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GEOLOGICAL AND GEOPHYSICAL SIGNATURES OF THE JEMEZ LINEAMENT: A REACTIVATED PRECAMBRIAN STRUCTURE

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ABSTRACT

The Jemez lineament (N52°E) is one of several northeast-trending lineaments that traverse the southwestern United States. It is defined by a 500-km-long alignment of late Cenozoic volcanic fields extending southwest from at least the Jemez Mountains in north-central New Mexico to the San Carlos-Peridot volcanic field in east-central Arizona. Other volcanic fields, both to the northeast and southwest, may lie on extensions of the lineament. The distribution of volcanic centers indicates the lineament has a width of approximately 50 km. Geochronologic data from Precambrian basement rocks indicate that the lineament is approximately coincident with a boundary between Precambrian crustal provinces.

Characteristics of the lineament are high heat flow (>104.5 mW/m^2), an attenuated seismic velocity zone from 25 to 140 km depth, and an upwarp of the crustal electrical conductor inferred from magnetotelluric studies. The high electrical conductivity is probably caused by the presence of interstitial magma in the rocks of the mid-to-upper crust. The average electrical strike within the Precambrian basement is N60°E, supporting a relationship between the Precambrian structural grain and the Jemez lineament.

The geological and geophysical data suggest that the lineament is a structural zone that extends deep into the lithosphere and that its location was

controlled by an ancient zone of weakness in the Precambrian basement. Ages of late Cenozoic volcanic rocks along the lineament show no systematic geographic progression, thus indicating that a mantle plume was not responsible for the alignment of the volcanic fields.

Most of the faults, dikes, and cinder cone alignments along the lineament trend approximately N25°E and N5°W. These trends may represent Riedel shears formed by left-lateral transcurrent movement along the structure. Less common trends of cinder cone alignments and dikes are approximately N65°W and N85°W. The diversity in orientation indicates that the magnitudes of the two horizontal principal stresses within the lineament have been approximately equal for at least the last 5 m.y.

INTRODUCTION

The Jemez lineament is one of several large northeast-trending lineaments that transect the southwestern United States. As originally defined by Mayo (1958) the Jemez zone (lineament) is delineated by a northeast-trending trough in southern Colorado, the Jemez Mountains (Valles Caldera), Mount Taylor, and the northwestern border of the Datil volcanic field. Mayo suggested that aligned post-Nevadan intrusions and other structural features in the Globe-Miami mining district are part of the zone. Between Globe and Ajo, Arizona, he thought the zone was concealed by overprinting of the Texas lineament. Mayo also suggested that the Pinacate volcanic field of northern Sonora, and a small group of volcanic cones in Baja, California may lie on an extension of the lineament (Figure 1). More recently, Suppe and others (1975), Laughlin, Brookins, and Damon (1976), and Chapin and others (1978) defined the lineament almost exclusively on the basis of the alignment of Quaternary volcanic centers. Suppe and others (1975) proposed that the young volcanic fields from the Great Plains (Raton-Clayton) to the White Mountains of east-central Arizona are part of one volcanic chain formed by a mantle hot spot that migrated northeastward. They suggested that the chain may extend to the head of the Gulf of California. They referred to the alignment of volcanic fields as the "Raton-Trans-New Mexico volcanic chain," failing to point out that this is the Jemez zone of Mayo (1958). Laughlin and others (1976) demonstrated that there is no progression in age of the volcanic rocks along the lineament and interpreted the feature as a linear zone that "leaked" basaltic magmas for at least 3 m.y. Chapin and others (1978) include the young volcanic fields of northeastern New Mexico and southeastern Colorado as part of the Jemez lineament, but place a kink in the lineament where it crosses the Rio Grande rift. Lipman and Mennert (1976) also stressed the lack of a progression in the age of volcanic rocks. They correlated the lineament with a lithospheric zone of weakness.

This paper brings together the results of several ongoing studies on the lineament, particularly that segment that crosses the Colorado Plateau from the San Carlos-Peridot volcanic field to the Jemez Mountains (Figure 1).

DESCRIPTION AND GEOLOGY

Since the Jemez lineament was first described by Mayo (1958), young (Pliocene-Quaternary) volcanic fields have been the principal feature used to determine its location. We believe that this criterion is useful because it is simple and straightforward and therefore accept it as the best means for delineating the lineament.

We include the San Carlos-Peridot volcanic field, Springerville-Show Low-St. Johns field, Catron County field, Zuni-Bandera field, Mount Taylor-Mesa Chivato, and the Jemez Mountains (Figure 1) as part of the lineament, giving it a minimum length of 500 km. The volcanic fields of the Great Plains east of the Rio Grande rift (Chapin and others, 1978) and the Pinacate field and cones on Baja California (Mayo, 1953) may lie on extensions of the lineament to the northeast and southwest. The addition of the northeast extension would give the lineament a length of 900 km, and if the southwest extension is added the total length is 1500 km. In the part of the lineament where we concentrated our efforts, the lineament width can be defined by two parallel lines 50 km apart between which most of the volcanic centers are included.

Four of the six volcanic fields on the Colorado Plateau portion of the Jemez lineament consist exclusively of basalt. In the Jemez Mountains and Mt. Taylor-Mesa Chivato fields, intermediate to silicic magmas were also erupted. The compositional range of the basalts is large, with silica contents from 44 to 53% and total alkali contents from 3 to 6.5% (Figure 2). Both petrographic and strontium isotopic evidence indicates that many basalts were contaminated by crustal rocks (Laughlin and others, 1972; Carden and Laughlin, 1974; Brookins and others, 1975). Crustal-derived xenoliths and xenocrysts are common, and $^{87}Sr/^{86}Sr$ ratios are variable and commonly high.

Ultramafic xenoliths have been found in alkalic basalts from the San Carlos-Peridot, Zuni-Bandera, and Mt. Taylor-Mesa Chivato fields (Laughlin and others, 1971; Kudo and others, 1972; Ander and others, 1981). These inclusions of dunites, websterites, lherzolites, and clinopyroxenites provide samples of the source region of the basalts.

The style of volcanism is also diverse along the Colorado Plateau portion of the lineament. Large fissure, cinder cone, maar, and stratovolcano eruptions have all occurred. The typical eruptive sequence is large, tholeiitic eruptions followed by smaller, alkalic cinder cone eruptions. The tholeiitic flows spread over large areas and traveled distances of tens of kilometers.

A large number of K-Ar dates for the late Cenozoic volcanic rocks of the Jemez lineament, are summarized in Table 1 and are shown graphically in Figure 3. There is no simple progression of ages along the lineament which contradicts the suggestion of Suppe and others (1975) that the lineament is the trace of a mantle plume. A more plausible model correlates known geology and geophysics to show that the volcanic centers were localized by a major crustal break or zone of weakness. Stress conditions have apparently been suitable for the zone to have served as a conduit for intermittent magma rise for at least the last four m.y.

PRECAMBRIAN STRUCTURE

Numerous workers (Slawson and Austin, 1962; Schmitt, 1966; Landwehr, 1967; Wertz, 1968; Gay, 1972; Laughlin and West, 1976; Cordell, 1978; Lipman and Mehnert, 1979; and Ander, 1980) have emphasized that lineaments such as the Jemez formed above zones of weakness in Precambrian basement rocks. Landwehr (1967) noted that the Globe belt (Jemez lineament) in the vicinity of Globe-Miami, Arizona strikes parallel with fold axes in the Precambrian Pinal schist, and parallel with an alignment of Precambrian granitic intrusions.

At the Copper Cities porphyry copper mine near Miami, Arizona the Lost Gulch quartz monzonite, the host rock for the ore body, was emplaced along a northeast-trending zone that separates Paleozoic and younger Precambrian rocks to the north from older Precambrian Pinal schist and intrusive rocks to the south (Simmons and Fowells, 1966). They cite Peterson's (1962) suggestion that the intrusive contact between the Ruin Granite (Precambrian) to the north and Pinal Schist to the south is the fundamental control for this zone.

Along the Jemez lineament, within the Zuni Mountains, New Mexico, Precambrian rocks are strongly foliated (Goddard, 1966). In general, the foliation strikes northeast to east-northeast and dips steeply to the southeast or northwest. Precambrian porphyritic granite dikes trend parallel with the strike of the foliation. Other Precambrian dikes ranging from hornblendite to granite invade the gneisses at right angles to the foliation.

