UNITED STATES DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

JOINT NETWORKS IN THE TIVA CANYON AND TOPOPAH SPRING TUFFS OF THE PAINTBRUSH GROUP, SOUTHWESTERN NEVADA

by

Constance K. Throckmorton[1] and Earl R. Verbeek[1]

Open-File Report 95-2

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards (or with the North American Stratigraphic Code).

1995

[1]U.S. Geological Survey, Denver, Colorado

Copies of this Open-File Report
may be purchased from

Books and Open-File Reports Section
Branch of Distribution
U.S. Geological Survey
Box 25425 Federal Center
Denver, Colorado 80225

PREPAYMENT IS REQUIRED

Price information will be published
in the monthly listing
"New Publications of the Geological Survey"

FOR ADDITIONAL ORDERING INFORMATION

CALL: (303) 236-7476

CONTENTS

ILLUSTRATIONS

TABLES

JOINT NETWORKS IN THE TIVA CANYON AND TOPOPAH SPRING TUFFS OF THE PAINTBRUSH GROUP, SOUTHWESTERN NEVADA

Constance K. Throckmorton and Earl R. Verbeek

ABSTRACT

Eight fracture sets were documented in the Tiva Canyon and Topopah Spring Tuffs at 41 localities in the northern half of Yucca Mountain and Fran Ridge. Two sets of steeply dipping cooling joints forming a rectangular array are present at many localities. Joints of the two sets are preferentially oriented within an area of at least 20 km^2 on Yucca Mountain; median strike directions are N. 45° W. and N. 50° E. In some places a third set of cooling joints is present. This set dips gently, parallel to compaction foliation in the tuff, and together with the other two sets forms a orthogonal, three-dimensional network. Common properties of cooling joints include exceptional surface smoothness; absence or sparsity of lithophysae intersecting the joint face; smooth, continuous traces; early age as demonstrated through abutting relations with other fractures sets; and large size. Tectonic fractures in the same exposures almost invariably are rougher and have more irregular traces.

Tectonic fractures at Yucca Mountain and Fran Ridge form five sets. Surface structures (inclusion and twist hackle, arrest lines) show that the fractures of all five sets are extension joints. Joints of three sets, all steeply dipping, have median strikes of N. 01° W., N. 31° W., and N. 38° E. and record noncoaxial extension through time during Basin-and- Range faulting. Later joints include a set of steeply dipping cross joints (median strike N. 82° W.) and a prominent set of gently dipping joints parallel or nearly so to compaction foliation in the tuff. Both sets are roughly contemporaneous and are interpreted as unloading joints that formed during erosion, as the tuffs adjusted to progressive reduction of confining pressure.

The nature of the fracture network, as defined by various combinations of the eight joint sets, differs from one volcanic unit to another in consistent ways. Cooling joints, for example, are the dominant components of the fracture network at nearly all localities examined in the upper lithophysal unit of the Tiva Canyon Tuff, but tectonic joints vastly outnumber cooling joints in the hackly unit lower in the formation. Strike-frequency distributions for the two units are dissimilar, and each must be modeled separately for fluid-flow simulations and mechanical stability. Other aspects of the fracture network (e.g., joint roughness) likewise differ from one unit to another. All networks examined to date, however, are well interconnected. The presence of alteration rinds and mineral coatings on joints of each set shows that all eight sets were conduits for subsurface fluid flow at Yucca Mountain and Fran Ridge.

INTRODUCTION

This study was undertaken as part of a larger effort by the U.S. Geological Survey to identify and characterize joint networks at Yucca Mountain, a candidate site for an underground high-level nuclear-waste repository in southwestern Nevada. The repository would be located about 150 m below the surface in the unsaturated zone below Yucca Mountain, and about 400 m above the water table. Joints provide potential paths by which water can reach the waste and transport it out of the repository, and paths by which gases can escape through the rock mass and into the atmosphere. An understanding of joint sets and how they interconnect to form a network is critical to understanding how fluids moving through the joint network may affect the suitability of the unsaturated zone under Yucca Mountain as a nuclear waste repository. Lateral and vertical variability, distribution, and other physical characteristics of joints provide information for development of hydrologic and tectonic models of the potential waste-storage site.

The primary goal of this study was to develop a conceptual understanding of the regional joint network: what joint sets exist, the sequence in which they formed, their characteristics as a function of unit lithology, and their relation to the regional tectonic history. Site-specific data were collected to characterize joints in units of the Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group, of Miocene age.

The study area (fig. 1) encompasses Yucca Mountain and Fran Ridge, the narrow north-trending ridge flanking the east side of the mountain. Fran Ridge was included in the study because it provides abundant exposures of the Topopah Spring Tuff, which is poorly exposed on Yucca Mountain. Because fluid-flow paths through fractures depend on the physical characteristics of the fracture networks within lithostratigraphic units, stations were chosen to provide lateral and vertical coverage in the primary tuff units comprising Yucca Mountain and Fran Ridge.

