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DISTINGUISHING TECTONIC JOINTS FROM COOLING JOINTS IN THE BANDELIER TUFF (PLEISTOCENE), PAJARITO PLATEAU, LOS ALAMOS COUNTY, NEW MEXICO

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Abstract—Most of the Bandelier Tuff's joints were produced by cooling after an ash flow or a series of ash flows was emplaced. The Los Alamos National Laboratory's (LANL's) waste management operations are primarily conducted on or in the fractured Bandelier Tuff, which crops out on the Pajarito Plateau near the western boundary of the Rio Grande rift. Cooling joints, in a semi-arid climate, may be of limited concern as potential contaminant migration pathways because of their restricted horizontal and vertical extent. Tectonic joints, however, could represent pathways for contaminants to reach surface water and/or ground water. In the Bandelier Tuff, almost all joints (both cooling and tectonic) are vertical or near-vertical. Joint data from pits at Materials Disposal Area G, TA-54, have azimuths that appear to have random distribution. If tectonic joints have preferred orientation, then cooling joints must behave as if they have random orientation. A statistical method was used to differentiate between joints with random orientation and joints with preferred orientation. It is inferred that the joints with preferred orientation are tectonic. No evidence was seen that cooling joints (at any given location or plateau-wide) have preferred orientation. Over 3000 joint measurements were made at 18 locations. Composite data show statistically-identified trends of N 20°-29° E, N 1°-10° W, and N 71°-80° W. This joint study was part of LANL's Program A415, Waste Disposal Sites Studies, a program to satisfy research needs for waste management operations and to establish site-specific monitoring systems.

INTRODUCTION

Los Alamos National Laboratory (LANL) is located on the Pajarito Plateau which flanks the eastern side of the volcanic Jemez Mountains in north-central New Mexico (Fig. 1). Joints represent a potentially important waste migration pathway at LANL materials disposal areas on the plateau. All waste disposal pits and shafts are excavated in the upper (Tshirege) Member of the rhyolitic Bandelier Tuff. The Tshirege and underlying Otowi Members of the Bandelier were deposited during caldera-forming eruptions in the Jemez volcanic field. Both members have a basal air-fall pumice followed by a series of ash flows (Bailey et al., 1969). The Bandelier contains numerous joints of cooling and tectonic origin. The semi-arid climate (approximately 18 in. of precipitation annually) reduces the impact the joints might have as a contaminant-migration pathway. However with time, contaminant migration through joints could contaminate surface and/or ground water. Tectonic joints are of more concern than cooling joints because they cross unit (depositional) boundaries and shorten the distance to canyon walls; they represent a faster pathway to both surface and ground water. Fieldwork for the purposes of distinguishing between tectonic and cooling joints was performed in 1977 and 1978. A draft report was prepared and reviewed in 1978 for publication by LANL. Reviewers' comments prompted a re-evaluation of the discriminating statistical test, the mean plus 2 standard deviations. The suggested χ^2 Test was applied, with mixed results, to the locations identified in the draft report with statistically significant trends. Because the number of joint measurements necessary to perform a valid χ^2 Test was unknown, joint data were arbitrarily doubled at those locations which failed the χ^2 Test or had trends identified at the 90% confidence level. The results of applying the χ^2 Test to the new joint data set were presented by Rogers and Christie (1980). The following report is a reexamination of this previous work.

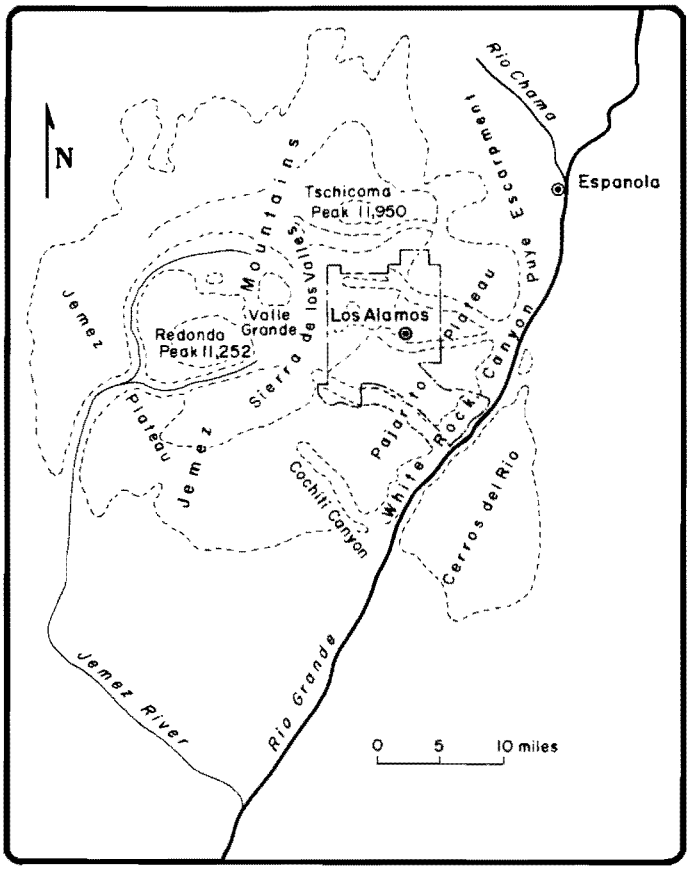

FIGURE 1. Map showing general geography of the Jemez Mountains area.

BACKGROUND

For several years prior to 1977, joint data were collected as part of mapping the walls of each new pit at Materials Disposal Area G, Technical Area (TA)-54. The rectangular pits are cut in Unit C (Rogers and Burton, 1980; Rogers, 1995) of the Tshirege Member of the Bandelier Tuff. For every joint in each wall, strike, apparent dip, and surveyed location were recorded. Fractures that did not reach either the bottom or the top of the wall were not recorded. Very rarely could a joint be traced with certainty from one wall to the other, a vertical distance of 25, 30, 50 or 100 ft. Joint spacing (or frequency) in pits was approximately 1 every 6 ft. At the edge of the mesa (in the canyon walls), joint spacing was notably closer. Because joint dips are predominantly nearly vertical, joint data were generally presented as rose diagrams.