Geochronological investigations of the Precambrian rocks of the southwestern United States suggest that the Jemez lineament may reflect the location of a suture in the Precambrian basement. Silver (unpublished data, cited in Cordell, 1978) draws a boundary between Precambrian-age provinces that is essentially coincident with the lineament. More recently, Van Schmus and Bickford (in press) show a similar province boundary, which is the contact between rocks of 1690 to 1780 m.y. ages and those of 1610 to 1680 m.y. ages. Lipman and Mehnert (1979) and Chapin and Cather (1981) have also recognized the apparent coincidence of the Jemez lineament with a Precambrian province boundary.

Geophysical Investigations

Recent studies indicate that the lineament has greater than normal heat flow (Figure 4) ranging from 63 to 105 mW/m^2, with a few measurements above 105 mW/m^2 (Reiter and others, 1975; Edwards and others, 1978). One area of particularly high heat flow is the region to the west of Grants and south of

Gallup, New Mexico. The highest value measured in this region is 125.4 mW/m^2 which is located south of the town of Zuni on the Zuni Indian Reservation.

A regional deep magnetotelluric (MT) sounding survey and a detailed magnetotelluric/audiomagnetotelluric (MT/AMT) survey of a 161 km^2 area were performed in this region (Ander and others, 1980a, b). The detailed survey was located in the area of highest heat flow to determine if a detailed electrical evaluation could recognize the presence of a deep-seated body of high-temperature basement rock. The regional survey was designed to determine the geometry of the pervasive deep electrical conductor in this region and to provide a regional background for the detailed site investigation. Within this area, the regional survey consisted of three roughly east-west profiles (Figure 5).

The estimate of the depth to a deep electrical conductor, based on one-dimensional inversion, is shown in each profile for the MT components parallel to strike and perpendicular to strike (Figure 6). The 50 ohm-m contour was arbitrarily chosen to represent the depth to the deep electrical conductor. On the northern and central profiles the conductive zone becomes shallower beneath the Jemez lineament for both the parallel and perpendicular electrical-strike components, while on the southern profile the conductive zone becomes shallow for only the parallel-to-strike component. It is thus apparent that the Jemez lineament is marked by an anomalously shallow electrical conductor, probably associated with partial melting of the crust. The results of the detailed MT/AMT survey support these conclusions.

The detailed MT/AMT survey consisted of 119 scalar AMT stations and 25 tensor MT stations (Figure 7). Although the AMT study was performed to search for any near-surface electrical structures or lateral contacts, none were found.

The detailed MT survey shows that at shallow depths the electrical strike approximately aligns with the axes of N30°W-trending broad anticlines and synclines (Figure 8) in sedimentary rocks. At greater depths the strike rotates about 90° to a distinct and consistent N60°E orientation. This rotation is commonly abrupt and almost certainly reflects a different trend within the Precambrian metamorphic basement. The near-parallelism between the Jemez lineament (N52°E) and tipper strike in the basement (N60°E) strongly suggests the lineament is structurally controlled by the fabric of the deeper Precambrian rocks.

A two-dimensional electrical model was developed for a line across the detailed survey area oriented perpendicular to the deep electrical strike. The resulting model (Figure 9) gives an excellent fit to the apparent resistivity sounding curves. The top 800 m is very conductive and overlies resistive electrical basement. A well located at sec. 5, T.9N., R.18W. in the northern portion of the study area showed that depth to basement is 767 m. From a depth of 800 m to 15 km the rocks are resistive. Below 15 km the rocks become much more conductive. This deep conductive zone is less conductive in the northwest and becomes more conductive to the southeast in the direction of the Jemez lineament.

Our MT results agree with the preliminary results of a teleseismic P-wave delay study that indicate that this portion of the Jemez lineament is associated with a zone of low seismic velocity from 25 to 140 km deep (Spence and others, 1979; Spence, U.S. Geological Survey, personal written communication, 1980). This zone varies from 50 to 120 km in width and has low P-wave velocities.

Regional geophysical studies, indicate that the Jemez lineament is associated with: 1) greater than normal heat flow (Edwards and others, 1978);

2) a low seismic velocity zone from 25 to 140 km deep inferred from teleseismic P-wave delay studies (Spence and others, 1979); and 3) anomalously high electrical conductivity at shallow depths inferred from a regional deep MT sounding survey and a detailed MT/AMT survey (Ander, 1980; Ander and others, 1980a, b).

STATE OF STRESS

Orientations of principal stress in areas along the Jemez lineament were determined from several different stress indicators including (1) the trends of young (Pliocene-Quaternary) dikes, (2) alignments of young cinder cones, (3) directions of oblique slip on normal faults that show displacement within the last 5 m.y., (4) earthquake focal mechanism solutions, and (5) in situ stress measurements from strain relief determinations and hydrofracturing. Zoback and Zoback (1980, p. 6114-6115, and 6128) discuss the assumptions associated with each indicator.

Our data show that the segment of the lineament between the Jemez Mountains and San Carlos-Peridot volcanic field is characterized by least-principal horizontal stresses that have widely different orientations. The stress is oriented west-northwest (approximately N65°W) in many areas along the lineament. Other orientations occur however; one to the north-northwest (approximately N25°W), another due north, and one east-northeast (approximately N85°E). At a few places the stress is oriented northeast (see Figure 10). The wide variation in orientation of the least principal horizontal stress indicates that the two principal horizontal stresses are approximately equal in magnitude within this segment of the lineament. This relationship is consistent with stress measurements made at Fenton Hill in the Jemez Mountains where S_1 is vertical and $S_1 >> S_2 \approx S_3$ (D. Brown, Los Alamos National Laboratory, personal communication, 1981).

The most commonly used stress indicators are dikes and cinder cone alignments. Most of these features trend north-northeast and north-northwest (Figure 11) approximately parallel to the two main fault trends along the lineament that Bartov (personal communication, 1981) found from LANDSAT, SEASAT, and other imagery. The 74 vents forming the Zuni-Bandera volcanic field follow the north-northeast trunk. The emplacement of the vents may have been influenced by the eastern edge of a shallow, 90 km long and 30 km wide mafic intrusion also trending north-northeast (Ander and others 1981; Ander and Huestis, in press). One of the largest northeast-trending faults (Ventana fault) is located on the east side of the Zuni-Bandera volcanic field south of Grants, New Mexico. The similarity in orientation of dikes and cinder-cone alignments with fault trends suggests that prior faults controlled the emplacement of the dikes and cinder cones. Movement on some of the faults also created topographic barriers that blocked and channeled basaltic lavas, as for example, the previously mentioned Ventana fault.

The north-northeast structural trend (N25°E) is the best developed and most persistent. The second most prominent trend is oriented N5°W (Figure 11). These fracture trends may represent Riedel shears formed by left lateral transcurrent movement along the lineament. Failure directions predicted by the Coulomb failure criterion for rock with an angle of shearing resistance, ϕ, between 50° and 55° are consistent with the observed fault trends on the lineament. A ϕ value of 50° to 55° is reasonable for the Precambrian basement rocks that may have controlled the orientation of the faults (c.f. Handin, 1966). Observed fracture trends and predicted trends are shown in Figure 12. Riedel shears with similar orientations with respect to the direction of movement formed during the 1968 Dasht-e Bayāz earthquake in Iran (Tchalenko and Ambraseys, 1970); their trends have been added to Figure 12 for comparison.

Supporting evidence for left-lateral movement is also present east of the Rio Grande rift where the frontal fault zone of the Picuris Range is parallel to the trace of the Jemez lineament (c.f. Lambert, 1966). Muehlberger (1978, p. 44) suggested that the frontal fault is a transform between the Española and San Luis basins and that it should show evidence of left-lateral slip.

Slickensides on the Ventana fault indicate older strike-slip motion and younger oblique-slip motion that is consistent with the interpretation that the faults formed from compressional stresses during Laramide wrench faulting and were later subjected to extension.

DISCUSSION

Our results support prior conclusions that the Jemez lineament is a major lithospheric flaw that developed along a Precambrian province boundary (Lipman and Mehnert, 1979 and Chapin and Cather, 1981). Where Precambrian rocks are exposed along the Jemez lineament as in the Zuni Mountains, the foliation generally trends parallel to the lineament. Our MT data show that the trend of the electrical conductivity to a depth of 40 km is parallel with this structural grain. The interpretation of the lineament as a zone of weakness is further substantiated by teleseismic data showing an attenuation of P-waves beneath the lineament (Spence and others, 1979). It is apparent that the lineament provides conduits for magma to reach the surface, which is probably the cause of the high electrical conductivity and P-wave attenuation associated with the lineament.