This study provides site-specific data from 41 localities (field stations). Most of the stations are located in natural exposures; however, a few stations are located in excavated trenches or test pits. Eight stations are located in four lithologic units of the Topopah Spring Tuff and 33 stations are in eight lithologic units of the Tiva Canyon Tuff. The lithologic units referred to in this report are those described by Scott and Bonk (1984), shown in figure 2.

Data were collected to (1) develop and test criteria to distinguish cooling joints from tectonic fractures, (2) document the existence of distinct fracture sets in each unit, (3) determine the fracture network distribution and provide information on how many fractures are potentially hydrologically active, (4) assess the fracture connectivity of the fracture network, (5) assess the effect lithology has on fracture abundance and fracture distribution, and (6) document the mineralization history of fractures at Yucca Mountain.

A phased approach was planned; during the first phase the authors addressed the first three issues. Subsequent phases were to provide information to address the remaining issues, through detailed collection and analysis of quantitative fracture data using the methods developed and tested. The authors were about midway into the first phase of the study when our involvement with the effort ended.

Data and interpretations from the first phase of this study are presented in this report. Data are sparse or absent in some units; thus the authors caution that the interpretations presented in this report are preliminary. Sampling and analyses of mineral fill, coatings, and alteration zones, planned for the next phase, would have contributed significantly to understanding of the fluid-flow history and episodes of reactivation of joint sets at Yucca Mountain. In spite of these limitations, we believe the data collected during this study present will be useful for comparison with studies of fractures exposed in walls of the drift currently under construction for the Exploratory Studies Facility at Yucca Mountain.

GEOLOGIC SETTING

Yucca Mountain is composed of two voluminous, compositionally zoned ash-flow sheets, the Topopah Spring Tuff (1200 km^3) and the Tiva Canyon Tuff (1000 km^3), 300 m thick and 100 m thick, respectively. The Tiva Canyon Tuff comprises most of Yucca Mountain; the Topopah Spring Tuff is exposed on Fran Ridge. These formations, along with several thinner tuffs, form the Miocene Paintbrush Group, erupted from the Claim Canyon caldera about 2 km north of Yucca Mountain. The tuffs grade upward from high-silica rhyolite in their basal and central portions to quartz latite that forms a densely welded caprock near the top of the each sheet. Ash-fall deposits occur between the two ash-flow sheets. The mountain is