Trend on rose diagrams shows the preferred joint orientation was strongly influenced by the orientation of the long axis of each pit (Fig. 2). Joint azimuths clustered in an ~90° arc centered orthogonally to the pit axis. North-south trending pits showed preferred joint orientation east-west; east-west trending pits showed preferred joint orientation north-south; and northwest-southeast trending pits showed preferred joint orientation northeast. An overlay, produced by stacking rose diagrams of data from pits with different orientations, showed an almost uniform distribution of joint azimuths. This seemingly random distribution of joints led to the conclusion that most, if not all, of the fractures were cooling joints (Purtymun and Kennedy, 1971). However, location of the plateau

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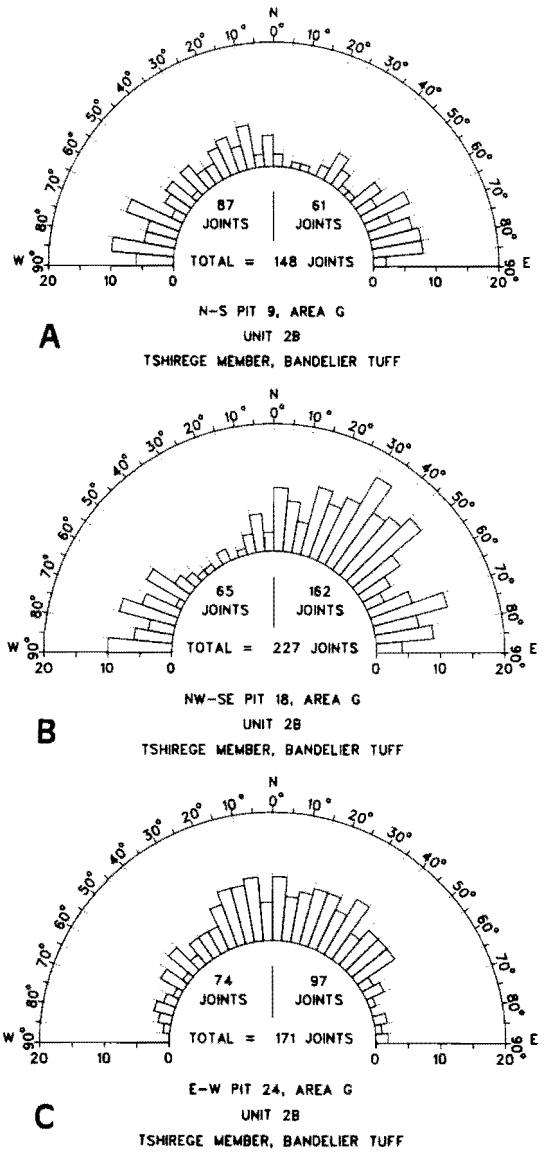

FIGURE 2. Examples of joint trends that are strongly influenced by the orientation of the transect, in this case the long axes of Materials Disposal Area G, TA-54 pits. A, Pit 9 is oriented north-south. B, Pit 18 is oriented northwest-southeast. C, Pit 24 is oriented east-west.

on the western edge of the Rio Grande rift suggested that some joints were the result of regional structure.

In the Bandelier Tuff, a clearly identifiable cooling joint is nonplanar. The strike is sinuous over distances of < 10 ft and the face is alternately convex and concave in vertical and horizontal directions. Iron-staining (ranging in hues from yellows-oranges-browns to pinks-reds-purples-black) is frequently present. A cooling joint may intersect, but more often terminates at, other joints. Cooling joints commonly form irregular polygonal columns with diameters of a few feet to more than 10 ft.

Textbook-classic, hexagonal columnar jointing produced by cooling stresses is rarely seen in the Tshirege Member on the Pajarito Plateau. It is restricted to some outcrops of unit B and unit C (Rogers and Burton, 1980; Rogers, 1995) along the eastern edge of the plateau near the Rio Grande.

On the western side of the plateau near the Pajarito fault zone is another type of fracturing interpreted to be the result of cooling stresses. The jointing is closely spaced (1–3 in.), horizontal to subhorizontal, discontinuous (<10 ft on vertical outcrop), nonplanar fracturing restricted to Unit E (Rogers and Burton, 1980; Rogers, 1995) in an approximate 0.5 mi band on either side of the fault zone. This type of fracturing may be present in unit E from here westward to the caldera, but is absent in units above and below unit E.

The Tshirege Member of the Bandelier Tuff is a compound cooling unit; therefore, the basal air-fall pumice and subsequent ash flows do not have a common cooling history (Smith, 1960). From bottom to top, units A, B, C, D, E and F (Rogers and Burton, 1980; Rogers, 1995) divide the ash flows in the Tshirege (Fig. 3). Although all units are separated by flow boundaries, none of the units may represent a single flow. Cooling joints in the tuff are confined to that ash flow or series of ash flows that cooled at a given time. Some units have a noticeably greater number of joints. Also, some units show lateral and vertical changes in jointing style.

A dramatic and easily observed example of jointing-style changes occurs in unit B. Near the Rio Grande, the base of unit B may show classic columnar jointing while the upper part shows the more irregular, widely-spaced polygonal jointing. As the unit is traced westward, the classic columnar jointing at the base becomes progressively more undefined and irregular until there is no distinction between the upper and lower parts. Where classic columnar jointing exists, it is difficult to trace a cooling joint from the upper part of unit B down into the lower part.

Upward propagation of cooling joints within and between units is infrequent in the Tshirege Member on the plateau. At any given outcrop, the exposed units show no systematic variation in joint frequency from bottom to top of section. Therefore, when a joint is planar and cuts more than one unit, it is more likely to be tectonic in origin.

Preferred orientation of cooling joints is unlikely. Beneath the plateau, the Bandelier Tuff rests on partially consolidated sediments assigned to the Santa Fe Group (Galusha and Blick, 1971) or the Puye Formation (Bailey et al., 1969). Near the Rio Grande the tuff may rest on the basaltic rocks of Chino Mesa (Griggs, 1964). The lower part of the Bandelier Tuff section is largely unindurated. This includes the basal Guaje pumice bed and overlying ash flows of the Otowi Member (Bailey et al., 1969), the interbedded Cerro Toledo Rhyolite tuffs (Smith et al., 1970), and the basal Tsankawi pumice bed (Bailey et al., 1969) and unit A of the Tshirege Member. This 100+ ft section of unindurated tuffs rests on unconsolidated sediments. Upward propagation of joint trends, from the sediments to the tuffs, would not be expected and is not observed in the field. Upward propagation of basalt jointing is not observed in the tuffs either.

