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# Determination of Stress Orientation Using Slip Lineation Data in Pliocene Ignimbrites Around Derinkuyu Fault (Nevgehir)

Vedat TOPRAK. Nuretdin KAYMAKÇI
Middle East Technical University. Geological Engineering Department. Ankara-TURKEY

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**Abstract:** Slip lineation data developed on the cooling joints of a Pliocene ignirnbrite sheet are measuremed in the vicinity of Derinkuyu Fault (Nevşehir) to determine the state and the orientation of stresses in the region. The data are taken along three different survey lines in order to improve the reliability of the data as well as to observe the change in the nature of reactivation as a function of distance to the main fault.

The analysis involved in the evaluation of the data to find the stress directions are graphical solutions, namely, the M-plane and P-T dihedra methods. The solutions of the methods have shown that a, is sub-vertical. and $\sigma_2$ and $\sigma_3$ are sub-horizontal ($\sigma_1 > \sigma_2 = \sigma_3$). There is no preferred orientation of reactivation as displayed by the development of slickensided surfaces in all directions. The patterns of the diagrams are consistent in all survey lines indicating that the distance to the main fault is not significant. Therefore, there is not any direct control of the main fault on the development of the reactivation of preexisting cooling joints, but rather the fault is a result of the present state of stress which reflects a typical example of radial stress field.

## Introduction

The main objective of this study is to determine the principal stresses acting during the neotectonic period using a population of the slip lineation data measured in the vicinity of Derinkuyu Fault. in Central Anatolia (Figure 1). All the data are measured from the same ignimbritic sheet which is one of the major volcaniclastic levels within the Urgup formation (Pasquare, 1968). The striated surfaces correspond to cooling joints and, therefore, are pre-existing fractures.

Derinkuyu Fault is considered to be an active fault since (1) it defines the boundary of the Quaternary Derinkuyu Basin deposits, and (2) it cuts Pliocene units of the Ürgüp formation. Development of the striated surfaces within the ignimbrites are contemporaneous with the activity of the Derinkuyu Fault. Therefore, the stresses involved in this study will reflect the nature of the deformation which occurred in Central Anatolia during the neotectonic period.

To achieve the objective of the study, statistical analyses are carried out in the evaluation of the data. During these analyses two graphical methods, namely "M-plane" and "P-T dihedra" methods, are utilized. Both methods require a population of striated surfaces that comprise the attitude of the plane and the slickenside direction.

The M-plane method utilizes the concept of the "movement plane" (Arthaud. 1969; Aleksandrowski. 1985) which is a plane perpendicular to the fault plane oriented in the slip direction. In the application of the method, all the M-planes are found for the data utilized and a "slip-linear plot" is prepared showing location of the maximum principal stress.

The P-T dihedra method (Angelier and Mechler. 1977; Angelier. 1984) basically uses the concept of the fault plane solution in which the boundaries of the pressure (P) and tension (T) areas are defined by the "fault plane" and the auxiliary plane". In this computer-processed method. first P and T areas of each measurement are found, and then a statistical analysis is carried out to find the minimum and maximum concentrations which correspond to maximum and minimum principal stresses. respectively.

The data collected in this study are taken along different survey lines with reference to the Derinkuyu

Fault in order to increase the reliability of the data as well as to investigate the following problems: (1) presence of any preferred direction in the reactivation of the cooling joints. (2) the genetic relationship between the reactivated joints and the main fault and, **(3)** change in the nature of the reactivated joints as a function of the distance to the main fault.

## Geological Setting

The study area is located within the Neogene-Quaternary Central Anatolian Volcanic Province (CAVP). The rock units older than Neogene are considered as the basement rocks in this study (Figure 1). The basement rocks in the area are composed of pre-Tertiary metamorphic and ultramafic rocks.

The CAVP is represented by volcanic rocks and a volcano-sedimentary sequence (Urgup formation) in the region. The volcanic rocks are mostly exposed in the western part of the area and are erupted from major volcanic centers situated to the west of the Derinkuyu Basin (Göncüoğlu and Toprak. 1992). Ürgüp formation (Pasquare, 1968). on the other hand, is composed of lacustrine to fluvial deposits intercalated with various volcaniclastic rocks such as ignimbrites and tuffs (Innocenti et al., 1975; Pasquare et al.. 1988). Radiometric dating from different ignimbritic levels (Innocenti et al., 1975) and paleontologic data from the sedimentary rocks (Şenyürek. 1953; Pasquare, 1968) suggest that the age of the Ürgüp formation is Late Miocene-Pliocene.