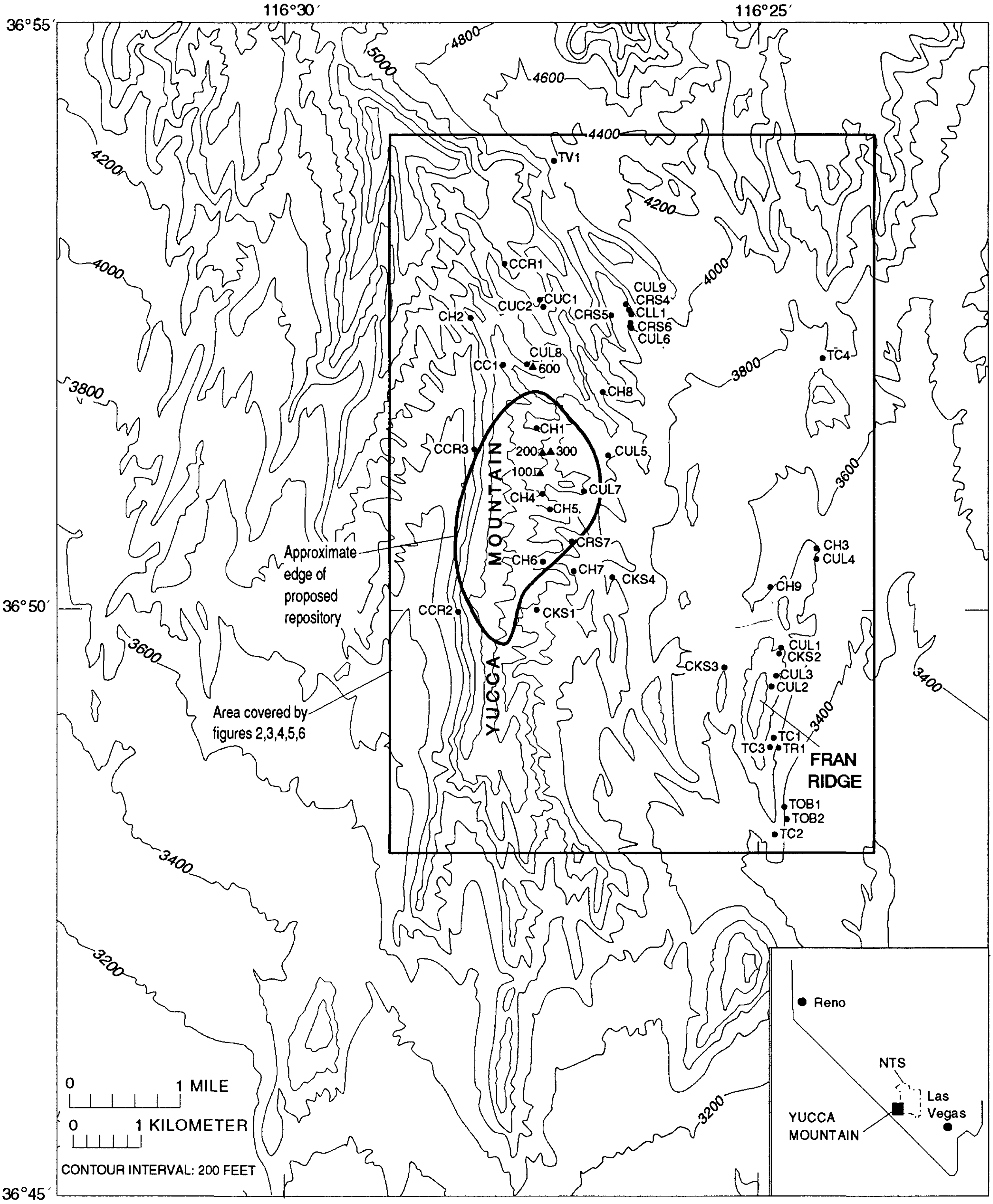


Figure 1.--Study area showing locations of 41 field stations in the Topopah Spring and Tiva Canyon Tuffs at Yucca Mountain and Fran Ridge.