Another possibility for preferred orientation of cooling joints is buried topography. The unconformity at the base of the Tshirege is only locally exposed on the plateau. If the exposures in Pueblo Canyon (Fig. 4) are representative of the pre-Tshirege surface, then (over most of the plateau)

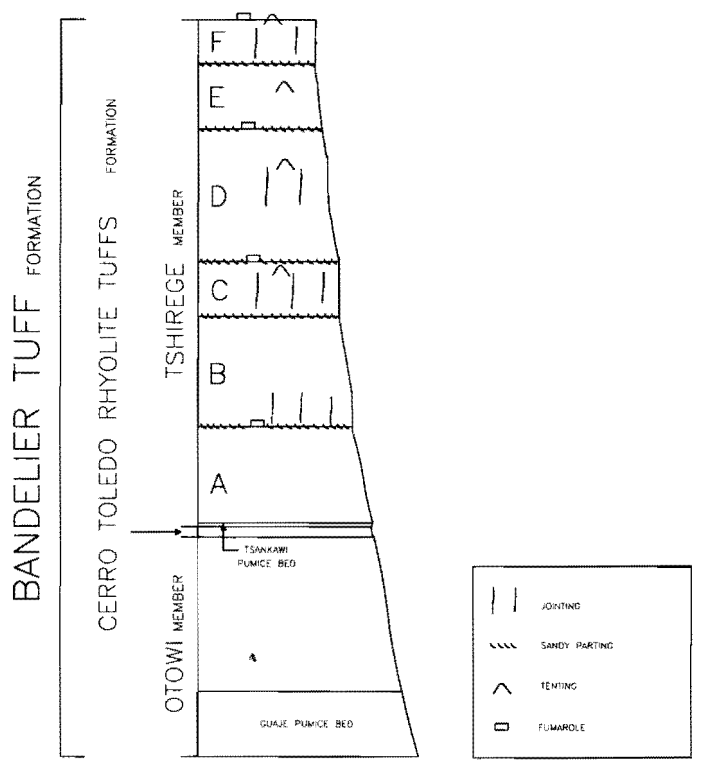

FIGURE 3. Idealized section of Bandelier Tuff, Pajarito Plateau.

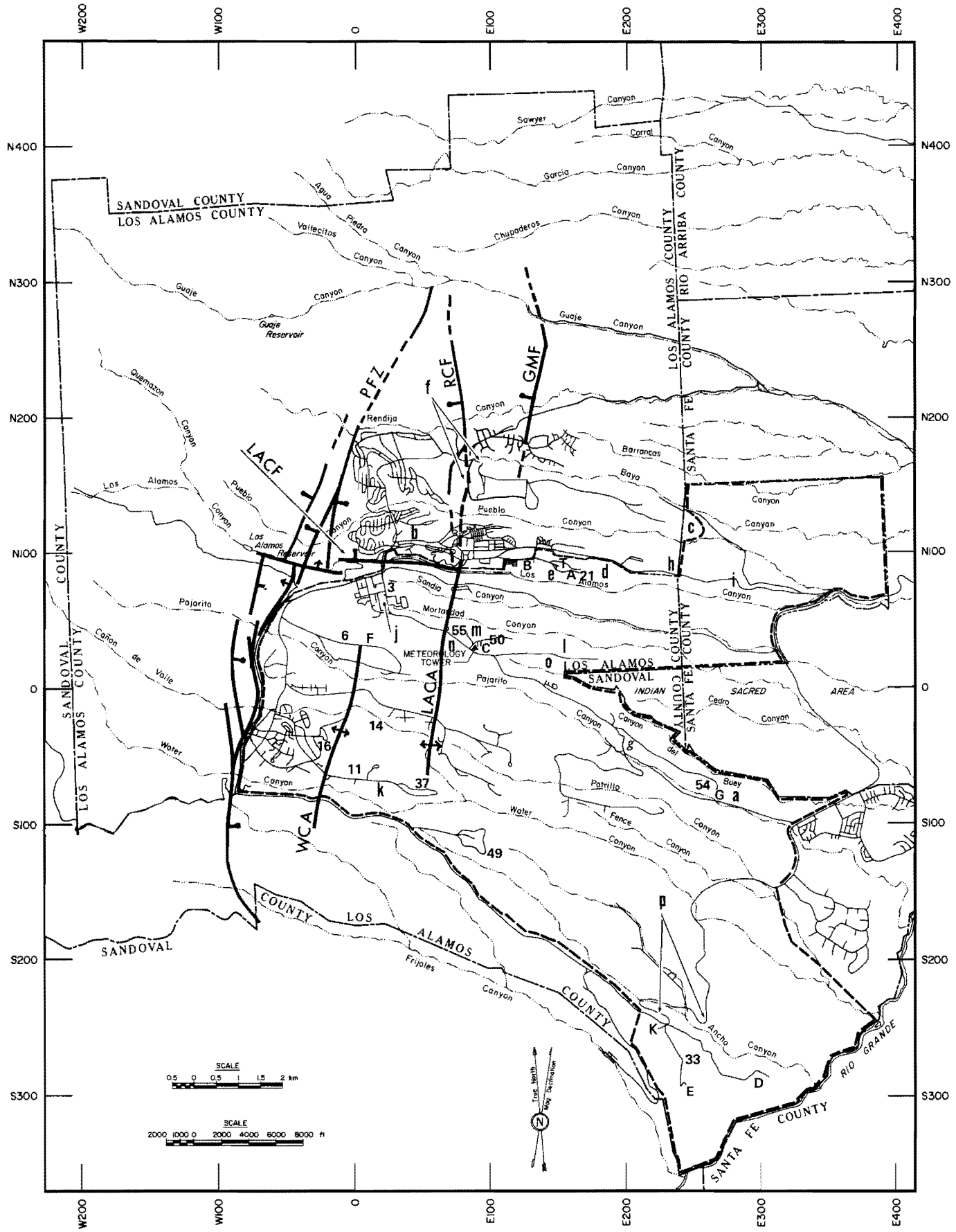

FIGURE 4. Map showing joint data locations (lower case letters), LANL materials disposal areas (upper case letters), LANL Technical Areas (numerals) and labeled faults and structures in the Los Alamos area. PFZ = Pajarito fault zone; RCF = Rendija Canyon fault; GMF = Guaje Mountain fault; LACF = Los Alamos Canyon fault; WCA = Water Canyon arch; LACA = Los Alamos Canyon arch.

there is very little relief on that surface. The unindurated base of unit A easily fills the gently undulating surface. To affect cooling joint orientation at the top of unit A, the effects of the underlying surface would have had to penetrate up to 140 ft of unindurated to very slightly indurated tuff. Unit A is assumed to have cooled more quickly from the top down than from the bottom up. The thickening and thinning of unit A across the pre-Tshirege surface produces no lithologic changes in the unit.

Near the Rio Grande, north and south of Ancho Canyon, is a buried paleo-canyon system. Unit A appears to have flowed over and down canyon walls rather than down a canyon axis. In Ancho Canyon, the flow boundary between units A and B is easily identified on the sides and in the bottom of the re-excavated paleo-canyon. Unit B filled the paleo-canyon system. Deposition of units C and D was completely unaffected by it. Unit A jointing would be the most influenced by rapidly-changing cooling stresses set up in a flow draped over the walls and covering the bottom of a canyon. The cooling stresses set up in the canyon-filling unit B would be different from those in unit A. In lower Ancho Canyon, neither unit A nor unit B appear to propagate more joints upward than they do elsewhere on the plateau. At any point in unit A or B outcrops, the cooling joints would have a very localized preferred orientation influenced by the underlying topography at the time of deposition. Such preferred orientations of cooling joints, seen in today's canyons walls, would not produce trends of any significance.

