6616

FREE AIR	BOUGUER	Earth curve	Gtheor	CBG(mgals)	Normalized
					976438.5
495.86159	-179.8575	-1.440484	979788.69	-976620.9	-182.3786
495.20781	-179.6203	-1.439786	979788.67	-976621.2	-182.7212
495.05208	-179.5638	-1.439619	979788.65	-976621	-182.5344
494.84021	-179.4869	-1.439392	979788.63	-976620.6	-182.1216
494.24441	-179.2707	-1.438751	979788.62	-976620.8	-182.2956
494.88863	-179.5045	-1.439444	979788.61	-976620.6	-182.0768
495.53903	-179.7405	-1.44014	979788.6	-976620	-181.4873
496.07501	-179.935	-1.440712	979788.59	-976620.2	-181.6748
496.43336	-180.065	-1.441092	979788.58	-976620.3	-181.8437
497.07234	-180.2969	-1.441769	979788.57	-976620.4	-181.8922
497.93182	-180.6087	-1.442674	979788.57	-976620.2	-181.6693
498.59609	-180.8498	-1.44337	979788.56	-976620.1	-181.5731
499.41332	-181.1463	-1.444222	979788.55	-976620.4	-181.9258
500.47355	-181.531	-1.44532	979788.54	-976620.2	-181.7404
501.38299	-181.861	-1.446255	979788.54	-976620.1	-181.5617
501.9313	-182.06	-1.446816	979788.53	-976620.4	-181.8686
502.68839	-182.3347	-1.447586	979788.52	-976620.3	-181.8026
503.55804	-182.6502	-1.448466	979788.51	-976620.4	-181.8914

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE#10000		N90° from	#10000
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	Gobs(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
10000	0	1597.649	35.6598	0.1271621	2854.5989
10090	90	1595.437	35.6598	0.1271621	2855.1119
10140	140	1594.344	35.6598	0.1271621	2855.3609
10190	190	1592.384	35.6598	0.1271621	2855.5885
10240	240	1592.349	35.6598	0.1271621	2855.5682
10270	270	1592.479	35.6598	0.1271621	2855.7244
10290	290	1592.429	35.6598	0.1271621	2855.5899
10310	310	1592.394	35.6598	0.1271621	2855.5802
10330	330	1592.019	35.6598	0.1271621	2855.8693
10350	350	1591.999	35.6598	0.1271621	2855.7637
10370	370	1591.789	35.6598	0.1271621	2855.6887
10390	390	1591.719	35.6598	0.1271621	2855.8013
10415	415	1591.514	35.6598	0.1271621	2855.8521
10440	440	1591.336	35.6598	0.1271621	2855.8018
10465	465	1591.224	35.6598	0.1271621	2855.8781
10490	490	1591.484	35.6598	0.1271621	2855.7857
10540	540	1592.634	35.6598	0.1271621	2855.7763
10590	590	1592.579	35.6598	0.1271621	2855.8713
10640	640	1591.733	35.6598	0.1271621	2856.0533
10690	690	1591.444	35.6598	0.1271621	2855.9752

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
492.88341	-178.7769	-1.437278	979789.15	-976621.9	-183.384
492.20125	-178.5294	-1.436534	979789.15	-976621.8	-183.3049
491.86418	-178.4071	-1.436165	979789.15	-976621.8	-183.2703
491.25973	-178.1878	-1.435502	979789.15	-976621.9	-183.4271
491.24894	-178.1839	-1.43549	979789.15	-976622	-183.4543
491.28903	-178.1984	-1.435534	979789.15	-976621.8	-183.2726
491.27361	-178.1928	-1.435517	979789.15	-976621.9	-183.4169
491.26282	-178.1889	-1.435505	979789.15	-976621.9	-183.4335
491.14717	-178.1469	-1.435378	979789.15	-976621.7	-183.2179
491.141	-178.1447	-1.435371	979789.15	-976621.8	-183.3275
491.07624	-178.1212	-1.4353	979789.15	-976621.9	-183.4437
491.05465	-178.1134	-1.435276	979789.15	-976621.8	-183.3448
490.99143	-178.0904	-1.435207	979789.15	-976621.8	-183.3342
490.93654	-178.0705	-1.435146	979789.15	-976621.9	-183.4194
490.902	-178.058	-1.435108	979789.15	-976621.9	-183.3651
490.98218	-178.0871	-1.435196	979789.15	-976621.9	-183.4065
491.33683	-178.2157	-1.435587	979789.15	-976621.7	-183.1903
491.31987	-178.2096	-1.435568	979789.15	-976621.6	-183.1061
491.05897	-178.1149	-1.435281	979789.15	-976621.6	-183.09
490.96984	-178.0826	-1.435183	979789.15	-976621.7	-183.2248