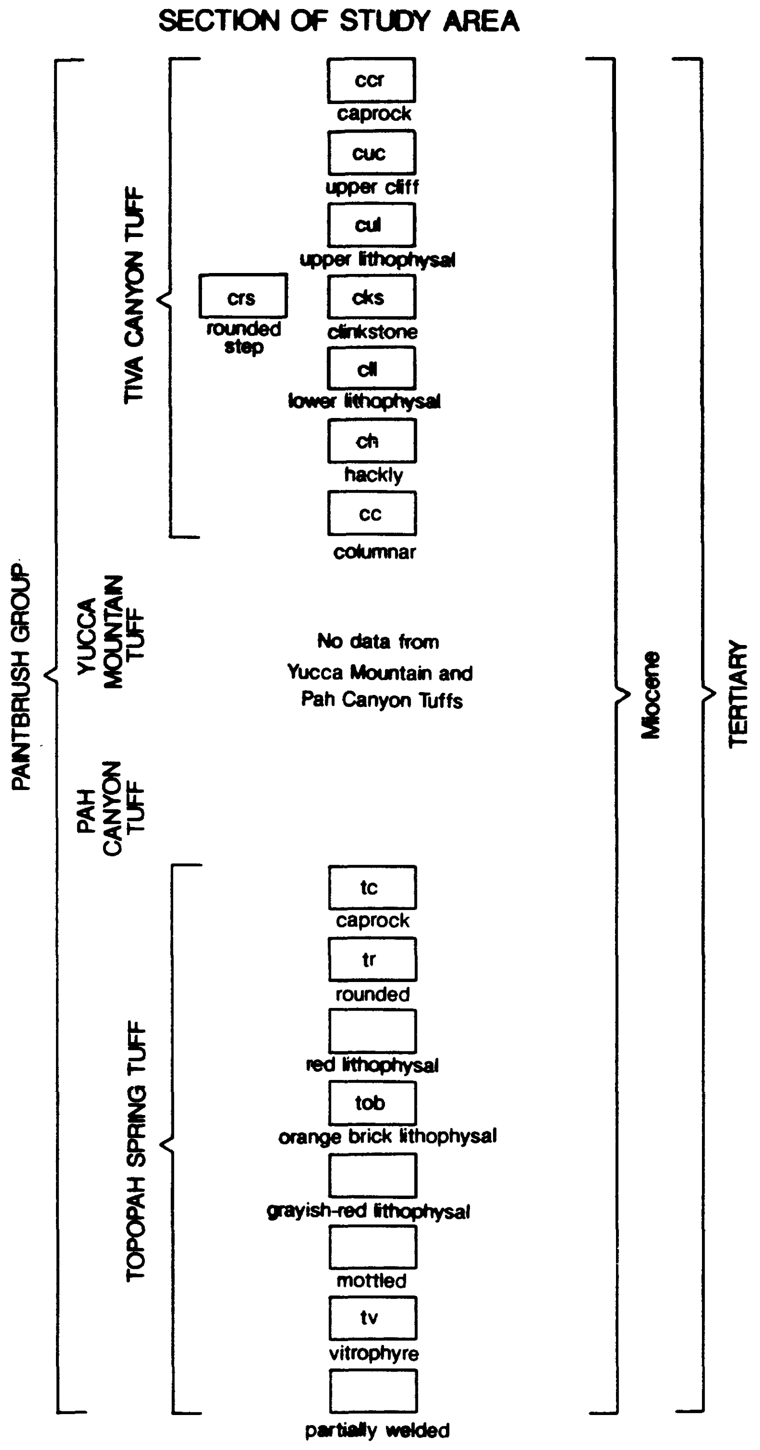


Figure 2.--Map units of the Tiva Canyon and Topopah Spring Tuffs in the study area. Boxes with no symbols are units for which no data were collected in this study. Refer to Scott and Bonk (1984) for detailed descriptions of units.

underlain at a depth of 1-2 km by Paleozoic marine clastic rocks and Mesozoic granitic intrusions (Snyder and Carr, 1982). Summit surfaces are relatively flat, and prominent north-trending ridges and steep-sided ravines and washes characterize Yucca Mountain. Yucca Mountain comprises several structural blocks, bounded by north-trending, westward-dipping, high-angle faults that displace the volcanic strata as much as 400 m (Scott and Bonk, 1984). The strata dip gently (5-10°) northeast, east, or southeast. Carr (1984) discussed the regional tectonic and structural setting of Yucca Mountain; the stratigraphic and structural framework are summarized in Spengler and Fox (1989).

The Tiva Canyon and Topopah Spring Tuffs are lithologically similar and are characterized by densely welded to partially welded to nonwelded lithophysal and nonlithophysal zones and vitrophyres characteristic of ash flow sheets. Scott and Bonk (1984) divided the Tiva Canyon and Topopah Spring Tuffs into several informal units at Yucca Mountain, based primarily on mineralogic features (presence of lithic fragments and phenocryst abundance), textural features (degree of welding, lithophysal cavity abundance), and weathering characteristics observed in the field. The two tuffs record different geomagnetic polarities; the Tiva Canyon Tuff is reversed and the Topopah Spring Tuff is normal (Rosenbaum, 1986). Paleomagnetic data from Miocene ash-flow sheets have been interpreted to show that Yucca Mountain has undergone a southward-increasing clockwise vertical-axis rotation as large as 30° since about 13 Ma (Rosenbaum and others, 1991; Hudson and Sawyer, 1994).

METHODS

The manner in which natural fracture networks should be studied and documented in the field has long been debated in the geologic literature. Though the methods used vary considerably with the problem to be addressed, opinion often is divided even where common purpose exists. Because fracture studies at Yucca Mountain are no exception, we here discuss both our general approach to such studies and our specific field procedures in some detail.

General Approach

Most fracture studies involve some variant of either a "global inventory" or a "selective inventory." A global inventory, as the name implies, involves measuring all fractures present within a prescribed area or along a prescribed scanline. A common variant is to measure fractures "at random" until some arbitrary number of measurements has been attained. Properties to be documented for each fracture vary with purpose and observer but commonly include, at a minimum, orientation and some indication of fracture size. Recognition of fracture sets and interpretation of the fracture network typically are accomplished after the fact, through statistical manipulation of the resultant data. Rose diagrams of fracture strike, for example, commonly are employed to define fracture sets. Advantages of this approach include objectivity, speed, high degree of data reproducibility, and minimal need for prior training in fracture analysis. The main disadvantage, discussed below, is that the data are of limited utility for some aspects of repository evaluation at Yucca Mountain.

Selective inventories generally are more demanding in that they require conceptual understanding of the local fracture network before measurements can begin. A necessary first step is to determine how many sets of fractures are present and the order in which they formed--in effect, to perceive the overall network in terms of its component parts. Once the evolution of the local network is understood, the properties of each fracture set can be documented in turn. An obvious advantage over global inventories is that data from individual fracture sets are kept separate from the beginning, and thus the relation between any given fracture-set property and other factors--rock composition, degree of welding, and stratigraphic position among them--can be more effectively defined and quantified. The main disadvantage is that quality of the results depends in part on the skill of the observer. Where fracture sets are well defined and readily recognized on sight, the fracture data are highly reproducible and require less time to gather than the equivalent data from a global inventory. In areas of exceptional complexity, however, reproducibility of data requires time, patience, and experienced personnel.