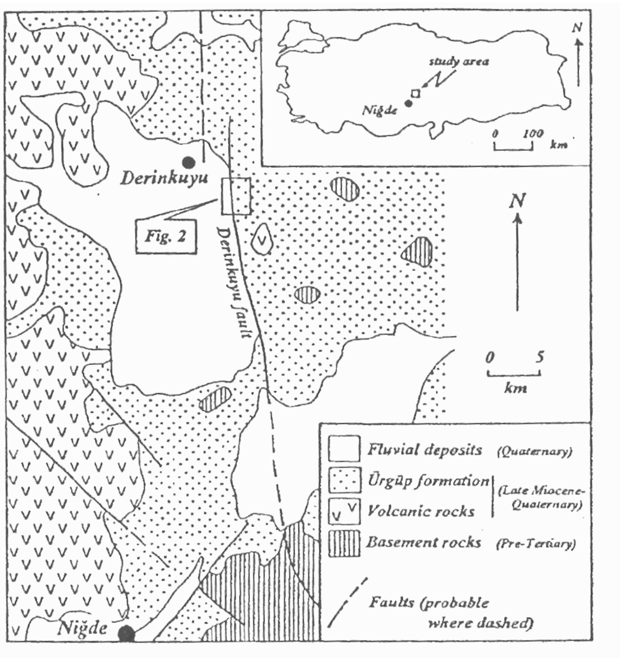



Figure 1. Geological map showing the regional setting of the study area

The ignimbritic unit from which the slip lineation data are collected is known as the "lncesu member" (Pasquare. 1968) or "Kızılkaya ignimbrite" (Batum. 1978). This ignimbrite with a thickness of 10-20 m is nearly a horizontal sheet and covers large areas beyond the limits of the study area between Nevşehir, Kayseri and Niğde (Pasquare. 1968; Pasquare et al., 1988). Radiometric age obtained from the units is 4.4-5.4 m.y. by lnnocenti et al. (1975) and 4.9-5.5. m.y. by Batum (1978).

The ignimbrite within the study area has a thickness of 5-6 m. Due to its resistance to erosion, it forms the caprock in the area. The unit is almost horizontal in the eastern part of the area. whereas it dips west in the close vicinity of the Derinkuyu Fault forming a broad monocline in the region which is attributed to a dragging caused by the activity of the Derinkuyu Fault.

Derinkuyu Fault is one of the major faults within the CAVP (Figure 1) which defines the eastern margin of the Derinkuyu Basin. The fault is oriented approximately N-S, makes a curvature at its southern tip, and strikes to NNW-SSE. It has a continuous scarp of about 20 km with the eastern block being uplifted. The amount of the vertical throw is estimated to be 50 m.

## Data and Analysis

### Type and nature of the striated surfaces

Since the striated surfaces utilized in the study belong to the ignimbrites, the first attempt in the study is towards the recognition of the geometry of these planes to understand whether the planes are reactivated cooling joint or newly formed fractures. For this reason a joint survey was carried out along a corridor **(3** m wide. 1.5 km long) normal to the strike of Derinkuyu Fault (CJ in Figure 2). All the joints (a total of 224) regardless of their nature and type were measured within this corridor. The joints obtained from this survey display typical characteristics of columnar cooling joints (Figure ***3)*** as evidenced by: (1) wide spacing. (2) shape of the blocks (usually tetragonal) bounded by joint planes. (3) almost vertical surfaces. (4) slight curvature of the strike and broad undulations of the surface. and (5) average aperture of 1-2 cm.