	SAN	FRANCISCO	VOLCANIC	FIELD	
	SPIDER	WEB	RANCH	GRAVITY	SURVEY
		LINE base#		N12.5° from	base #1
STATION#	DISTANCE	ELEVATION	LATITUDE	Sigma	GOBS(mgals)
	(M)	(M)	(DEGREE)		
base #1		1598.676			
base #1	0	1598.676	35.6589	0.1271557	2854.3807
#18	100	1598.106	35.658021	0.1271494	2854.5287
#19	150	1599.076	35.657581	0.1271463	2854.3982
#20	200	1599.451	35.657141	0.1271432	2853.9965
#21	230	1600.001	35.656877	0.1271413	2853.7967
#22	280	1600.441	35.656437	0.1271382	2853.8396
#23	330	1600.971	35.655998	0.127135	2853.7877
#24	362	1601.996	35.655716	0.127133	2853.4982
#25	386.4	1602.936	35.655501	0.1271315	2853.3169
#26	436.4	1605.236	35.655062	0.1271283	2852.6838

FREE AIR	BOUGUER	Earth Curve	Gtheor	CBG(mgals)	Normalized
					976438.5
493.20014	-178.8918	-1.437622	979789.08	-976621.8	-183.3237
493.02436	-178.8281	-1.437431	979789	-976621.7	-183.2122
493.32351	-178.9366	-1.437756	979788.96	-976621.6	-183.1147
493.43916	-178.9786	-1.437881	979788.92	-976621.9	-183.4052
493.60878	-179.0401	-1.438065	979788.9	-976622	-183.4746
493.74447	-179.0894	-1.438212	979788.86	-976621.8	-183.3077
493.90793	-179.1487	-1.438388	979788.83	-976621.7	-183.218
494.22403	-179.2634	-1.438729	979788.8	-976621.8	-183.2823
494.51392	-179.3685	-1.439041	979788.78	-976621.8	-183.2609
495.22322	-179.6259	-1.439803	979788.75	-976621.9	-183.4051

SAN	FRANCISCO	VOLCANIC	FIELD	
SPIDER	WEB	RANCH	MAGNETIC	SURVEY
	LINE #5000		N124 from	base #1
station#	distance	reading	time	drift corr.
	(M)	(nT)	(min.)	(nT)
base #1	0	51321.7	0	51321.7
5050	50	51320.6	2	51320.8779
5100	100	51355.8	5	51356.4947
5150	150	51342.9	7	51343.8726
5175	175	51356.9	9	51358.1505
5200	200	51326.3	12	51327.9674
5225	225	51298.3	15	51300.3842
5250	250	51314.1	17	51316.4621
5270	270	51279.7	22	51282.7568
5290	290	51362.6	26	51366.2126
5305	305	51331.6	29	51335.6295
5320	320	51381	32	51385.4463
5327.5	327.5	52785.7	36	52790.7021
5335	335	52099.3	39	52104.7189
5342	342	52167	43	52172.9747
5350	350	51026.3	45	51032.5526
5365	365	52366.1	47	52372.6305
5395	395	51589.6	52	51596.8253
5420	420	52172	55	52179.6421
5445	445	50343	58	50351.0589
5470	470	50744	60	50752.3368
5495	495	51308.2	62	51316.8147
5520	520	51300.3	65	51309.3316
5570	570	51291.5	68	51300.9484
5620	620	51286.7	70	51296.4263
5670	670	51281.7	73	51291.8432
base #1	0	51308.5	95	51321.7

SAN	FRANCISCO	VOLCANIC	FIELD	
SPIDER	WEB	RANCH	MAGNETIC	SURVEY
	LINE#6000		N124° from	#6000
station#	distance	reading	time	drift corr.
	(M)	(nT)	(min.)	(nT)
6000	0	51387	0	51387
6050	50	51408	15	51407.5673
6100	100	51645	20	51644.4231
6125	125	50940	25	50939.2788
6175	175	51525	29	51524.1635
6225	225	51269	33	51268.0481
6245	245	51352	37	51350.9327
6265	265	51387	40	51385.8462
6285	285	51398	43	51396.7596
6305	305	51390	46	51388.6731
6325	325	51407	48	51405.6154
6345	345	51458	50	51456.5577
6365	365	51465	52	51463.5
6385	385	51497	54	51495.4423
6405	405	51385	56	51383.3846
6410	410	51372	0	51372
6415	415	51426	0	51426
6420	420	51559	0	51559
6422.5	422.5	52060	0	52060
6425	425	52913	60	52911.2692
6427.5	427.5	52089	0	52089
6430	430	50630	0	50630
6435	435	50930	0	50930
6440	440	51085	0	51085
6445	445	51130	0	51130
6450	450	51162	63	51160.1827
6475	475	51210	66	51208.0962
6525	525	51210	70	51207.9808
6575	575	51282	75	51279.8365
6625	625	51302	78	51299.75
6000	0	51390	104	51387