Most previous studies of fractures at Yucca Mountain, published and unpublished, employed some variant of a global inventory approach: the fracture network was studied *in toto*, and various of its properties were portrayed in synoptic plots. That network, however, evolved over time and is the end product of several disparate processes, including (1) contraction upon cooling of the rock, (2) tectonic extension, (3) unloading during erosion of overburden load, and (4) weathering. To study some or all of these fracture types together limits the usefulness of the data obtained and invalidates some of the results. What significance, for example, should one attach to frequency distributions of fracture lengths when the fracture network at locality X is an amalgam of sets A, C, and D and that at locality Y is some combination of sets B and C? Such plots cannot readily be compared from one locality to another in any meaningful way, and the combined data provide only limited understanding of geologic controls on spatial variability in network geometry. More importantly, the manner in which any given fracture property (length, height, spacing . . .) varies with other properties (lithology, unit thickness, depth) is not always constant but differs from one fracture set to another. One might predict, for example, that joints due to tectonic crustal extension are present throughout the volcanic sequence at Yucca Mountain, whereas late "cross joints" formed during erosional unloading decline rapidly in abundance with depth--thus, fracture networks exposed in surface rocks must differ in some important respects from those at depth, even in identical rock types. Lorenz and Finley (1991) discussed a prominent example for an area of sedimentary rocks in western Colorado. Measured properties of the total fracture network as seen in surface exposures, then, can prove misleading unless the geologist understands which components of that network have significance at repository depths and which do not.

We conclude that both approaches to joint studies have merit, but for different purposes. The voluminous data from global inventory studies doubtless will prove useful for modeling the near-surface fracture network at those specific localities where data were gathered, and for gaining some preliminary impression of network heterogeneity in different volcanic units. However, true understanding of geologic controls on fracture-network geometry within large, heterogeneous masses of rock such as the Yucca Mountain block cannot be achieved through such an approach. Our study thus concentrated on selective inventories from the outset.

Field Procedures

Most stations are in areas of discontinuous natural outcrop. Five stations are located in excavated trenches or test pits. Each station was restricted to one lithologic unit so comparison of fracture networks from other units could be made. The size of field stations was determined by (1) degree of exposure, (2) complexity of fracture network, (3) "coarseness" of the fracture network, and (4) orientation of fractures with respect to exposure surface. Initial efforts were concentrated in the northern half of Yucca Mountain to avoid possible structural complications due to the rocks being rotated (Rosenbaum and others, 1991) at the southern half of Yucca Mountain.

Choice of exposure

Acceptance or rejection of an exposure as a study site was guided by several factors, including the need for a reasonable geographic distribution of data points, the need to study all volcanic units present, and quality of the exposure. The most important factor, however, was the nature of the fracture network itself. During the initial phases of any regional fracture study it is imperative to gather data only from exposures where fracture sets are visually obvious and the relations among them clear, for only then does one have any chance of deciphering basic elements of the regional network quickly and reliably using the selective inventory approach. Study of exposures where fracture sets are ill-defined is inadvisable during early stages of the study because the observer is not yet sufficiently knowledgeable to deal with them. Later, however, when the general nature of the regional fracture network is well understood, one should return to such sites. Exposures once deemed so complex as to be uninterpretable may then yield a wealth of new information.

Most of our field stations were chosen in accordance with these guidelines, but exceptions were made for several localities of particular scientific interest. Chief among these are the two test pits near the south end of the east flank of Fran Ridge and a trench exposure west of the same ridge, near the Paintbrush fault. In all three of these places the local fracture network is incompletely understood and only partially documented.

Preliminary evaluation of fracture network

A preliminary evaluation of the fracture network was made at each study site to accomplish several objectives: (1) to determine how many sets are present and the order in which they formed, (2) to develop some familiarity with the general physical characteristics of the fractures in each set, and (3) to locate and mark sites of particular importance for later study (for example, where fractures showed well-exposed mineral coatings, prominent surface structures, or clear age relations with other fractures). Also important during this phase was to differentiate between cooling joints, tectonic joints, and fractures due to weathering or blasting. Fractures in the latter two categories were immaterial to our study and hence were excluded from measurement; in any case they generally comprised a negligible proportion of the total fracture network. Characteristics collectively indicative of weathering-induced fractures include lack of mineral coatings or fillings other than caliche, young age (they abut all other fractures present), small size (lengths <50 cm; heights <20 cm), nonsystematic orientation, irregular surfaces, and fresh, relatively unaltered walls. Blast-induced fractures, potentially present in only two (TOB1, TOB2) of the 41 exposures studied, commonly were recognizable by their radiating pattern away from the borehole. Their surfaces tend to be much rougher than those of other fractures, a consequence of high-energy fracture propagation; prominent twist hackle over appreciable portions of the fracture surface is typical (Kulander and others, 1979). Blast-induced fractures, like those due to weathering, have fresh, unmineralized surfaces and abut all other fractures present.

Documentation of fracture-set properties

The method utilized in this study is one in which fracture sets were defined in the field and the properties of each set were described separately. Recognition of genetic sets of fractures in the field was based on multiple properties which in combination are unique to each set; these properties include orientation, length, height, shape, surface roughness, surface structures, alteration and mineralization, and abutting and crosscutting relations with other fractures. The first and last of these properties are most critical in defining fracture sets and in establishing the sequence of fracture in each exposure. Knowledge of which sets exist and the order in which they formed then enabled us to (1) correlate sets from one locality to another and thereby define the overall fracture pattern, and (2) document geologic controls (rock type, previous fracture history, unit thickness) on fracture-set geometry and differences in network characteristics from one volcanic unit to another.