The geological and geophysical signatures of the Colorado Plateau segment of the Jemez lineament (from the Jemez Mountains to the San Carlos-Peridot volcanic field) are different from those of its possible extensions to the southwest or northeast. The most obvious difference is a scarcity of Pliocene-Quaternary volcanic rocks southwest of the San Carlos-Peridot field and the broader distribution of volcanic centers northeast of the Rio Grande rift. This broader distribution of centers may result from movement of the Colorado Plateau northward (60 to 120 km) relative to the continental interior during the latest Paleocene and middle Eocene as suggested by Chapin and Cather (1981). If this is true, then the Precambrian flaw forming the Jemez lineament on the Colorado Plateau is no longer on strike with its original northeast extension and may be approximately aligned with an entirely different Precambrian basement flaw. The absence of young volcanic activity southwest of the San Carlos-Peridot field may result from destruction of the upper crustal portion of the lineament in southern Arizona by large-scale Laramide thrust faulting of the crust above a décollement.

Changes in the orientation of the stress field exist along and across the lineament. Studies by Zoback and Zoback (1980) and Aldrich and Laughlin (in press) suggest that the stresses associated with any given segment of the feature are controlled by the regional stesses. Along the lineament segment between the Jemez Mountains and the San Carlos-Peridot volcanic field stresses characteristic of both the Colorado Plateau interior and Basin and Range Province (Zoback and Zoback, 1980) are present.

Chapin and Cather (1981) propose that during the Laramide orogeny, 80 to 40 m.y. ago (Coney, 1972), there were two different orientations of the stress field. They suggest that during the early part of the orogeny, 80 to 55 m.y. ago, the maximum principal horizontal stress was oriented east-northeast as a result of the Colorado Plateau being crowded against the rigid craton to the east. Because the Jemez lineament trends N52°E, this east-northeast compression favored right-lateral movement along the lineament. At about 55 m.y. (latest Paleocene) the stress orientation changed to northeast (N45°E) due to an anticlockwise rotation of the North American plate (Chapin and Cather, 1981). This N45°E orientation persisted until the compressive forces relaxed during the middle Eocene (45 m.y. ago). A maximum principal compressive stress direction of N45°E favored left-lateral motion on the Jemez lineament. Evidence of this later left-lateral motion is present as the Reidel shear planes associated with the Colorado Plateau segment of the Jemez lineament.

Contemporary stress conditions on the Colorado Plateau segment of the Jemez lineament are substantially different from those existing during the Laramide orogeny. In situ stress measurements and the presence of older faults, such as the Ventana, with Holocene, normal, oblique slip movement show that the maximum principal stress (S_1) is now vertical. Several large earthquakes recorded near the Jemez lineament northwest of Mount Taylor were predominantly strike-slip events at depths of 30 to 40 km near the base of the crust (Sanford and others, 1979). The earthquake data suggest that the orientation of the principal stresses within the lineament may change with depth.

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FIGURE CAPTIONS

Figure 1. Index of late Cenozoic volcanic fields along the Jemez lineament. Exposures of Precambrian rocks near and on the lineament are shown by lined pattern.

Figure 2. Variation in silica and alkali content in basaltic rocks of the Jemez lineament.

Figure 3. Range of K/Ar ages in volcanic rocks along the Jemez lineament. S.C-P. = San Carlos-Periudot; S.-S.-S. = Springerville-St. Johns-Show Low; C.C. = Catron County; B.Z. = Bandera-Zuni; M.T.-M.C. = Mount Taylor-Mesa Chivato; J.M. = Jemez Mountains; T.P. = Taos Plateau, M.C. = Mora County; R.-C. - Raton Clayton.

Figure 4. Heat flow map of northern New Mexico and southern Colorado (modified from Edwards and others, 1978).

Figure 5. Map of west-central New Mexico and part of Arizona showing Cenozoic volcanic rocks, Rio Grande rift, and location of magnetotelluric sites.

Figure 6. Portions of three east-west magnetotelluric profiles (Figure 5) indicating the estimates of depth to deep electrical conductor for both polarizations based on one-dimensional analysis, showing inferred 50 ohm-meter contour interval; a, b, and c are the northern, central, and southern profiles respectively. The lineament is located between stations 40 and 42 on the northern profile, between stations 32 and 33 on the central profile, and between stations 46 and 47 on the southern profile.

Figure 7. Location of magnetotelluric/audiomagnetotelluric stations in detailed survey site.

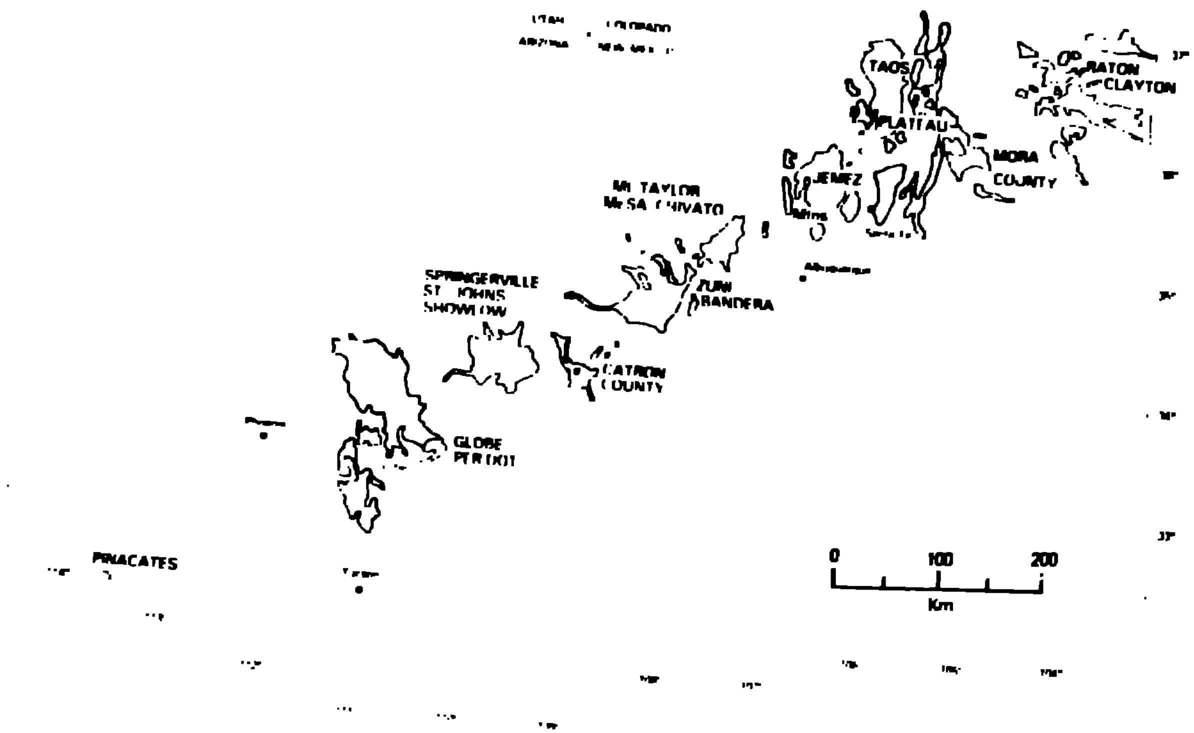
Figure 8. Estimate of electrical strike directions for the short period and the long period portions of the magnetotelluric spectrum at the detailed survey site.

Figure 9. Two-dimensional electrical model based on detailed site magnetotelluric survey.