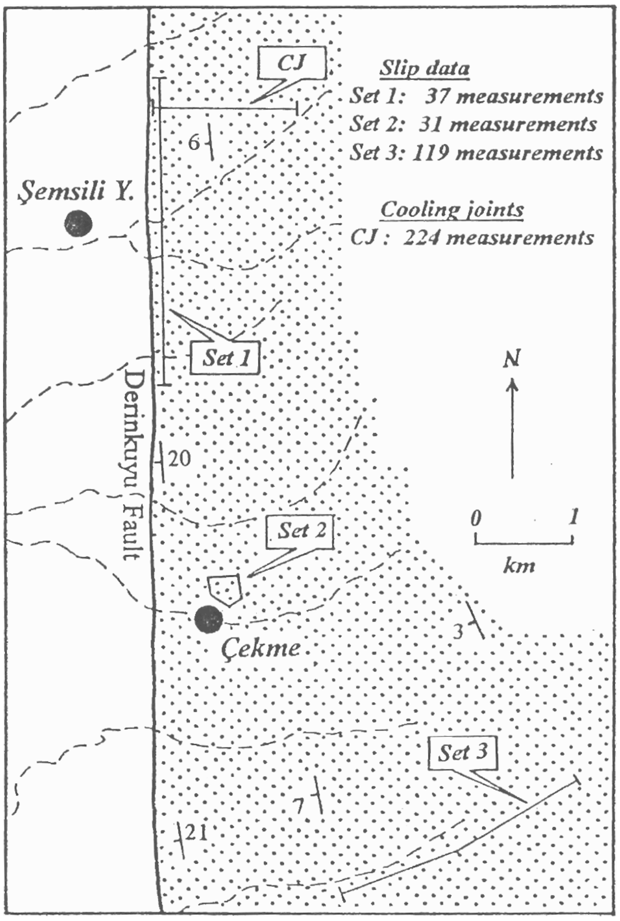



Figure 2. Geological map showing location of the survey lines along which the measurements were taken (lithologies the same as in Figure 1).

The pattern of the rose diagram prepared from this survey also confirm that these planes are cooling joints as indicated by the development of joint planes almost in all directions (Figure 4-A). However, two dominant concentrations are noted in the diagram, namely, N30°-40W with 9.4% and N30°-40°E with 9.8% densities. (Figure 4-A). The dominance of these two directions are also well observed in the planimetric arrangement of the planes in the field (Figure 3).

## General Characteristics of Striated Surfaces

The slip lineation data that belong to the striated joint surfaces were measured at the rock quarries . All the measurements were tested for the reliability of the data with associated mesoscopic features indicating natural movements along the joint planes. Most of the surfaces are characterized by a slight hydrothermal alteration and fibrous calcite growths aligned parallel to

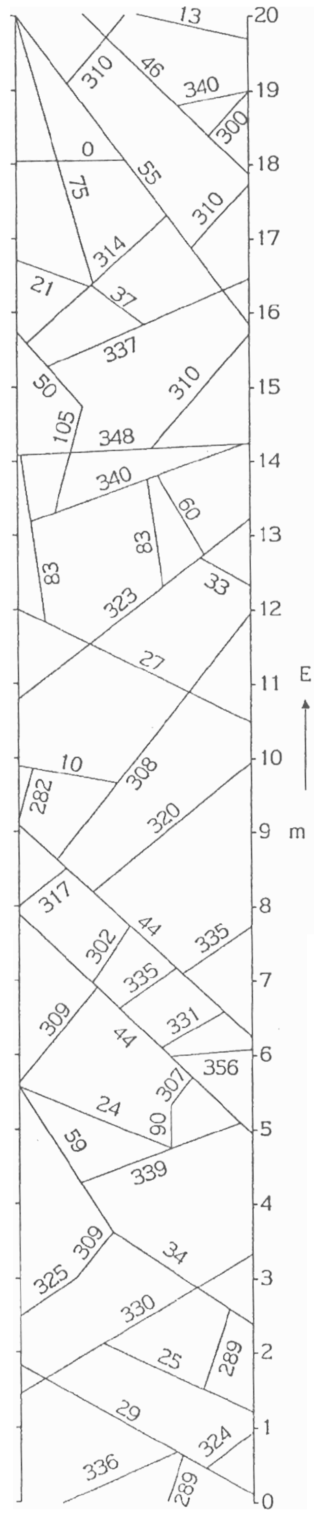



Figure 3. A 20 m long sample of joint survey carried out to determine the dominant directions of the coling joints. Measurements were taken at the upper surface of the horizontal ignimbrite (Numbers refer to the azimuth of the joint planes).

the direction of the movement. Other features frequently observed are mesoscopic faults with the throws of 5-40 cm developed along the joint planes (Figure 5-A), fault steps or shatter marks (Figure S-B). and polished surfaces developed as parallel belts on the undulating joint planes (Figure 5-C).

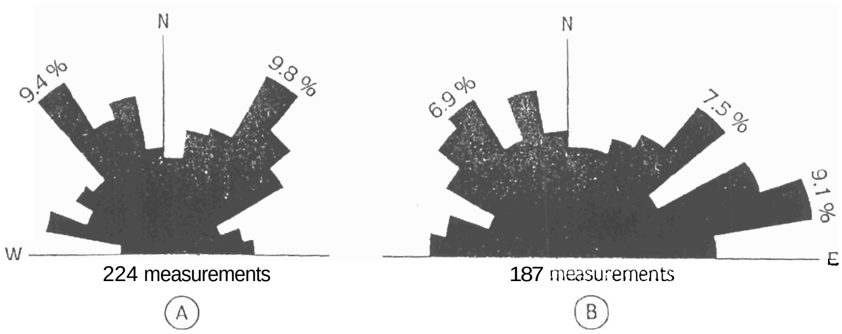
Slip lineation data were measured as three sets along different survey lines (Figure 2). The first set comprises 37 measurements and was taken along a line parallel and close to the Derinkuyu Fault. The second set with 31 measurements was taken from a small circular area at a certain distance from the fault. The third set, with 119 measurements, on the other hand, was collected along a line almost normal to and away from the fault (Figure 2).