In most cuts (ditches, trenches, shafts, pits, roadcuts) low-angle to horizontal fracturing is seen to a depth of ~ 5 ft below ground surface. These fractures are neither cooling joints nor tectonic joints, but are produced by physical and chemical weathering. Tree roots initiate the fracturing. On a fresh cut, close examination over 10-30 ft reveals all stages of fracture development from small roots that appear to penetrate fresh tuff to large roots with significantly expanded fractures. The majority of these fractures are clay-filled. Microscopic examination of fracture margins show that delicate rock structures extend from unaltered tuff into the clayey material of the fractures without geometric disruption (Renault, 1977). Some fractures that are not filled with clay are the product of bulldozers, backhoes, and bucket-augers with attached reamers. LANL waste management operations has never had a policy allowing disposal in excavations 5 ft deep or excavations to be filled with waste to ground level.

Field observation shows cooling joints to be more numerous than tectonic joints. Detailed geologic mapping of the LANL Reservation (Rogers, 1995) revealed some small-scale faulting with displacements of 3–20 ft, but more faulting was expected given the proximity of the major Pajarito fault zone. Rogers' mapping on the Edwards Plateau in Texas, beginning at the Balcones fault zone and moving westward some 10 mi, revealed systematic small-scale faulting (Rogers, 1969; Garner et al., 1976). The absence of systematic small-scale faulting and lack of clearly identifiable tectonic joints seems to argue that cooling joints probably released some tectonic stresses that existed prior to, or resulting from or after eruption. Geologic field evidence shows displacements along some cooling joints of 1–12 in.

METHOD

Locations

Because data from disposal pits, utility ditches, and straight roadcuts tended to show directional bias, locations were sought on mesa tops, with little soil cover, for this study. Furthermore, they were chosen on the basis of proximity to LANL materials disposal areas and/or on the basis of good geographical coverage of the plateau in the Los Alamos area. One location, *f*, was chosen because it was along the trace of the Los Alamos fault (Budding and Purtymun, 1976), renamed Rendija Canyon fault by Dransfield and Gardner (1985).

Measurements

Joint strike was measured with a Brunton compass at each location. The minimum number of measurements was 75. Distances over which measurements were taken varied from 0.2 mi to 0.8 mi.

Joint data collected for this study did not include dip measurements. Measuring dip is largely impractical whether on a mesa top or in vertical cuts. Very rarely do joint faces weather in relief on mesa tops and vertical cuts are relatively smooth-surfaced also. Most joints to a depth of ~35 ft are filled with soil, caliche, or clay. Any dip or strike data collected from canyon walls could not be treated as accurate because of mass wasting movements. In the pits at Area G, every effort was made to get true-dip measurements. Since these measurements were made 25–30 ft below ground surface it was sometimes possible to insert a map case into an open fracture.

Observation plus previous work in the pits and elsewhere show the majority of the joints to be nearly vertical. In any data set, the mode for dip measurements is 90°. Composite data for 412 joints from 6 locations show 38% dip 90°, 76% dip 80°, and 84% dip 75°. The composite data also show 5% between 70°–74°, 4% between 60°–69°, 4% between 50°–59°, 2% between 40°–49°, and <1% between 30°–39°. In the pits, the next joint with <80° dip might occur from 1 ft to 154 ft down a wall. For most locations in the 412-joint composite, >82% of the joints dip 80°. At one location, 75% of the joints dipped 90° and 95% dipped 80°.

The object of this joint study was to find tectonic joints. Screening tools were necessary in order to avoid swamping a data set with fractures that were obviously not tectonic. On mesa tops, strike was not taken on any joint less than 10 ft long. Length was recorded for every joint measured. If the screening length had been longer, it would have been too difficult (because of soil cover) to find a sufficient number of joints in any study location. In roadcuts, the screening tool for measurement was vertical continuity from bottom to top. Most roadcuts were at least 30–35 ft high.

Statistical analysis

Data from this study and previous work were processed by a software package that produces a rose diagram for each location. This mode of representation was chosen because the majority of the joints dipped 80° or more.

With the exception of location *f*, tectonic joints cannot easily be distinguished from cooling joints on the rose diagrams. The rose diagrams show weak preferred orientations and tend toward random distribution. Therefore, various statistical tests were reviewed. Because cooling joints are expected to be far more numerous than tectonic ones, the Poisson's Test and the *zI* Test were chosen (Langley, 1971). These tests compare the number of isolated occurrences in a random sample of a certain size and the expected number for such a sample as indicated by a large set of observations of at least 10 times the sample size. Poisson's Test was used if the number in the sample was ≤40 and the *zI* Test if the number was greater (Langley, 1971).

If the joints are randomly distributed, an equal number of joints should fall in each 5° or 10° segment of a rose diagram. If more than the mean number fall in any 5° or 10° segment, then the difference might indicate a preferred joint orientation if statistically significant. Overlays, produced by stacking rose diagrams of data from Area G pits of different orientations, show an almost uniform distribution of joint azimuths. If tectonic joints have preferred orientation, then cooling joints must behave as if they have random orientation. It is inferred that joints with statistically significant preferred orientation are tectonic.

Example

If a sample of 180 joints is randomly distributed, then 5 joints will fall in each 5° segment (10 for each 10° segment). If more than 5 joints fall in any 5° segment, the statistical test of significance is applied. A rose diagram plotted in 5° segments will have greater discrimination than one plotted in 10° segments for the same number of measurements. The mean of this example is found by the expression: m = 180/36 = 5.00 (for 5°).

The expected number (E) of occurrences for a sample of the size being investigated is given by the expression: $E = P_x \times n$, where x = number of occurrences (joints) in sample (particular segment) = 11 (eleven was arbitrarily chosen for this example. Eleven is <40; therefore, Poisson's Test is the appropriate one); n = sample size = 1 segment; P_x = average number of occurrences per segment = 5.00 (for 5°); and $E = 5.00 \times 1 = 5.00$.

From the E table for Poisson's Test for Probability (P) when $x > E$ and number in sample (x) is 11: 5.00 (E) is between 5.5 (P = 5%) and 4.7 (P = 1%). This means that the observed number of occurrences (11 joints in

1 segment) could be expected to arise by chance in less than 5% of the occasions, so that the difference between the observed number in the segment (11) and the expected number in the segment (5) is *a difference probably significant*.

An x of 12 would have given a probability of *a difference almost certainly significant* because 5.00 (E) is between 5.05 (P = 1%) and 4.4 (P = 0.2%) for x = 12. An x of 10 or 9 would have given a probability of *a difference probably significant* and *a difference not proven*, respectively, because 5.00 (E) is between 5.1 (P = 5%) and 4.1 (P = 1%) for x = 10, and 5.00 (E) is greater than 4.7 (P = 10%) for x = 9. A probability >5% is considered insufficient to deny a tentative assumption. In this example, a probability >10% is not even close to being sufficient to deny the tentative assumption that a 5° segment containing 9 joints (in a location where 180 joint measurements were made) is the result of the same source (cooling). Because the possibility exists that a larger number of measurements (>180) may reverse this verdict, this situation is described as *significant difference not proven*.