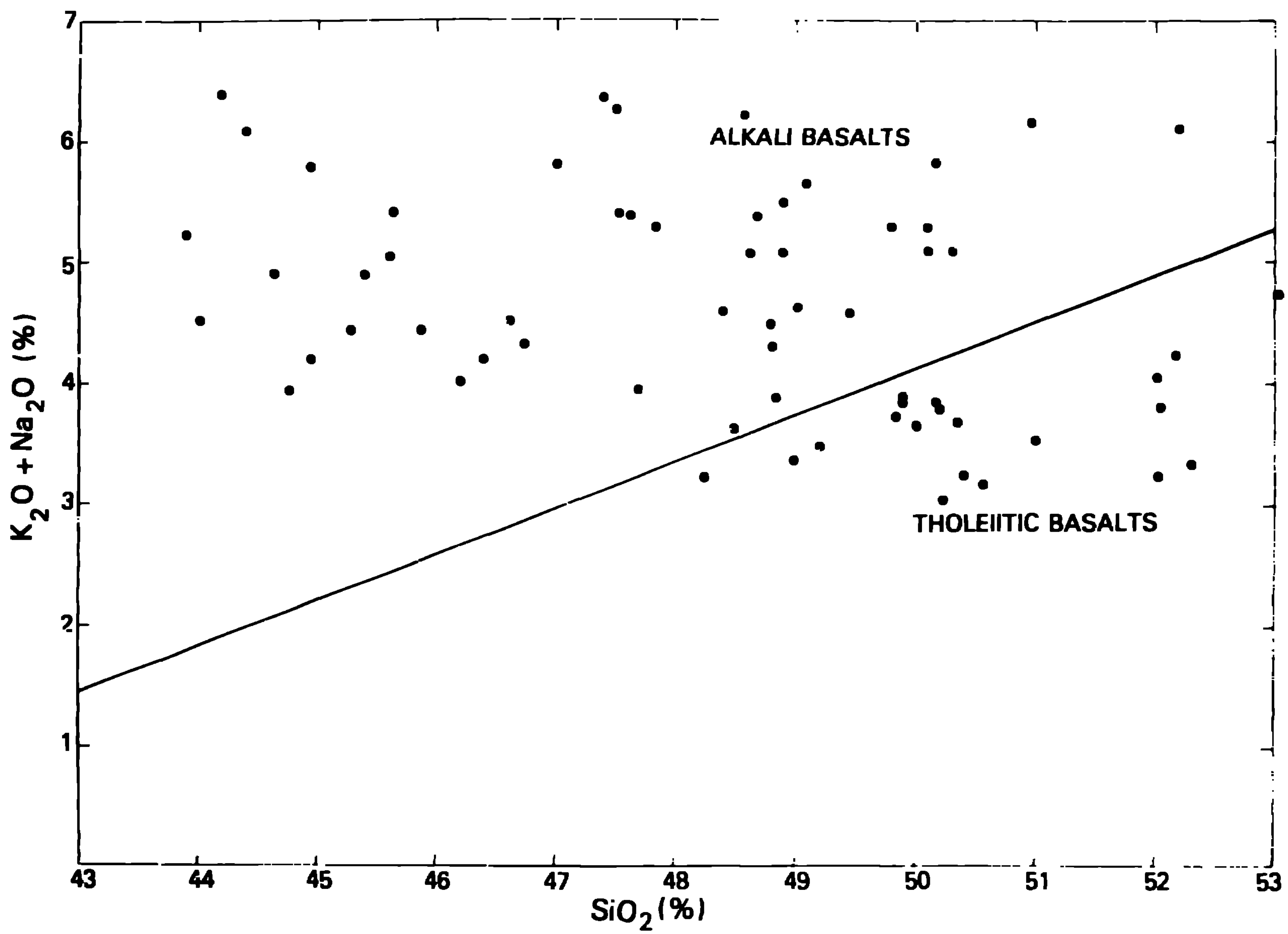
Figure 10. Orientation of 32 least-principal horizontal-stress indicators along the Jemez lineament from the vicinity of the San Carlos-Peridot volcanic field to the Jemez Mountains.

Figure 11. Orientations of 26 dike trends and cinder cone alignments along the Jemez lineament.

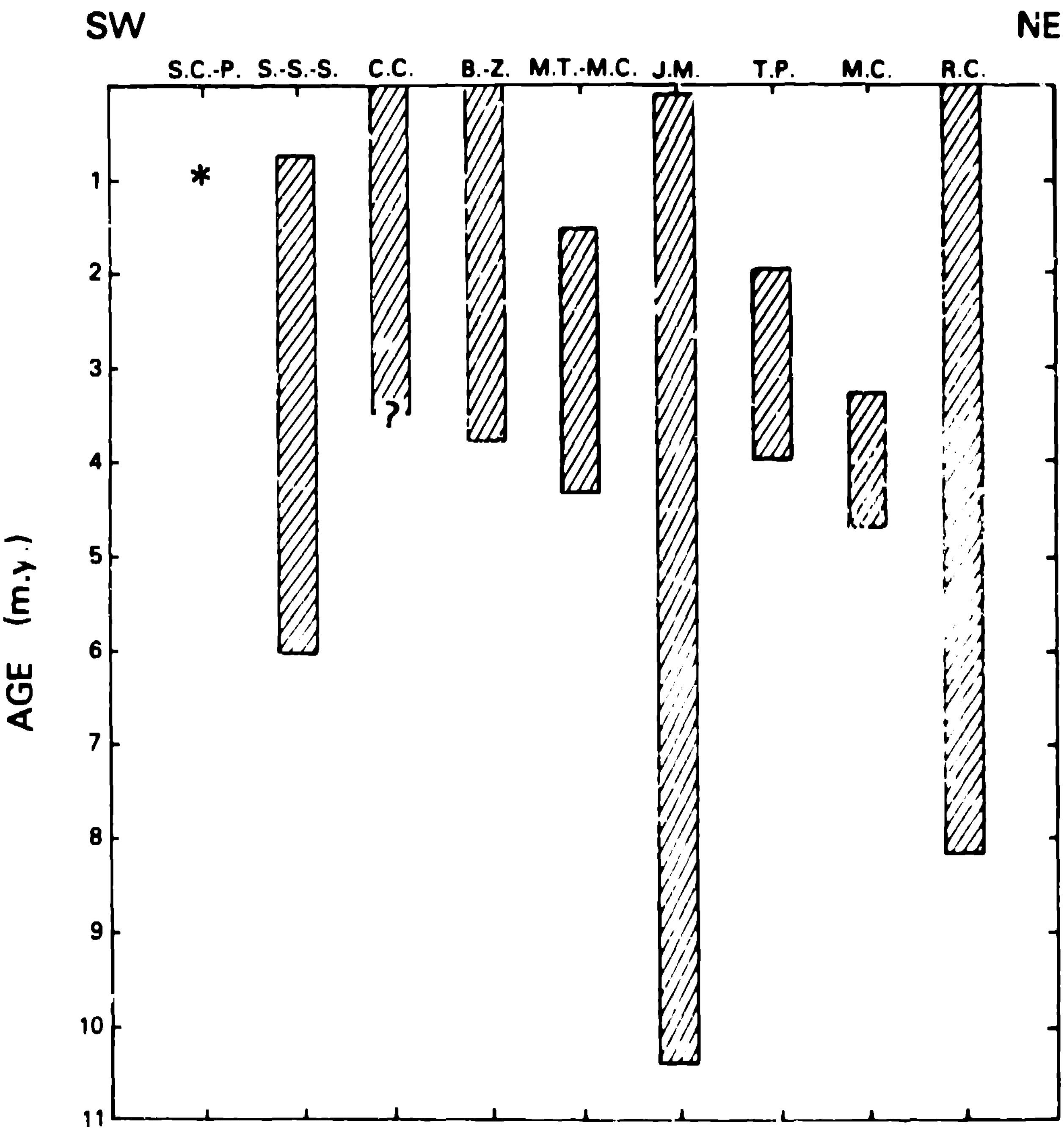
Figure 12. Orientations of dike trends and cinder cone alignments along the Jemez lineament (stippled pattern). Black areas are direction of Riedel shears predicted by the Coulomb failure criterion for crystalline rock with $50° \leq \phi \leq 55°$ and left-lateral displacement. For comparison, lined areas delineate Riedel shear directions in fault zone associated with Dash-e-Bayaz earthquake of August 31, 1968 (Tchaenko and Ambraseys, 1970); data are rotated so that fault zone parallels trend of Jemez lineament.