SAN	FRANCISCO	VOLCANIC	FIELD	
SPIDER	WEB	RANCH	MAGNETIC	SURVEY
	LINE #7000		N124° from	base #1
station#	distance	reading	time	drift corr.
	(M)	(nT)	(min.)	(nT)
7000	0	51294	0	51294
7050	50	51288	2	51288.2824
7100	100	51283	4	51283.5647
7150	150	51255	7	51255.9882
7200	200	51286	9	51287.2706
7252	252	51349	11	51350.5529
7270	270	51256	13	51257.8353
7295	295	51127	16	51129.2588
7320	320	50882	21	50884.9647
7345	345	51427	28	51430.9529
7400	400	49832	36	49837.0824
7418	418	52781	40	52786.6471
7445	445	50887	45	50893.3529
7468	468	51138	48	51144.7765
7500	500	51040	50	51047.0588
7550	550	52611	53	52618.4824
7600	600	51229	57	51237.0471
7700	700	51240	62	51248.7529
7750	750	51282	63	51290.8941
7800	800	51278	65	51287.1765
7000	0	51282	85	51294

SAN	FRANCISCO	VOLCANIC	FIELD	
SPIDER	WEB	RANCH	MAGNETIC	SURVEY
	LINE #8000		N124° from	#8187
station#	distance	reading	time	drift corr.
	(M)	(nT)	(min.)	(nT)
6000	-187	51352	0	51352
8050	-137	51108	3	51110.04
8100	-87	51515	6	51519.08
8150	-37	50637	9	50643.12
8187	0	50548	11	50555.48
8237	50	51165	14	51174.52
8290	103	51326	17	51337.56
8340	153	51275	19	51287.92
8365	178	51291	21	51305.28
8377	190	51308	23	51323.64
8390	203	51323	26	51340.68
8400	213	51333	27	51351.36
8410	223	51413	30	51433.4
8420	233	51368	32	51389.76
8430	243	51412	33	51434.44
8435	248	51901	39	51927.52
8440	253	52963	36	52987.48
8445	258	52126	40	52153.2
8450	263	51823	42	51851.56
8455	268	50978	45	51008.6
8460	273	50498	47	50529.96
8470	283	51036	50	51070
8480	293	51122	52	51157.36
8490	303	51138	54	51174.72
8500	313	51108	57	51146.76
8510	323	51131	59	51171.12
8520	333	51120	61	51161.48
8530	343	51153	62	51195.16
8550	363	51177	63	51219.84
8570	383	51190	65	51234.2
8595	408	51200	67	51245.56
8620	433	51190	69	51236.92
8645	458	51160	71	51208.28
8670	483	51216	72	51264.96
8695	508	51229	74	51279.32
8720	533	51238	75	51289
8770	583	51222	77	51274.36
8820	633	51236	80	51290.4
6000		51284	100	51352

SAN	FRANCISCO	VOLCANIC	FIELD	
SPIDER	WEB	RANCH	MAGNETIC	SURVEY
	LINE #10000		N90° from	#10000
station#	distance(m)	reading	time	drift corr.
		(nT)	(min.)	(nT)
4050		51310	0	51310
10000	0	51320	4	51319.8532
10090	90	51275	8	51274.7064
10140	140	51282	11	51281.5963
10190	190	51284	13	51283.5229
10240	240	51293	16	51292.4128
10250	250	51273	18	51272.3394
10270	270	51320	20	51319.2661
19275	275	51327	26	51326.0459
10280	280	51466	21	51465.2294
10282.5	282.5	51140	29	51138.9358
10285	285	51105	23	51104.156
10287.5	287.5	51204	30	51202.8991
10290	290	51238	24	51237.1193
10295	295	51298	31	51296.8624
10300	300	51260	33	51258.789
10310	310	51290	35	51288.7156
10320	320	51293	36	51291.6789
10330	330	51292	39	51290.5688
10340	340	51292	40	51290.5321
10350	350	51284	42	51282.4587
10360	360	51328	46	51326.3119
10370	370	51296	44	51294.3853
10390	390	51371	48	51369.2385
10400	400	51288	50	51286.1651
10415	415	51239	51	51237.1284
10440	440	51307	53	51305.055
10465	465	51309	55	51306.9817
10490	490	51295	56	51292.945
10540	540	51271	59	51268.8349
10590	590	51282	64	51279.6514
10640	640	51276	66	51273.578
10690	690	51305	68	51302.5046
4050		51314	109	51310