For $x > 40$, the zI Test is used. Calculate E as for the Poisson's Test: $E = P_x \times n$. The statistic (z) is calculated from the formula:

$$Z = \frac{|E - x| - c}{\sqrt{ExP_y}}$$

where c = a correction factor = 0.5 if $x > E$, and $P_y = 1$. The virtual proportion of 'non-occurrences' (cooling joints) reflects the fact that the actual occurrences (tectonic joints) only take up a small fraction of the total number of readings. The probability of no significant difference between E and x is taken from the z TABLE.

RESULTS

Joint data for locations *a, b, c, d, f, k, l* and *p* follow. Data from other locations shown on Figure 4 are not reported because either the measurements were insufficient in number for statistical analysis or the measurements showed a transect bias.

Location *a*

Joints were measured on Mesita del Buey immediately east of Materials Disposal Area G (Fig. 4). The 200 joints in unit C were plotted in 10° segments. Poisson's Test showed N41°–50°W (21 joints) with a P <1%, as a *difference almost certainly significant*. This represents a >99% confidence level that the N41°–50°W trend is the result of preferred orientation and, by inference, is a tectonic joint trend. N40°–49°E (17 joints) with a P >5%, is a *significant difference not proven* (Fig. 5).

Location *b*

Ninety joints were measured in unit D along the north rim of a branch of Pueblo Canyon south and east of Los Alamos High School (Fig. 4). Two joint trends were identified in a 5° plot, N30°–34°W (7 joints) and N70°–74°W (6 joints) with a P <5% for both, a *difference probably significant* (Fig. 6). This represents a >95% confidence level that the N30°–34°W and N70°–74° W trends are the result of preferred orientation and, by inference, are tectonic joint trends. Trends N41°–45°E and N10°–14°W (5 joints each) with a P >10% have a *significant difference not proven*.

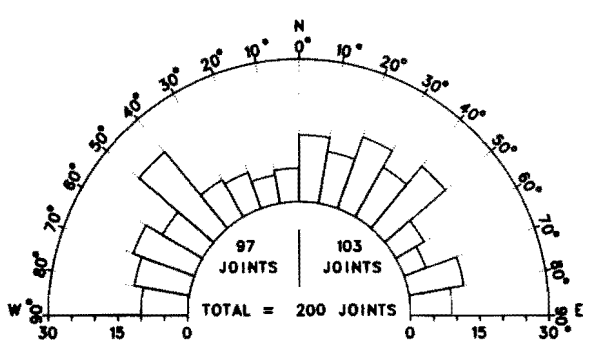

FIGURE 5. Location *a*. Joint data from unit C, Tshirege Member, Mesita del Buey, east of Materials Disposal Area G, TA-54.

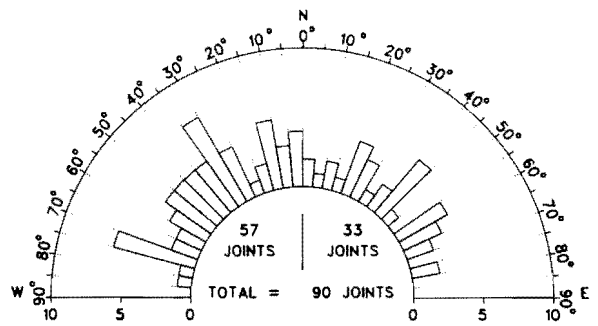

FIGURE 6. Location *b*. Joint data from unit D, Tshirege Member, north rim of Pueblo Canyon branch, south and east of Los Alamos High School.

Location *c*

Measurements were taken on a bench (unit C) at the eastern end of Kwage Mesa overlooking the sewage disposal plant in Pueblo Canyon and along a sloping portion of the north wall (unit B) of Bayo Canyon adjacent to the bench (Fig. 4). The 193 joints, plotted in 5° segments, show statistically significant trends of N16°–20°E (11 joints) with a P <5% and N70°–74°W (12 joints) with a P <5% (Fig. 7). This represents a >95% confidence level that the N16°–20°E and N70°–74°W trends are the result of preferred orientation and, by inference, are tectonic joint trends. Trend N41°–45°E (10 joints) with a P >5% and trends N31°–35°E and N60°–64°W (9 joints each) with a P >10% have a *significant difference not proven*.

Location *d*

One hundred joints were measured along a bench (unit C) in the bottom of DP Canyon northeast of Materials Disposal Areas A and T (Fig. 4). The only statistically significant trend is N86°–90°E (7 joints) with a P <5% (Fig. 8). This represents a >95% confidence level that the N86°–90°E trend is the result of preferred orientation and, by inference, is a tectonic joint trend. Trends N60°–64°W, N20°–24°W, N10°–14°W, N66°–70°E, and N71°–75°E (5 joints each) with P >10% have a *significant difference not proven*.

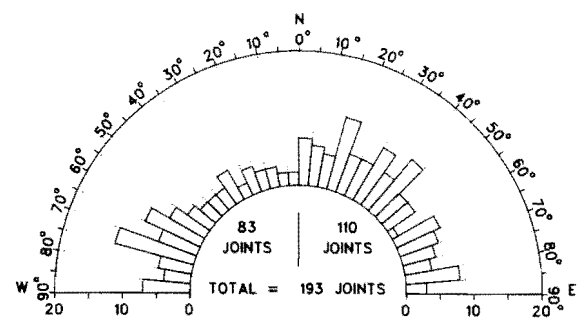

FIGURE 7. Location *c*. Joint data from units B and C, Tshirege Member, eastern end of Kwage Mesa.

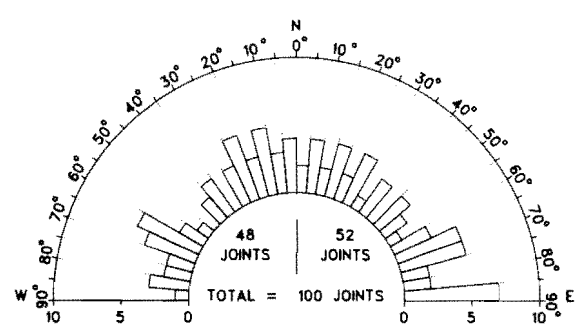

FIGURE 8. Location *d*. Joint data from unit C, Tshirege Member, DP Canyon, northeast of Materials Disposal Areas A and T.

Location *f*

This location was chosen because it is along the trace of the Rendija Canyon fault. Joints were measured down San Ildefonso Road from the Camino Redondo intersection to Diamond Drive and then turning right up North Mesa Road from Diamond Drive to the top of the hill (Fig. 4). The roadcut has 180° of curvature. The 102 joints in unit D show a preferred direction of north-south, which is the trend of the fault. Statistically significant trends are N00°–04°W (11 joints) with a P <0.2%, N01°–05°E (9 joints) with a P <1%, and N10°–14°W (7 joints) with a P <5% (Fig. 9). For N00°–04°W, N01°–05°E, and N10°–14°W there is a >99.8%, a >99%, and a >95% confidence level, respectively, that the trends are the result of preferred orientation and, by inference, are tectonic joint trends.