Some of the data recorded at each station pertain to individual fractures, while some of the information characterizes the set as a whole. Fracture orientations (strike and dip) were measured for individual fractures comprising the set. Semiquantitative and descriptive data recorded for each set include joint expression, size (height and length), shape, spacing, and surface roughness. Much of these data are commonly expressed as a range. Surface structures were noted from individual joint surfaces, as were mineral coatings and fillings, and alteration rinds along fracture surfaces. Terminating relationships were recorded for individual fractures.

In addition to the joint-set attributes mentioned above, descriptive data recorded at each station include stratigraphic unit, approximate size of exposure, percent of area exposed, slope inclination, and (if appropriate) comments on compaction foliation in the tuff. Fracture apertures were not measured because joint-bounded blocks at the surface almost everywhere have moved somewhat with respect to neighboring blocks as a result of several processes, among them root and frost wedging, and downhill creep. The magnitude of these effects is such that we place little value in aperture measurements from surface exposures. More useful measurements of fracture aperture are obtainable from drill cores and from the repository shaft and associated drifts.

The fracture properties recorded for each set are defined below and summarized in Appendix A for each locality.

Fracture orientation

The orientation (strike and dip) of fractures identified as belonging to a set is listed in Appendix B. The number of fractures measured for each set was determined by orientational variability or, at some stations, by the number of joints available for measurement. Fewer measurements are required to derive a median orientation characteristic of the set where joints of a given set show little variation in both strike and dip. However, where orientations are more variable (greater than 20°), more measurements are needed to ensure that the calculated median is truly representative. Median orientations, rather than mean orientations, are preferred, because means calculated from small samples are highly sensitive to outlier measurements. In addition, the mean is a statistic properly applied only to normal distributions, whereas the actual shapes of frequency distributions of fracture strike and dip for the various sets at Yucca Mountain remain undefined.
Median strikes for fractures of gentle dip, whose strikes commonly box the compass and thus define circular distributions, cannot be defined. For these sets a visual measure of central tendency was defined from the distribution of points as shown on a stereographic plot.

Expression

Expression is a descriptive term indicating the degree of visual prominence of a joint set. Descriptors used in this study range from *very well* (signifying an obvious set, usually the most prominent of those present), *well* (fairly obvious or quickly seen), *moderate* (not obvious, but discernible with little effort), to *poor* (difficult to recognize). These descriptors are useful to the current investigators as they serve as reminders of the relative importance of the specific set to the local fracture network and alert subsequent investigators visiting the same exposures to the degree of effort required to recognize the joint sets.

The expression of a fracture set at any given locality is influenced by several factors, including the orientation of the exposure, fracture spacing, fracture size, and fracture abundance. Set expression varies considerably from one locality to the next, reflecting not only variation in orientation of the exposed surface, but also lithologic changes and natural variation in fracture abundances. For example, a station may not contain a well-expressed set, or four fracture sets may be present at a station but all may be poorly expressed.

The orientation of the exposure with respect to the orientation of the fracture set greatly influences set expression. For example, only a few fractures with orientations parallel to a vertical cliff face may be visible if the face does not extend far into the cliff, while numerous fractures with strikes perpendicular to the cliff face are easily seen. Similarly, gently sloping exposures readily expose steeply dipping fractures rather than horizontal fractures or fractures with low dip. Fractures may also be more readily seen in lithologic units where weathering has exposed intersections of horizontal and vertical fractures, to form ledges comprising steps and risers. Exposures of the rounded step unit of the Tiva Canyon Tuff commonly form conspicuous ledges where both fracture sets are obvious.

Shape

Shape refers to the overall configuration of a joint surface. The joint surfaces may be nonplanar, subplanar, or planar. Additional descriptors (gently, sharply, curviplanar, sinuous, etc.,) were used where appropriate.

Surface roughness

Roughness, in addition to shape, is an important surface morphology characteristic because it affects fluid flow through fractures of small aperture and also is a prime factor in determining fracture shear strength. In our study, fractures were described as very smooth, smooth, fairly smooth, fairly rough, rough, or very rough as judged by running one's hand over the fracture surface. This descriptive measure of roughness thus refers to small (a few millimeters or less) irregularities within areas of 10-50 cm^2 on the fracture surface. Our tactile impression has the advantage of speed and revealed consistent differences among fracture sets of different genesis. Barton and Choubey (1977) used a semiquantitative measure of roughness, the Roughness Coefficient, to refer to surface irregularities over a linear distance of 20 cm rather than within a discrete area of the fracture surface.