All the data measured indicate a normal (gravity) type of movement. There is not any field indication of the reverse movement. A few high angle reverse striated planes are encountered in the close vicinity of the Derinkuyu Fault. The bedding plane. however, at these localities dips by an amount of more than 25°. Therefore, the reverse character of these surfaces is attributed to the rotation of the joint planes due to dragging caused by the main fault. For this reason, such data are considered to be of normal type in the graphical solutions and no rotation is involved in the analysis.

The first step in the analysis of the slip data is the comparison of the dominant directions of the striated surfaces with the directions of the cooling joints. The rose diagram prepared from 187 striated measurements (Figure 4-B) indicates that there are at least five major directions along which movement occurs. A careful analysis of these surfaces shows that all the dominant directions exist in the pattern of the cooling joints although some of these directions are more emphasized during reactivation (e.g., N60-80E and N70-90W). Therefore. all the striated surfaces correspond to pre-existing joint planes indicating that new planes are not formed during later tectonism. This is also approved by the absence of any field observation implying joints of tectonic origin.

The nature of the slip surfaces is investigated by the density diagrams of the joint planes prepared for each set separately (Figure 6). Although there are slight differences in the patterns of three sets (Figure 6. A, B and C. respectively) they have the following common points: (1) all the sets comprise steep to vertical striated joint planes. (2) all sets have at least five dominant concentrations that resemble the rose diagram prepared from all measurements (Figure 4-B). and (3) none of the concentrations has a value greater than 7-9%. The pattern obtained from all data gives a better picture of the nature of striated surfaces (Fig-

Figure 4. Rose diagrams prepared from the cooling joints (A) and striated surfaces (B).



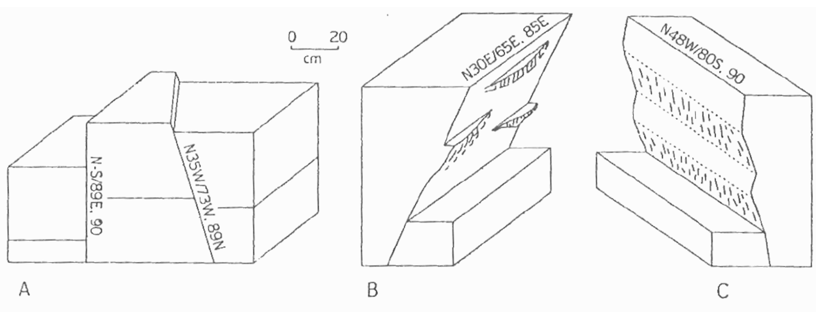




Figure 5 Block diagrams showing various mesoscopic structures developed at the striated surfaces (A: mesoscopic faults. B: fault steps. C: polished surfaces).

ure 6-D). This diagram. although **it** has a differential weight of three sets because of the number of measurements. suggests that there are not well-defined concentrations in certain directions. The striated surfaces are developed almost in all directions with a maximum concentration being not more than 3-5%.

The density diagram of the slip data has been prepared from the striated surfaces to understand the nature of the slip in the striated surfaces (Figure 7). The diagram displays a uniform distribution of the slip data with a maximum concentration of 16-18 % at 80/096N. This sub-vertical concentration indicates that the movements are of dip-slip type and the lateral movements along the surfaces are negligible.

**Stress Analysis**

Two graphical methods are utilized in this study to find the stress orientations in the area. These are M-plane and P-T dihedra methods. Both methods require a certain population of slip lineation data to localize the principal stresses.

The basic concept of the M-plane method (Arthaud. 1969: Aleksandrowski. 1985) is summarized in Figure 8. The "M-plane" is a plane which is perpendicular to the fault plane and includes the direction of the slickenside (Figure 8-A). In the stereographic plot, the M-plane. is represented by a great cricle that passes through the pole of the fault (P) and the slip lineation (S) (Figure 8-B). This plane comprises the maximum ($\sigma_1$) and minimum ($\sigma_3$) principal stresses. The M-planes drawn for 187 measurements are illustrated in Figure 9. With the exception of a few gently dipping planes. almost all the M-planes are vertical to sub-vertical. intersecting at the center. This common intersection point usually indicates the location of $\sigma_1$ (Aleksandrowski. 1985).