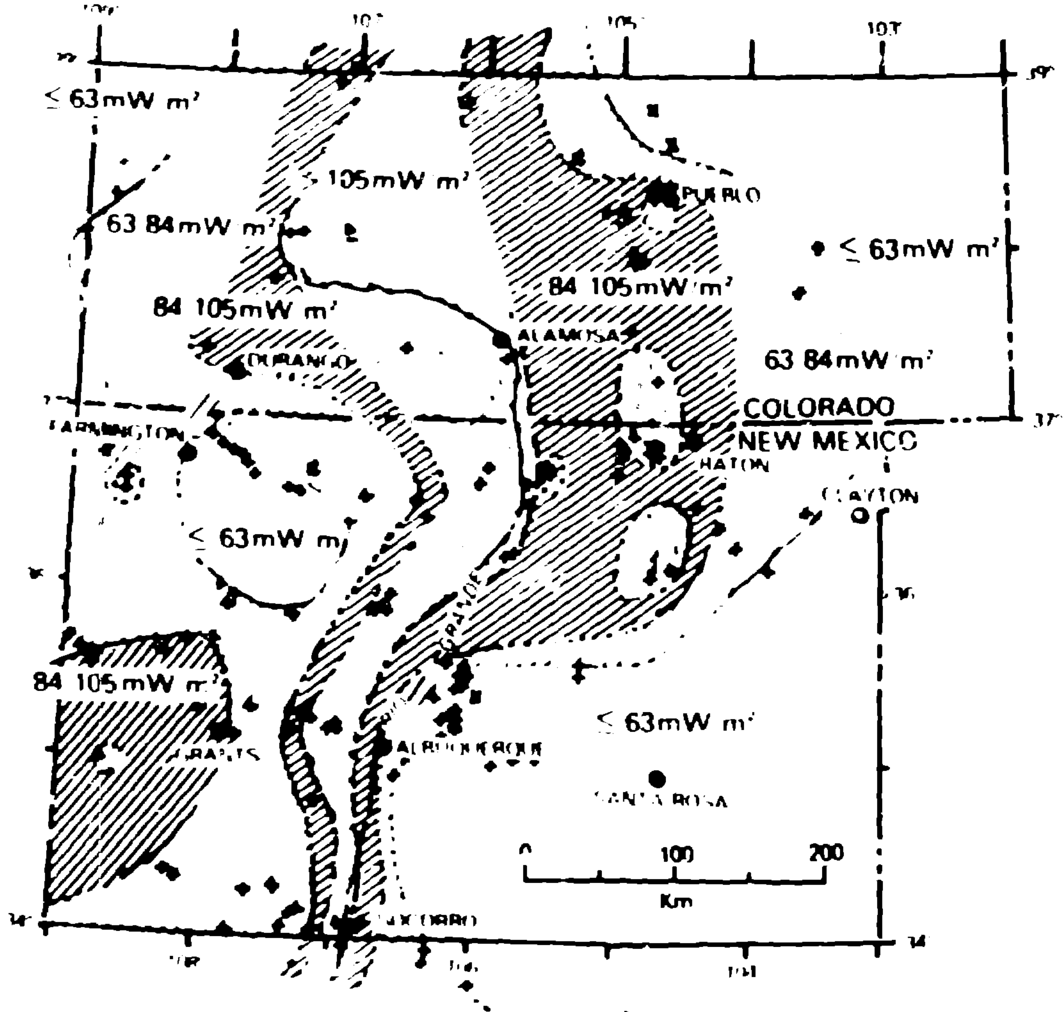
TAOS
PLATEAU
RATON
CLAYTON
MORA
COUNTY
JEMEZ
MT. TAYLOR
MESA CHIVATO
ZUNI
BANDERA
SPRINGERVILLE
ST. JOHNS
SHOWLOW
CATRON
COUNTY
GLOBE
PERIDOT
PINACATES
0
100
200
Km



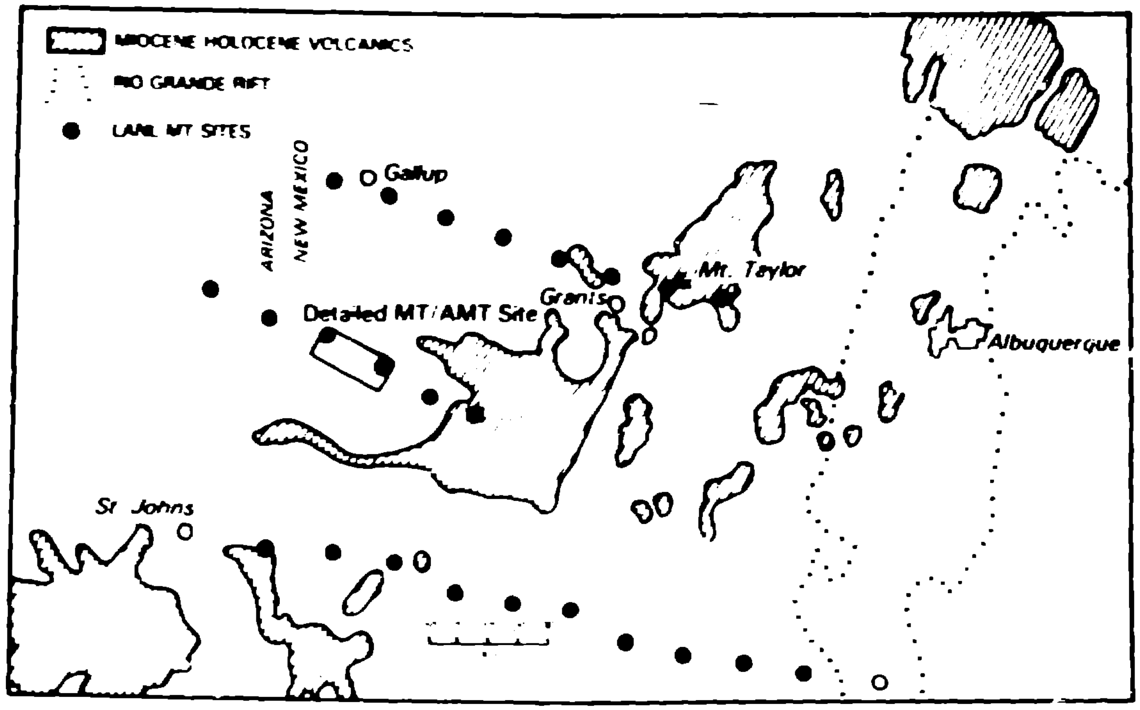
ALKALI BASALTS
THOLEIITIC BASALTS
$K_2O + Na_2O$ (%)
SiO_2 (%)
7
6
5
4
3
2
1
43
44
45
46
47
48
49
50
51
52
53



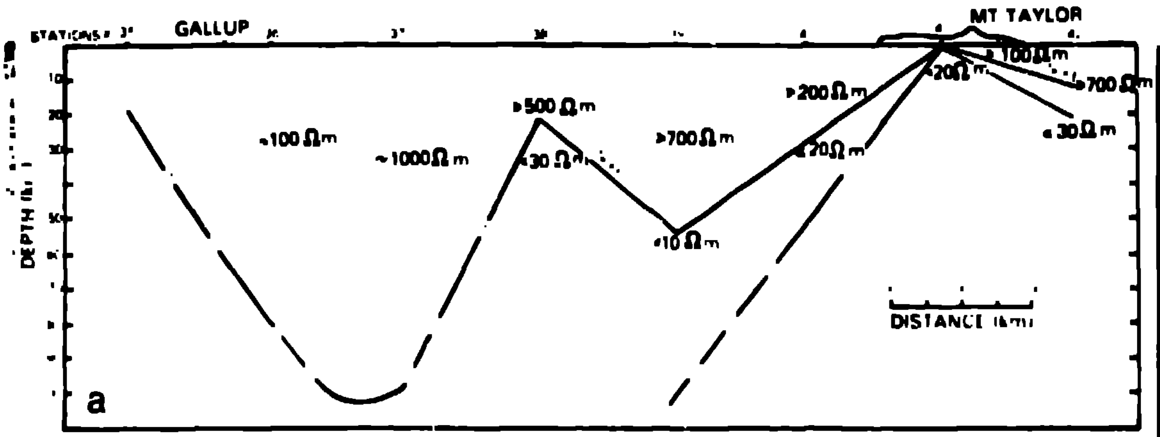
SW
NE
S.C.-P.
S.-S.-S.
C.C.
B.-Z.
M.T.-M.C.
J.M.
T.P.
M.C.
R.C.
AGE (m.y.)
1
2
3
4
5
6
7
8
9
10
11
?
*