Length, height

Fracture lengths and heights are measured parallel to the strike and dip lines, respectively, of the fracture surface. Fracture visibility is greatly influenced by the orientation of the exposure. Lengths of fractures are best measured on gently sloping exposures and their heights on cliff faces; only rarely are both dimensions obtainable from the same exposure. In many places, only small portions of fractures are visible. Thus, our field notes commonly make a distinction between *exposed* lengths and heights versus *true* lengths and heights. Total ranges and common ranges for the set were recorded, if appropriate. True lengths and heights typically represent a conservative measure of the actual fracture size because the dimensions measured represent only the actual fracture dimensions within the plane of the outcrop.

For horizontal or gently dipping fractures of insignificant height, the maximum dimension of the exposed part of the fracture was recorded as an estimator of the fracture diameter. As for fractures of steeper dip, a distinction was made between exposed maximum dimension and true maximum dimension.

Surface structures

Fracture-surface structures, such as arrest lines, inclusion hackle, and twist hackle, all of which indicate extensile failure of the rock, were noted. At several localities, fractures were observed to *hook* (curve toward and terminate against another nearby fracture at high angles). Slickenside striations were noted at one locality.

Spacing

Spacing is the perpendicular distance between adjacent fractures of the same set within the outcrop. At most localities, a common range and the total range of spacings were recorded.

Mineralization/alteration

Field tests to characterize minerals were limited to inspection with a hand lens, simple hardness tests, and checking for the presence of carbonate minerals with dilute hydrochloric acid. Mineral coatings and fillings were noted and described along with alteration rinds and discolored surfaces along the fracture surfaces. Commonly, minerals on the joint surfaces were observed to be layered. Evidence of recracking and healing of the fracture was noted.

Terminations

Under this heading we recorded the principal evidence by which the sequence of fracture-set formation was interpreted. Abutting and crosscutting relations among coexisting sets of fractures were noted whenever observed. At any given locality, fractures of the first set to form show mostly blind endings within the rock--the fractures gradually taper to hairline cracks and then to zero width because no other fractures were yet present to impede their growth. Fractures of later sets, however, have less rock volume within which to grow before encountering another fracture. The mechanical properties of existing fractures generally are much different from those of the adjacent rock and represent physical barriers to fracture propagation. Thus, younger fractures commonly terminate against older ones. Also common are crosscutting fractures, which represent places where the walls of older fractures were bonded together in stress-transmitting contact, generally through cementation by minerals precipitated in the intervening void space ("healed" fractures). If both fractures are filled, the fracture with the continuous, unbroken fill is the younger. All of these relative-age criteria are for extension fractures, or common joints such as those discussed in this report. Relative-age criteria for crosscutting shear fractures are well known and not repeated here.

Although abutting and crosscutting relations generally offer the most powerful means of determining sequence of fracture, ambiguous relations were commonly observed. These arise from several causes: tectonic reactivation, so that newly propagated segments of old fractures grow to abut younger ones; offset of crosscutting fractures to produce false terminations; and surficial movement of joint-bounded blocks due to gravitative relaxation, downhill creep, frost-wedging, root wedging, etc., which alter the original geometry of fracture terminations and intersections. Careful observation can minimize the complications. Younger growth segments of older fractures, for example, commonly are of different orientation and may be unmineralized, although the original segment is filled.

Station symbols

Field descriptions and stereoplots for the various stations are arranged in the appendices in stratigraphic order. The prefix letters used for each station (CH, CKS, TR, etc.) correspond to the lithologic unit within which the data were taken and are identical to the symbols used by Scott and Bonk (1984) on their geologic map (fig. 2). A number placed after the letter designation (CH1, CH4, CKS4, CKS5, TR1) distinguishes different localities within the same lithologic unit. Specific fracture sets at each station are identified by the suffixes described below.

Fracture-set symbols

As knowledge grew as to how many sets exist, the order in which they formed, and how the sets of one locality correlate to those at another, we developed a formal symbology wherein each label has a consistent, specific meaning from one locality to another.

Extension joints that formed during cooling of the ash-flow tuffs at Yucca Mountain are common elements of the regional fracture network and were recorded at numerous localities. Cooling joints in many places show sufficiently strong evidence of preferential orientation that they can be divided into sets, designated C1, C2, etc. in relative order of decreasing prominence. Commonly two sets of steeply dipping joints at approximate right angles are present. In some localities a third set of cooling joints nearly parallel to the rock foliation is present. Because the cooling sets formed during a comparatively short interval of geologic time and are roughly contemporaneous, no implication of relative age is given by the symbols. As noted above, the numbers given to the sets imply relative prominence rather than relative age. Even so, among sets of steep to vertical cooling joints, the most prominent set often can be shown to be the oldest.