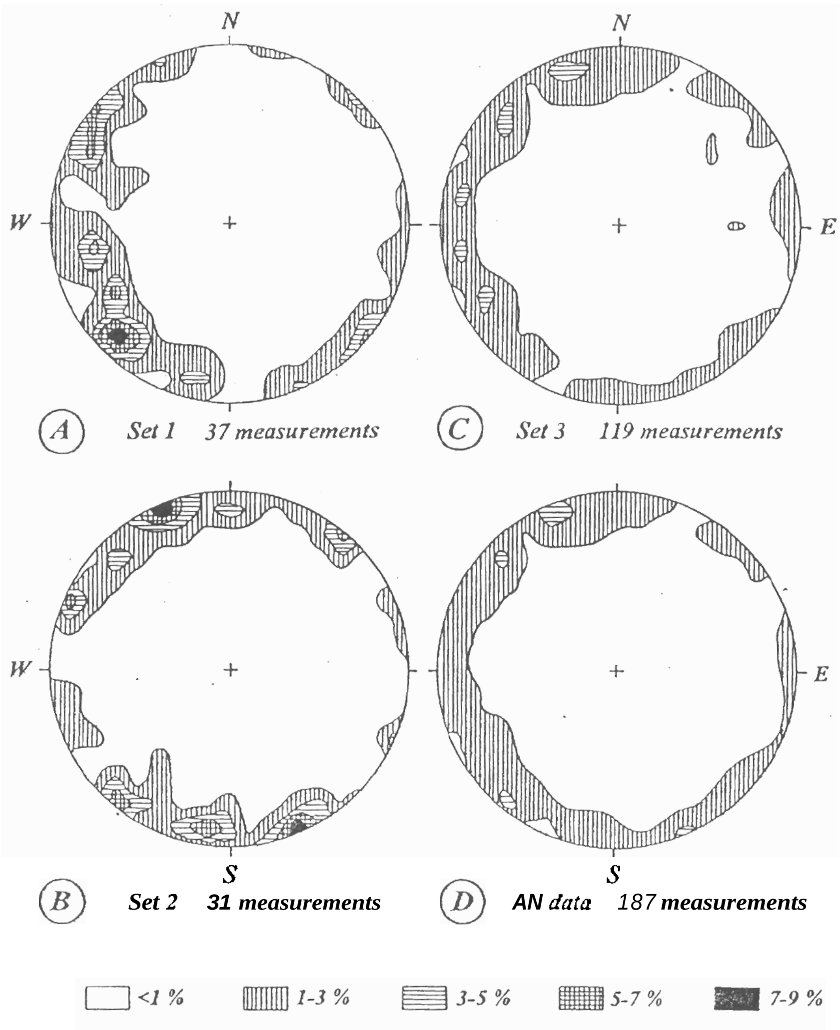



Figure 6. Density diagrams prepared from the poles of striatedjoint planes.

In the application of the method, the M-planes can be handled in several ways to find the stress orientation. The slip-linear plot is the simplest way to evaluate the data. This plot is composed of arrows drawn along the M-plane pointing in the direction of the movement. The arrow could be located at the fault pole (P) towards $\sigma_1$ or at the slip lineation (S) towards $\sigma_3$

In the slip-linear plot prepared for this study, the arrows are located at the poles of the fault planes (Figure 10); therefore. they point the location of the $\sigma_1$. The output produced from this plot has an inward radial pattern. With the exception of a few points at the periphery. the great majority of the data point to the center of the stereograph suggesting that $\sigma_1$ is located at the center (vertical). and $\sigma_2$ and $\sigma_3$ at the periphery (horizontal). However, since the striated surfaces used in the diagram are steeply dipping planes. the central part of the plot does not contain enough data to locate the principal stresses accurately.