Location *k*

Seventy-five joints were measured in unit D along the north rim of Water Canyon south of K Site Road between TA-11 and TA-37 (Fig. 4). Only one statistically significant trend was identified in this 5° plot, N31°–35°E (6 joints) with a P <5% (Fig. 10A). This represents a >95% confidence level that the N31°–35°E trend is the result of preferred orientation and, by inference, is a tectonic joint trend. The axis of the Water Canyon arch (Rogers, 1995) (Fig. 4), approximately 4000 ft west, trends N30°E. Trends N06°–10°E and N70°–74°W (5 joints) with a P >5%, are a *significant difference not proven.*

An additional 124 joint measurements were taken. The combined data, 199 joints, were plotted in 5° (not shown) and 10° segments (Fig. 10B). The 5° and 10° plot had statistically significant trends, N60°–64°W (11 joints) with a P <5% and N61°–70°W (18 joints) with a P <5%, respectively. This represents a >95% confidence level that the N60°–64°W and N61°–70°W trends are the result of preferred orientation and, by inference, are tectonic joint trends. These trends also match small-scale fault trends in the immediate vicinity. One, N69°W, is 400 ft south of the location; and another, N62°W, is 400 ft west of the location (Rogers, 1995).

There is a striking difference in north-south jointing trends between the 75- and 199-joint sets. In the 199-joint plot, the cluster of joints between N10°W and N29°E (14 joints per 10° segment) with a P >10% per segment has a *significant difference not proven* as does the N06°–10°E trend in the 75-joint plot.

Because a much larger area had to be covered to collect the additional 124 joint measurements, the 199-joint set may include joints influenced by different stress conditions. In addition to the two previously mentioned faults and arch, there is a small-scale fault trending N49°E which runs through the southern part of the location (Rogers, 1995). Location *k* is part of an area (which extends to the south of Water Canyon) of complicated stratigraphy and structure. The locations and trends of the arch and faults (Rogers, 1995) were aerial photo lineations that offered a best-match for field observations.

Location *l*

Measurements were taken along a bench (unit C) in the bottom of a branch of Mortandad Canyon 0.7 mi east of Materials Disposal Area C (Fig. 4). The 102 joints show only one statistically significant trend of N50°–54°W (7 joints) with a P <5% (Fig. 11A). This represents a >95% confidence level that the N50°–54°W trend is the result of preferred ori-

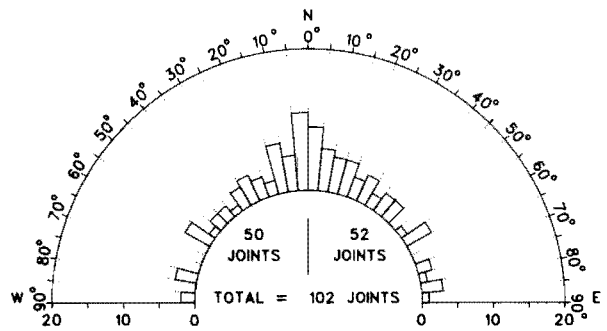

FIGURE 9. Location *f*. Joint data from unit D, Tshirege Member, North Mesa trace of Rendija Canyon fault, San Ildefonso and North Mesa Roads.

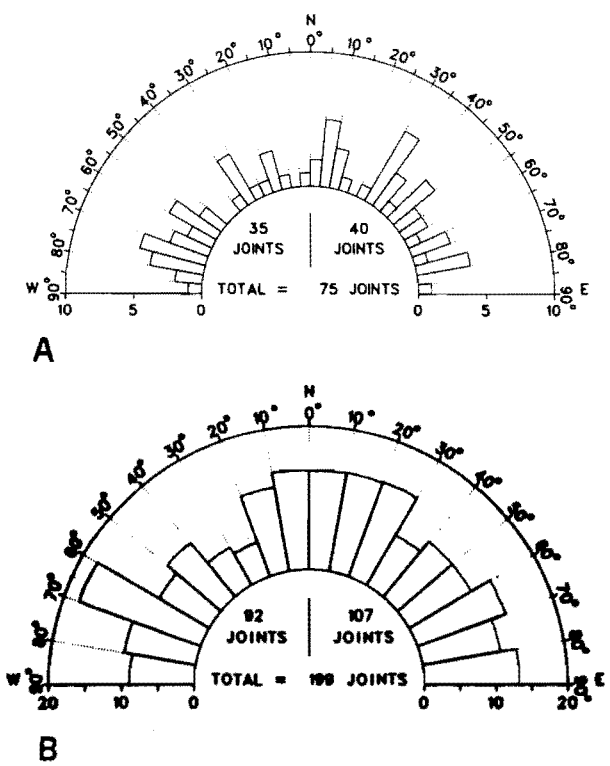

FIGURE 10. Location *k*. Joint data from unit D, Tshirege Member, north rim Water Canyon between TA-11 and TA-37. A, 5° plot of 75 joints, original set. B, 10° plot of 199 joints, original set plus an additional 124 joint measurements.

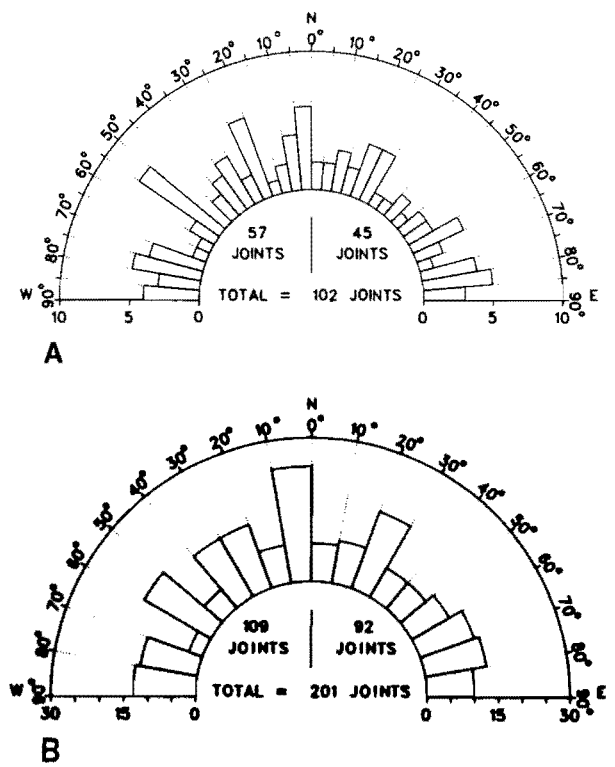

FIGURE 11. Location *l*. Joint data from unit C, Tshirege Member, Mortandad Canyon branch ~0.7 mi east of Materials Disposal Area C. A, 5° plot of 102 joints, original set. B, 10° plot of 201 joints, original set plus an additional 99 joint measurements.