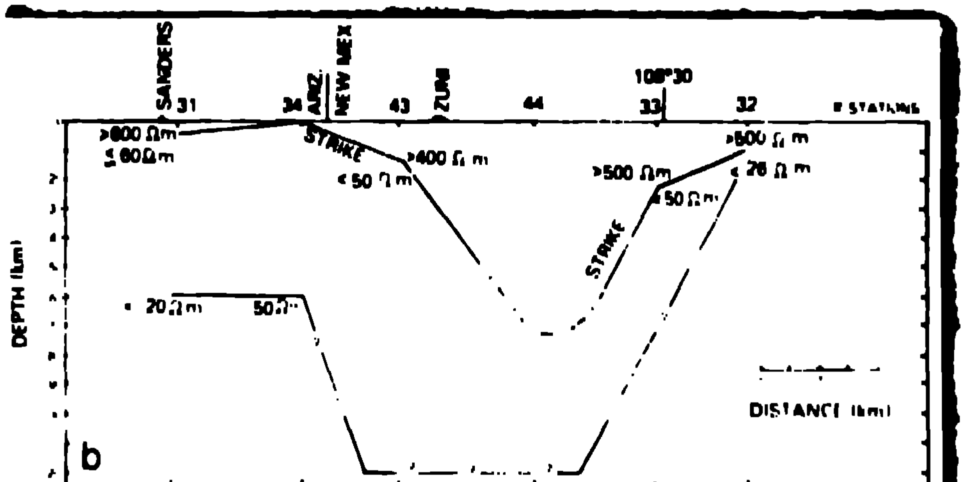
Modified from Edwards et al (1978)



MIOCENE HOLOCENE VOLCANICS
RIO GRANDE RIFT
LANL MT SITES
ARIZONA
NEW MEXICO
Gallup
Mt. Taylor
Grants
Detailed MT/AMT Site
Albuquerque
St Johns



ESTIMATE OF DEPTH TO DEEP CONDUCTOR
BASED UPON 1-DIMENSIONAL MODELS



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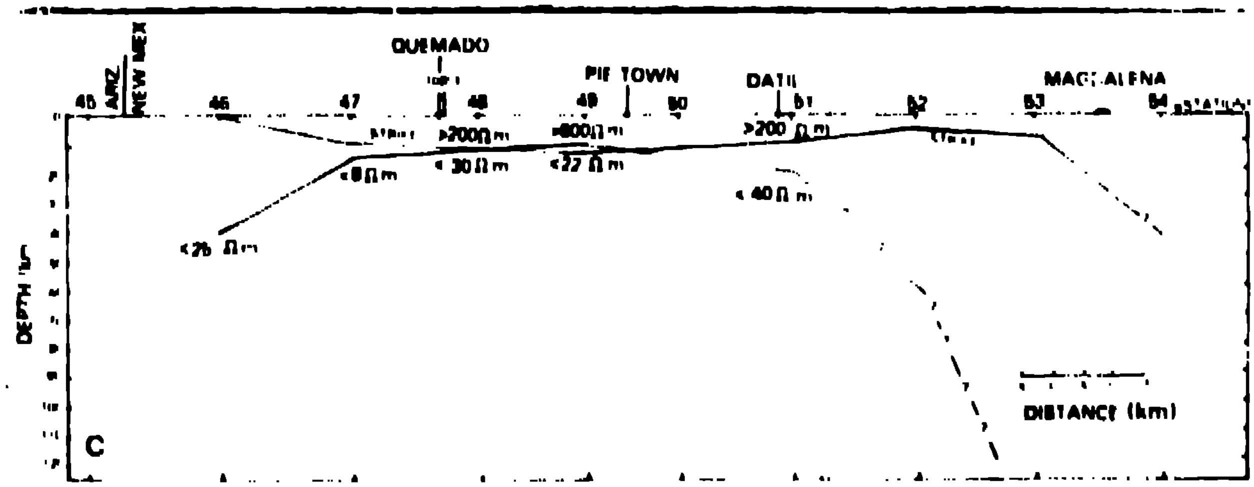
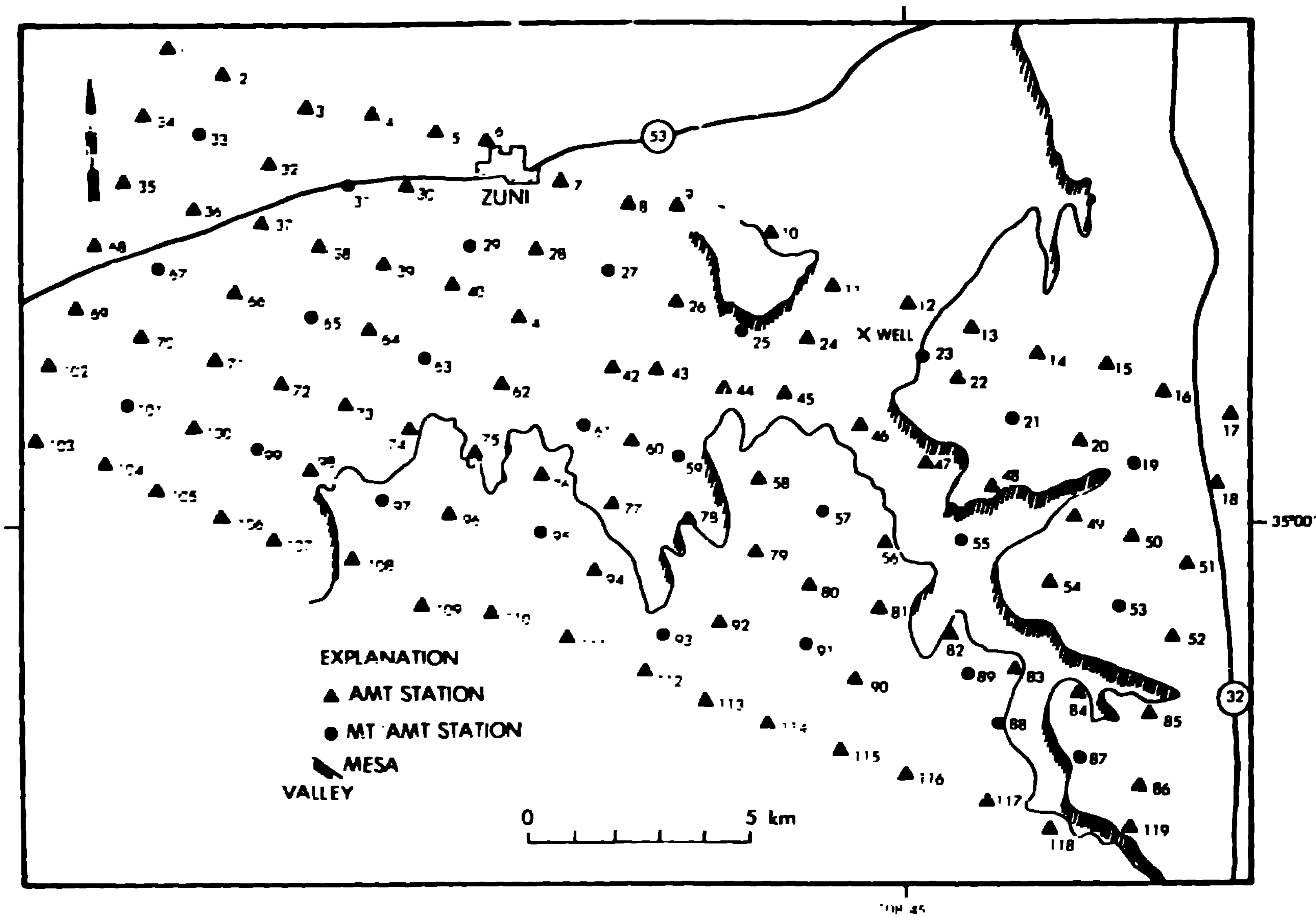
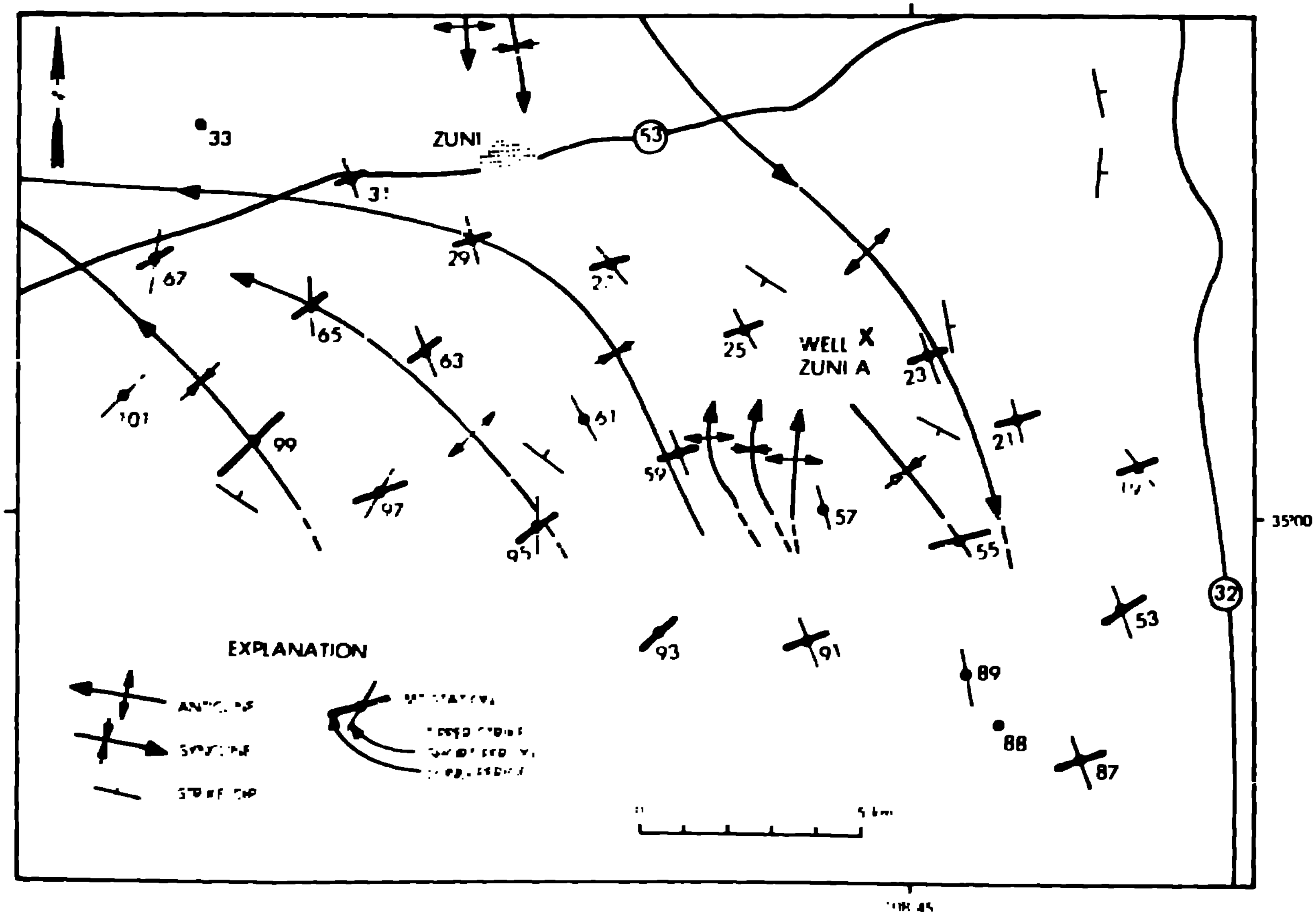
1-DIMENSIONAL ANALYSIS