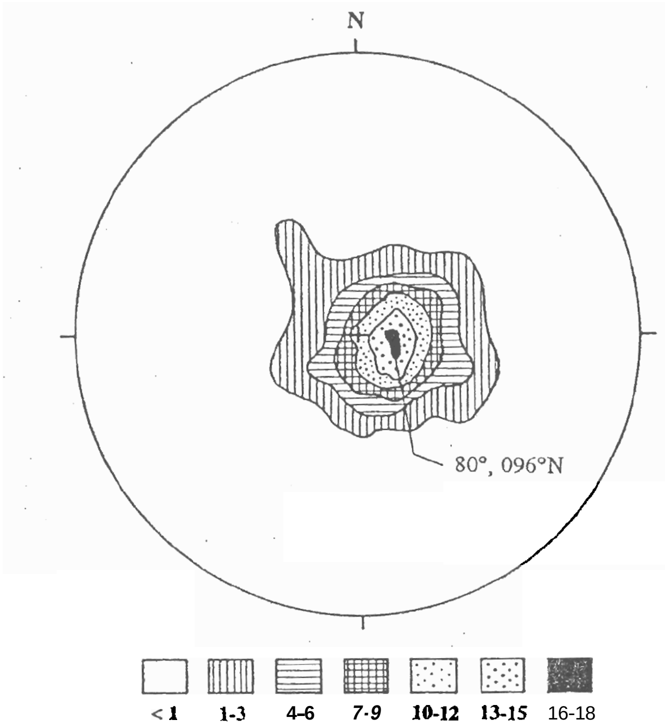



Figure 7. Density diagram prepared from the slip lineations (rake and direction) measured in the area.

For a precise location of the principal stresses. the slip data were processed for the P-T dihedra method (Angelier and Mechler. 1977; Angelier, 1984). According to the numerical output (Figure 11-A) the minimum concentration which corresponds to $\sigma_1$ with a value of 0 % is almost at the center. The maximum concentration ($\sigma_3$). on the other hand, with a value of 79 % is located at the western part of the periphery. After contouring the numerical output. the following values were obtained for the principal stresses (Figure 11-B): $\sigma_1$: 86.347N. $\sigma_2$: 04. 176N. and $\sigma_3$: 00.266N. The pattern of the contours suggests that there is not much difference between $\sigma_2$ and $\sigma_3$. This is also indicated by their close numerical values of 72% and 79%. respectively. $\sigma_2$ is parallel to, and $\sigma_3$ is perpendicular to the strike of the Derinkuyu Fault.

## Discussion and Conclusions

### Stress Orientation

Orientation of the principal stresses are found using two graphical methods. The first method (M-plane method) roughly localizes the maximum principal stress ($\sigma_1$) and gives and idea about the stress regime in the region (Figure 10). According to the solution by this method, $\sigma_1$ is at the center of stereonet, indicating a vertical orientation. However, since the data are

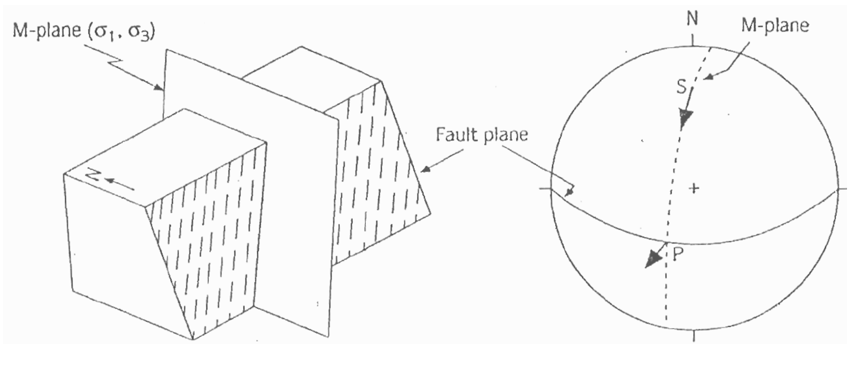



Figure 8. A:Block diagram showing the M-plane of a fault plane. B: Stereographic plot of (A). Note that M-plane contains the pole of the fault (P) and the slip lineation (S)