entation and, by inference, is a tectonic joint trend. Trends N00°–04°W and N20°–24°W (6 joints each) with a P >10% have a *significant difference not proven.* The 10° plot (not shown) shows the largest number of joints in N01°–10°W (10 joints) with a P >5%, a *significant difference not proven.*

An additional 99 joints were measured. The 10° plot of the 201 joints shows a trend of N01°–10°W (24 joints) with a P <0.2% (Fig. 11B). This represents a >99.8% confidence level that the N01°–10°W trend is the result of preferred orientation and, by inference, is a tectonic joint trend. N20°–29°E (17 joints) with a P >5% and N51°–60°W (16 joints) with a P >10% are trends which have a *significant difference not proven.*

The N01°–10°W trend is an important one on the plateau. Additional measurements confirmed it at Location *l*. With a sample size of 201, another important trend on the plateau began to emerge, N20°–29°E. Although the N 51°–60°W trend was *not proven* in the larger joint set, it is persistent enough to merit environmental/waste management consideration at this location. Location *l* is the easternmost location for its latitude. It could be influenced by a different stress field located to the east.

Location *p*

Joints were measured along NM-4 as it enters and leaves Ancho Canyon 0.5 mi to 1.5 mi upstream from the paleo-canyon system exposed in lower Ancho Canyon (Fig. 4). Both roadcuts curve and are oriented at approximately 90° to each other. Location *p* is north and west of nearby Materials Disposal Areas E, K and D. The 180 joints in units A, B and C show statistically significant trends of N26°–30°E, N31°–35°E, and N61°–65°E (11 joints each) with a P <5% (Fig. 12A). This represents a >95% confidence level that the N26°–30°E, N31°–35°E, and N61°–65°E trends are the result of preferred orientation and, by inference, are tectonic joint trends. N70°–74°W and N75°–79°W (9 joints each) with a P >10% are trends with a *significant difference not proven.*

The 10° plot shows N30°–39°E and N71°–80°W (18 joints each) with a P <5% as trends while N20°–29°E (16 joints) with a P >5% and N60°–69°E (15 joints) with a P >10% are trends with a *significant difference not proven* (Fig. 12B). This represents a >95% confidence level that the N71°–80°W and N30°–39°E trends are the result of preferred orientation and, by inference, are tectonic joint trends. The N30°–39°E trend includes the N31°–35°E trend from the 5° plot. Both trends, N61°–65°E (5° plot) and N71°–80°W (10° plot), are prominent in the drainage pattern of Ancho and nearby canyons.

Composites

The composites were done with data from locations *a, b, c, d, f, k, l* and *p* plus data from location *j*. All of these locations had trends identified as statistically significant. At location *j*, 264 joints were measured in steam-line trenches dug in 1972 on the north and east sides of the CMR Laboratory, TA-3-29 (Fig. 4). Location *j* was included because it had an identified trend, N 30°-34° W, using the mean-plus-2-standard-deviations test and the χ^2 Test. Poisson's Test gave the result for N30°–34°W (13 joints) with a P >5%, as a *significant difference not proven.*

Composite

The 1207-joint Composite rose diagram had statistically significant trends identified by the mean-plus-2-standard-deviations test. The trends were N70°–74°W and N26°–30°E (Fig. 13A). The *zI* Test identified these same trends. Trend N26°–30°E (47 joints) had a P <1%, a *difference almost certainly significant*; and trend N70°–74°W (46 joints) had a P <5%, a *difference probably significant*. For N70°–74°W and N26°–30°E, there is a >99% and a >95% confidence level, respectively, that the trends are the result of preferred orientation and, by inference, are tectonic joint trends. N16°–20°E and N31°–35°W (43 joints each) both had a P >5%, a *significant difference not proven*. The east-west trend, N71°–74°W, is consistent with the trends of the Los Alamos Canyon fault and other unnamed small-scale faults (not shown) in the western half of the plateau (Rogers, 1995) (Fig. 4).

Composite III

Composite III includes the data from Composite plus an additional 462 joint measurements from locations *a, b, c, k* and *l*. These additional data were taken in order to re-evaluate χ^2 Test results for those particular locations. The χ^2 Test identified the trends, N00°–09°W and N20°–29°E

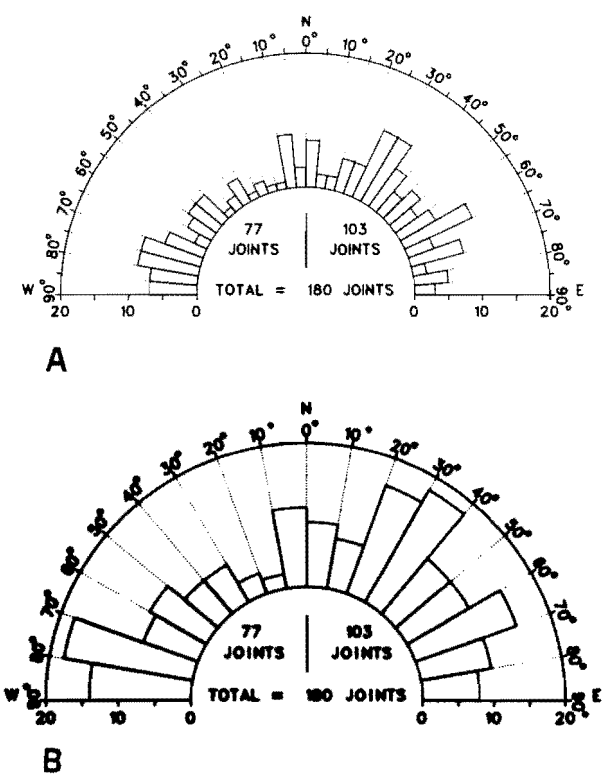

FIGURE 12. Location *p*. Joint data from units A, B, and C, Tshirege Member; NM-4 roadcuts entering and leaving Ancho Canyon. A, 5° plot of 180 joints. B, 10° plot of 180 joints.