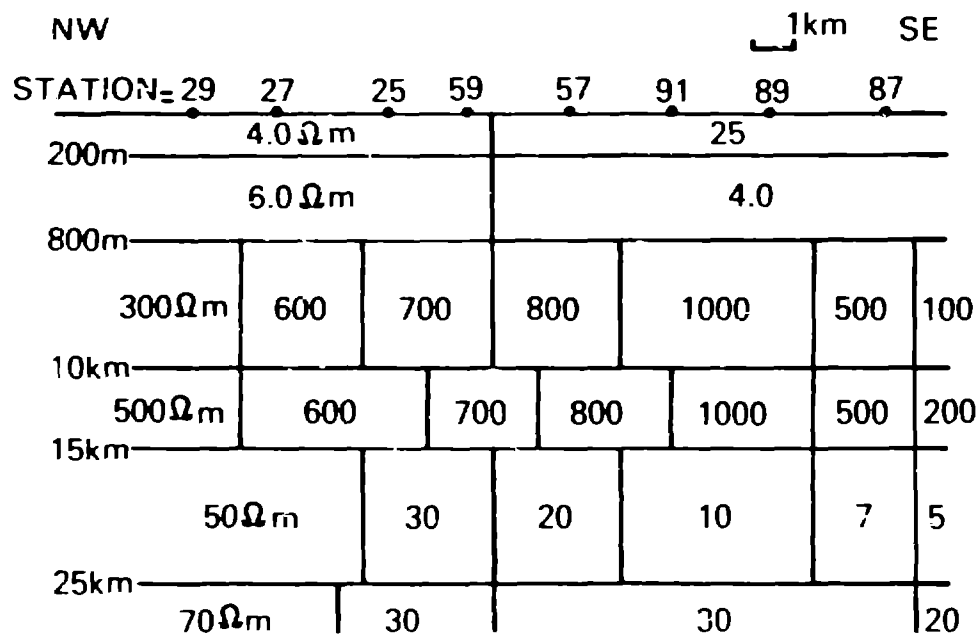
ESTIMATE OF DEPTH TO DEEP CONDUCTOR BASED ON 1-DIMENSIONAL ANALYSIS



GENERALIZED GEOLOGY AND TOPOGRAPHY WITHIN ZUNI SURVEY AREA (MODIFIED FROM HACKMAN AND OLSON, 1977)