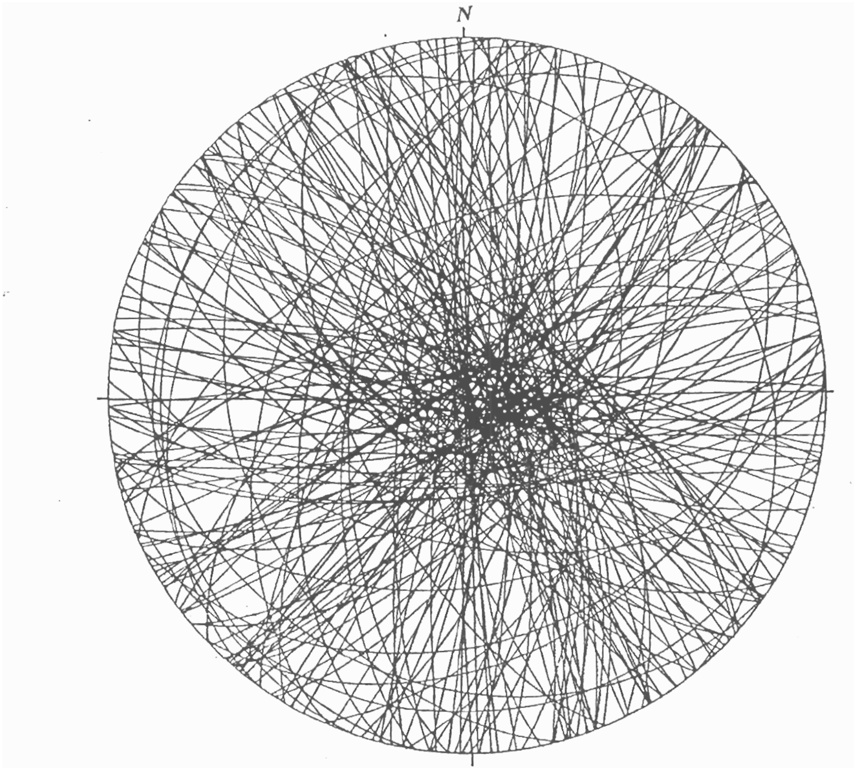



Figure 9. M-planes prepared from 187 striated planes measured in the study area.

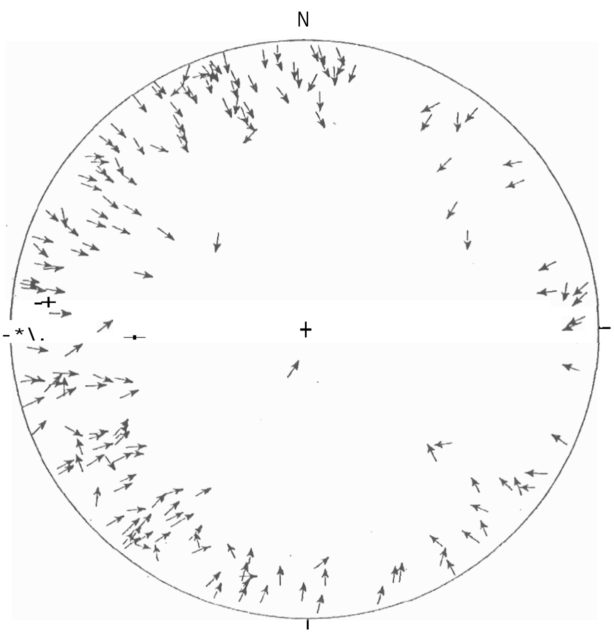



Figure 10. Slip linear plot of the striated surfaces. Arrows are located at the pole of the fault planes arid being parallel to the M-plane. point to the direction of the movement.

measured from steep surfaces, most of the arrows are confined to the periphery of the stereonet and a sensitive location of the $\sigma_1$ could not be possible. The pattern obtained from this method is a typical example of radial stress field (Alexsandrowski, 1985) with C being equal to or greater than 10 where C = $(\sigma_1-\sigma_3)/(\sigma_2-\sigma_3)$. In such a stress field. $\sigma_2$ and $\sigma_3$ are expected to be almost equal to each other.

The principal stresses are accurately determined using the second method, the P-T dihedra method (Figure 11). According to the solution obtained from the output of this method. all the 187 measurements consistently indicate that the minimum concentration (here maximum principal stress) is very close to the center of the stereonet with a density of 0 %. This point corresponds to 86. 347N. The maximum concentration ($\sigma_3$) with a density of 79 % is at 00,266N. Accordingly. $\sigma_2$ is at 04. 176N with a density of about 70%. Similar densities of $\sigma_2$ and $\sigma_3$ confirm that these two principal stresses have close values or are equal to each other. The circular pattern of the contoured densities also indicates that it is difficult to make an obvious distinction between the locations of $\sigma_2$ and $\sigma_3$ (Figure 11-B). There is a slight elongation in the contours in the N-S direction which is almost parallel to the Derinkuyu Fault.

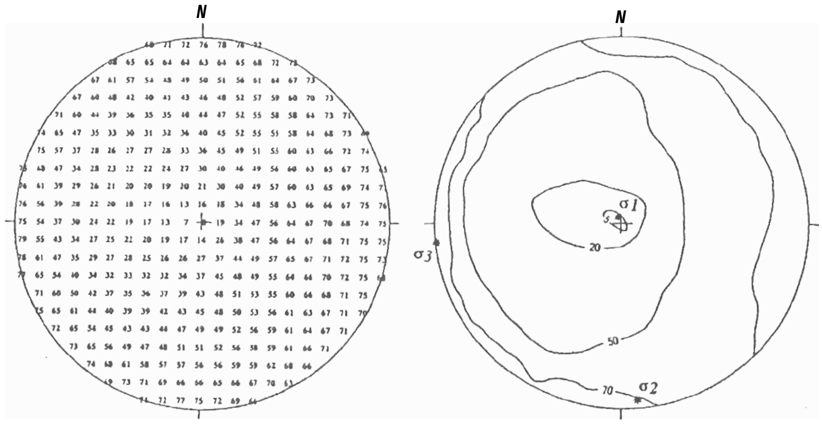



Figure 11. Result of the P-T dihedra solution. A: Numerical output. B: Contoured plot showing locations of the principal stresses ($\sigma_1$: $\sigma_2$: $\sigma_3$)