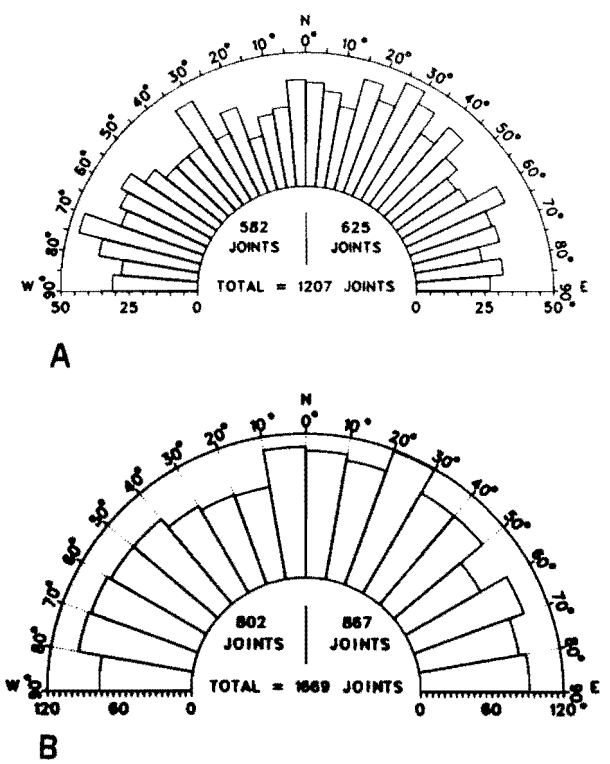

FIGURE 13. Composite joint data for the Pajarito Plateau in the Los Alamos area from Locations *a, b, c, d, f, j, k, l*, and *p*. A, 5° plot of Composite (1207 joints), original data set. B, 10° plot of Composite III (1669 joints), original composite data set plus an additional 462 joint measurements.

in this 1669-joint set (Fig. 13B). The *zl* Test identified the same trends as the χ^2 Test. The result for N20°–29°E (119 joints) was P <1%, a *difference almost certainly significant* and for N00°–09°W (115 joints) was P <5%, a *difference probably significant*. For N20°29°E and N00°–09°W, there is a >99% and a >95% confidence level, respectively, that the trends are the result of preferred orientation and, by inference, are tectonic joint trends. The north-south and northeast trends are consistent with the trends of unnamed small-scale faults (not shown), the Pajarito fault zone, the Rendija Canyon fault, the Guaje Mountain fault, the Water Canyon arch, and the Los Alamos Canyon arch (Rogers, 1995; Fig. 4). The northeast trend is the same one identified in Composite.

DISCUSSION

The data in this study were not collected to form a composite data-set to represent the mode trends of the Pajarito Plateau but to identify trends with preferred orientation at specific locations on the plateau. Identified trends reoccur at other locations and in the drainage pattern of the plateau. As an example, the lower parts of Chaquehui Canyon, Ancho Canyon, and Water Canyon seem to be strongly influenced by the N71°–80°W, N26°–30°E, and N61°–65°E trends established at Location *p*. N 26°–30°E (included in N20°–29°E) is the strongest trend on the plateau occurring in both Composite and Composite III. The N71°–80°W trend seems to control the Rito de los Frijoles drainage across most of the plateau and sections of Water Canyon and Potrillo Canyon in the middle part of the plateau. It is again present at Locations *b* and *c* as Composite trend, N70°–74°W. Los Alamos, Pueblo, Bayo, and Barrancas Canyons are strongly influenced by it. The other trend established at Location *p*, N31°–35°E, is also present at Location *k* and occurs repeatedly in the Water Canyon, Ancho Canyon, and Frijoles Canyon drainage patterns.

The size of data collections from specific locations varied. The ideal size is still unknown. An experiment increasing the size to approximately 200 joints per location did not always result in the clarification of suspected trends. Several factors may be involved. To go from a size of 100 to 200 joints requires data collection over a much greater distance because of soil cover. A location over 0.5 mi long may be influenced on both ends by different structure; it is no longer a "spot" location. Also, increasing the size may do nothing more than swamp a data set with cooling fractures.

The object for environmental/waste management purposes is to be able to distinguish an isolated occurrence (a preferred orientation) with the least number of measurements. With a sample size of less than 50, it would be hard to convincingly argue that the sample was large enough to distinguish preferred orientation from random distribution. The mean for such a sample would be less than two joints per 5° segment. From a sample size of 50 to 150, there is an increasing statistical advantage. The mean number of joints that must fall in any 5° segment triples. The mean, or the number of joints expected in each 5° segment if the joints were all randomly distributed, is extremely important in the application of any statistical test to discriminate an 'isolated occurrence', a preferred orientation.

In the case of Location *j*, the 264 joint measurements in unit E taken from the steam-line trenches at the CMR Laboratory failed to have a tectonic trend identified. With trenches running both north and east, directional bias should have been overcome. Thirteen joints was the largest number in any 5° segment, the N30°–34°W one; and 21 was the largest number in any 10° segment (N20°–29°E and N60°–69°E) (Fig. 14). If one more joint had plotted in the N30°–34°W segment and/or two more joints had plotted in the N20°–29°E or N60°–69°E segments, Poisson's Test would have identified them as statistically significant. The CMR Laboratory data set should have shown the influence of a shallow monoclinal fold axis (N21°E) 500 ft east or a shallow synclinal fold axis (N14°E) ~1600 ft west or a small-scale fault (N76°W) 400 ft south. The locations and trends of these features (Rogers, 1995) were aerial photo lineations which offered a best-match for field observations.

At other locations, joint sets with far fewer than 264 joints have identified trends. The unknown that upsets the idea of an 'ideal' sample size is the ratio of cooling joints to tectonic joints at any given location. Field observation shows that some units of the Tshirege are more fractured than others. Therefore, increasing the sample size at any given location locally does not guarantee that more tectonic trends or even a tectonic trend can be statistically identified.

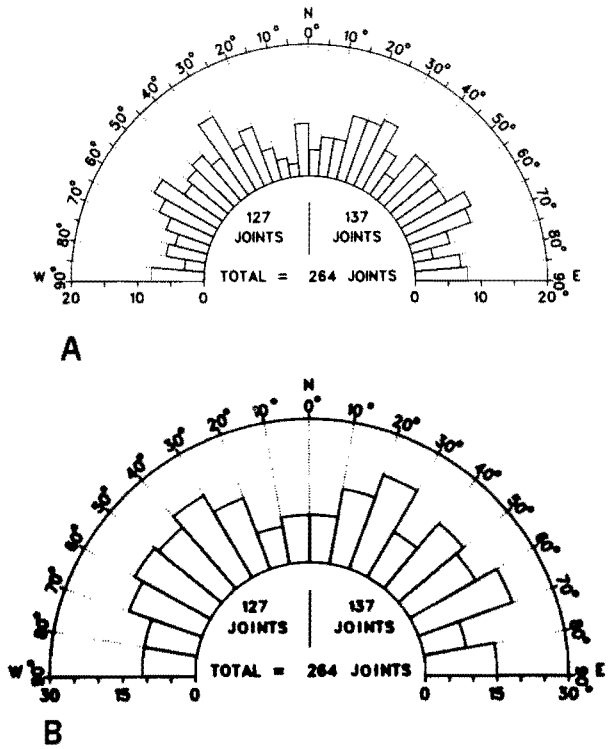

FIGURE 14. Location *j*. Joint data from unit E, Tshirege Member, steam-line trench, north and east of CMR Laboratory, TA-3-29. A, 5° plot of 264-joint data set. B. 10° plot of 264-joint data set.

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