ZUNI
53
33
67
29
65
63
25
WELL
ZUNI A
X
23
99
61
21
59
57
97
55
35°00
32
53
93
91
89
88
87
EXPLANATION


NW
1km
SE
STATION= 29
27
25
59
57
91
89
87
4.0 Ωm
25
200m
6.0 Ωm
4.0
800m
300Ωm
600
700
800
1000
500
100
10km
500Ωm
600
700
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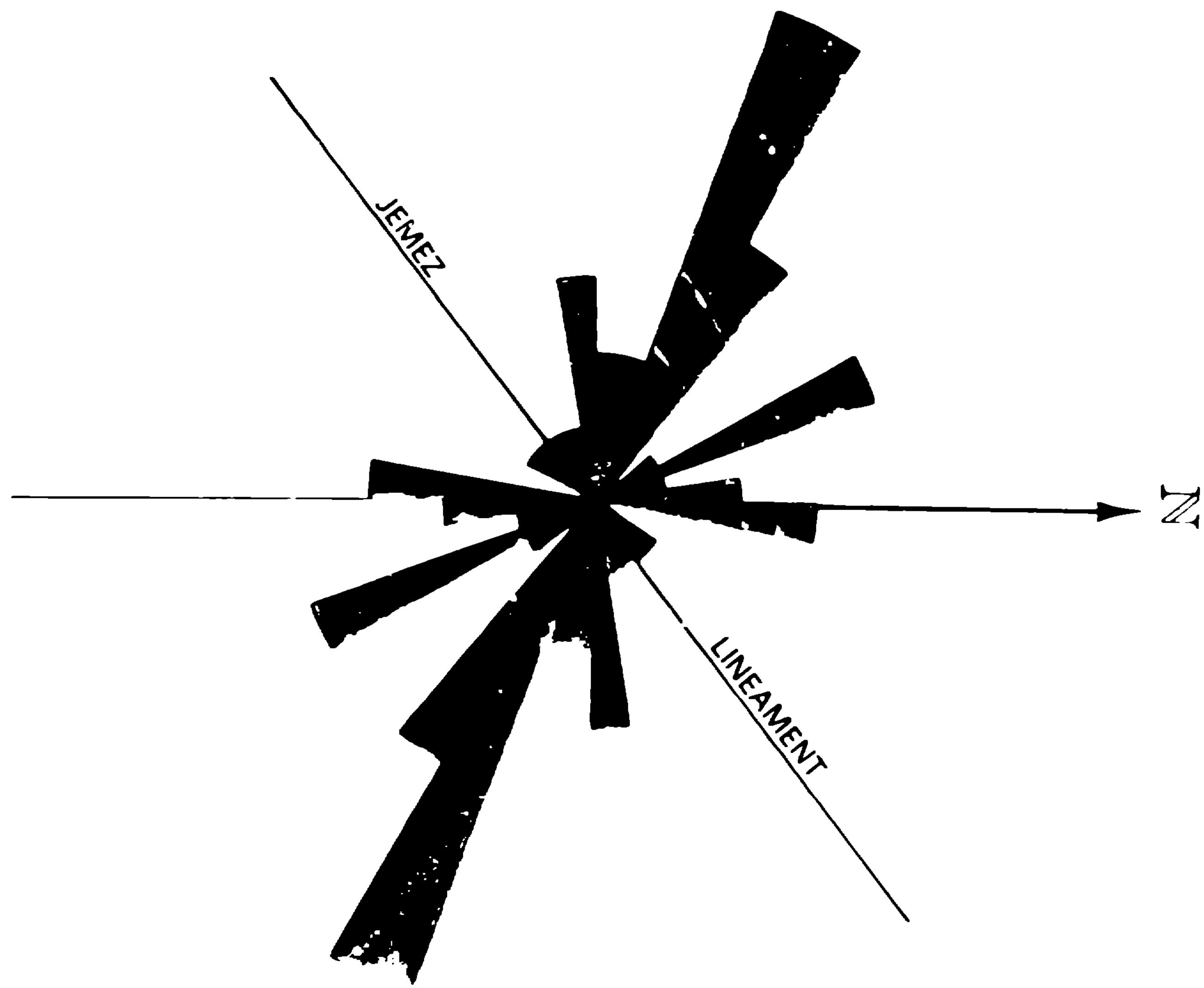
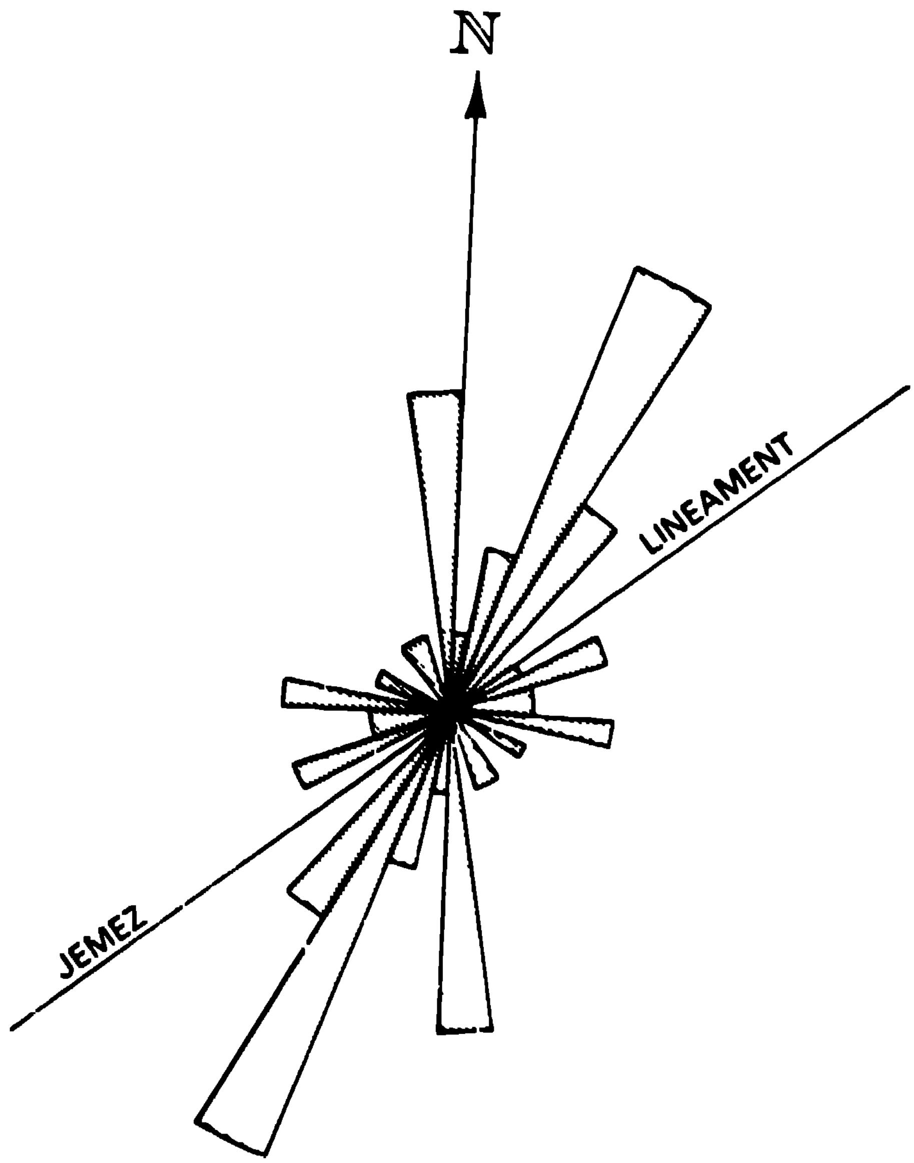
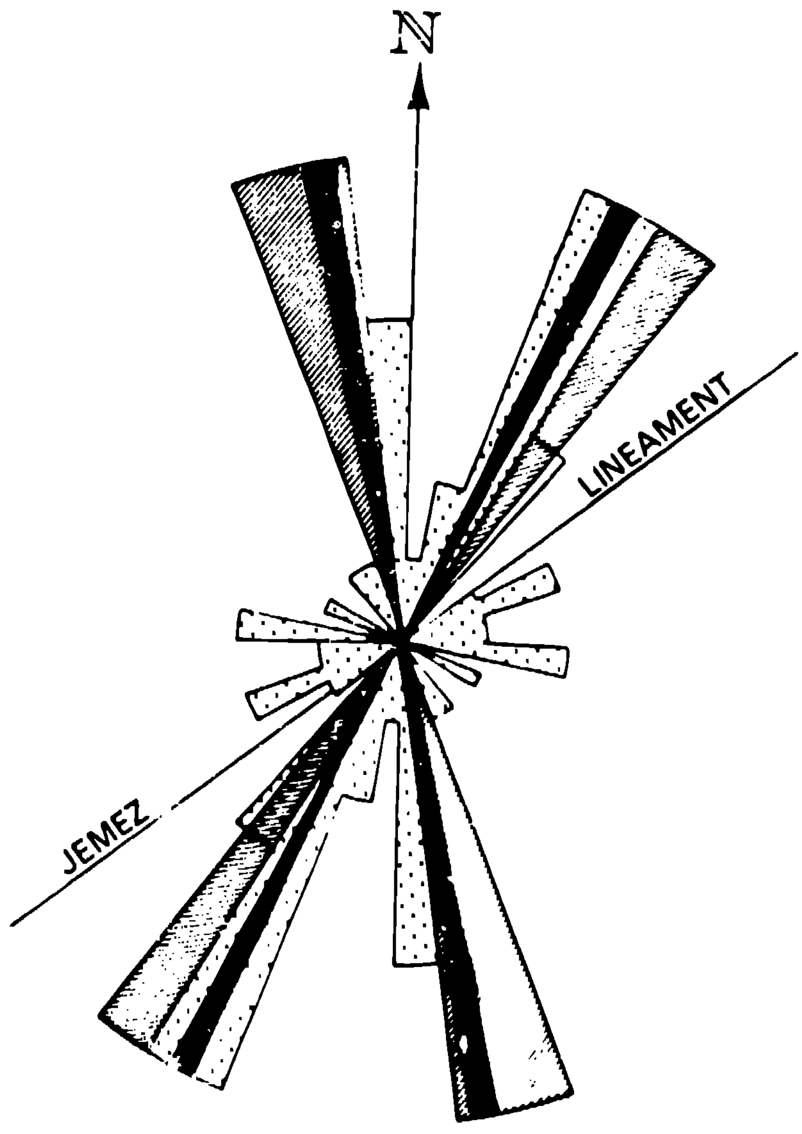
5
25km
70Ωm
30
30
20


JEMEZ
LINEAMENT
N


N
LINEAMENT
JEMEZ


N
LINEAMENT
JEMEZ