The density diagram of the slip lineation data (rake and direction of slickensides) gives a uniform distribution with a maximum concentration at 80, 096N (Figure 7). This point coincides with the poles of bedding planes which dip westward and increase in the close vicinity of the Derinkuyu Fault. This is because the eastern block of the Derinkuyu Fault forms a broad monocline due to the dragging of the fault. Therefore. the joint planes together with the bedding planes are rotated by an amount ranging from a few degrees up to 20 (Figure 2). If the slickensides (80. 096N) are also rotated in accordance with the westerly dipping strata, the maximum concentration will approve that the movement along the joint planes is basically dip-slip.

## Reactivation of the Cooling Joints

Slip lineation data measured in the area belong to the reactivated cooling joints developed within an ignimbrite. No field evidence was noticed during the measurements, indicating that these fractures are newly formed discontinuities. The geometric pattern of the joint planes also displays typical characteristics of cooling type (Figure 3). The cooling joints are dominantly developed in two directions. namely N30-40W and N30-40E (Figure 4-A). During the reactivation of these joints, on the other hand. one of the directions which is not obvious in the cooling joints (N60-80E. Figure 4-B) is over-emphasized. This direction is almost parallel to the direction of $\sigma_3$ and normal to the major fault. Therefore, under the present stress regime, the joints in this direction are preferred to reactive although they are less frequent.

The stress field and the resultant structures observed in the area are illustrated in Figure 12. The number of striated surfaces (five in the figure) is random and can be more or less than this. This configuration is the interpretation of the results of the graphical solutions as well as the field evidences which are as follows: (1) All the striated surfaces with different attitudes indicate a normal movement as displayed by mesoscopic structures (Figure 5) and slip-linear plot (Figure 10). (2) Statistical analysis of the slip lineation data indicates that the movements are dominantly dip-slip and the lateral movements are negligible (Figure 7). Although a few strike-slip movements also occur in the area (e.g., the arrows parallel to the periphery in Figure 10). these are attributed to the local rotations that occurred within ignimbrites which are composed of columnar tetranonal blocks bounded by cooling joints. (3) Since the striated surfaces are steep planes with dip-slip movement. the M-planes of these surfaces are also expected to be steep to vertical planes. Therefore. all the M-planes intersect at a common point that corresponds to o,.

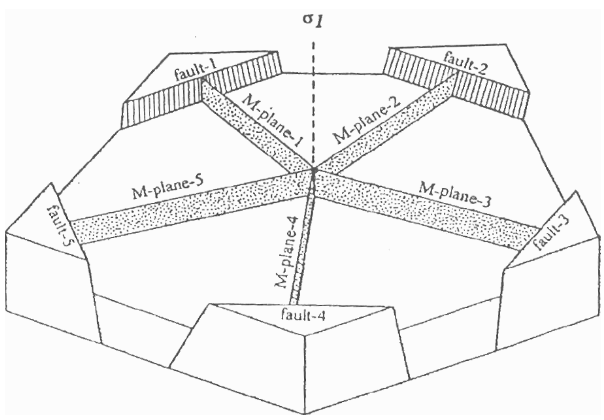



Figure 12. Schematic block diagram showing development of normal faults under radial stress conditions Number of the surfaces given in the figure is random and they correspond to the reactivated joint planes in the study area.

The nature of the reactivation does not have any relationship with the distance to the main fault. The patterns of the different sets of the striated surfaces measured at different sites have several common features (Figure 6). This implies that the direction of the Derinkuyu Fault is not an obvious determinative factor in the development of the striated surfaces, but rather the fault itself is a result of the present state of stress in the region.

## Regional consideration

The principal stresses found in this study reflect the nature of deformation in central Anatolia during Plio-Quaternary because: (1) the ignimbrite which hosts the striated surfaces is of Late Miocene-Pliocene in age, and (2) the major Derinkuyu Fault is an active fault since it defines the boundary of the Quaternary Derinkuyu Basin.

Although the Derinkuyu Fault carries some evidence for the right-lateral. strike-slip movement as noted by the bending of streams and a few slickensides this observation is not approved by the statistical analysis of the striated surfaces. The dip-slip normal nature of the Derinkuyu Fault suggests the presence of an extensional regime which is opposed to the current idea of a N-S compressional regime in the region.

## Acknowledgement

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