Cooling joints at a few localities show such weak evidence of preferred orientation that sets cannot be defined with confidence; these joints we label CM (for cooling joints, miscellaneous).

Tectonic joints are labeled T, and for these the numerical suffix *is* an indicator of relative age. T1, for example, refers to all joints that formed during the earliest known period of tectonic jointing at Yucca Mountain, T2 to the joints formed during the next-younger period, and so on. In one case, a tectonic set was identified but the authors were uncertain of its correlation to other tectonic sets. This set is labeled T without a numerical suffix.

SH is used as a general term to refer to sets of subhorizontal or gently dipping joints where proof or strong evidence of an origin by cooling is lacking. Nearly all of these are unloading joints that formed during erosion and consequent decrease of lithostatic load, but whether there was more than one such episode currently is uncertain. Foliation-parallel unloading joints in the Topopah Spring Tuff, for example, could have formed early, during erosion of the upper parts of that unit, or later, after eruption and subsequent removal of the overlying Tiva Canyon Tuff. For this reason we do not fit the SH joints into the T1-T4 fracture chronology but at each locality have attempted to deduce their origin.

Finally, M refers to sparse miscellaneous joints or joints that cannot be assigned to sets with confidence.

RESULTS

Introduction

The fracture network in the study area includes cooling joints of various types, at least four sets of tectonic fractures, weathering joints, and local blasting fractures. Only those fractures in the first two categories are discussed here. Sets of cooling and tectonic joints are present in different combinations and to various degrees of expression at different localities. The character of the local fracture network thus differs, sometimes markedly, from one locality to another, but a strongly defined regional pattern nonetheless exists.

Median orientations of all cooling joint sets are listed in Table 1 and those for tectonic sets are listed in Table 2 and plotted on figure 3. In addition, regional properties of each tectonic set (grand median orientation, strike range, strike dispersion) are given in Table 2. Median orientations were also calculated for cooling joint sets with preferred NE and NW strikes (table 3). Fracture orientations for sets from each station, plotted onto lower hemisphere equal-area projections (Schmidt net) are provided in Appendix B. For sets of horizontal joints, an informal measure of central tendencies was plotted on the stereonets, since medians cannot be calculated. Orientations of individual fractures belonging to T1-T4 joint sets are plotted in figure 4.

Cooling Joints

Field distinction between cooling and tectonic joints

Cooling joints in the volcanic units at Yucca Mountain and Fran Ridge comprise an important and locally dominant component of the fracture network (fig. 5). In some places they are instantly recognizable by the presence of "tubular structures" on their surfaces (fig. 6). Tubular structures were first studied in the upper lithophysal unit of the Tiva Canyon Tuff by Morgan (1984), who described them (p. iii-iv) as "distinctive channels or tubes, usually one centimeter or less in diameter, that characteristically form a braided pattern within the plane of the fracture". Their origin was later attributed to tensional tearing of joint surfaces upon vertical expansion of the ash-flow sheet as gases exsolved from the cooling tuff (Barton, 1984; Barton and Larsen, 1985; Barton and others, 1993). Formation of joints with tubular structures must thus be envisioned as a two-stage process: thermal contraction of the tuff during early cooling to form the initial fractures with quenched, smooth surfaces, followed by gas-driven expansion of the tuff upon further cooling to stretch the fracture surfaces and form the tubes. These gases caused the volume of the rockmass to expand during this latter stage so that cohesion between the two fracture surfaces was regained. Photomicrographs of thin sections across such healed fractures are shown in Morgan (1984).

A further characteristic of cooling joints in the upper lithophysal unit is their exceptional smoothness. Small-scale topographic relief on a fracture face can be expressed by a Joint Roughness Coefficient (RC) (Barton and Choubey, 1977) on a scale from 0 (very smooth) to 20 (exceedingly rough). Morgan's data for 5,000 fractures in the upper lithophysal unit showed that most of the smoothest fractures in that unit, those with roughness coefficients of only 0-1, also have tubular structures and thus are cooling joints. Morgan further noted that these smooth joints tend to be both long and nearly planar, and that none of them intersect the abundant lithophysal cavities in the rock. The latter observation implies that the tubular structures themselves served as avenues of gas escape at the cooling joint surfaces so that lithophysal cavities formed only at a certain distance away from them. Fractures with rougher surfaces almost uniformly lack tubular structures, intersect numerous lithophysal cavities (and hence postdate them), and were interpreted by Morgan as tectonic fractures if fairly long and as weathering joints if short. Later studies on cleared pavement surfaces (Barton and others, 1993) confirmed these results. Measured roughness coefficients for cooling joints range only from 1 to 4 with a peak at RC = 2, whereas those for later tectonic fractures range from 3 to 18 with a peak at RC = 10 (Barton and Hsieh, 1989; Barton and others, 1993).

Tubular structures, where present, provide undisputed evidence for cooling joints and are prominently developed in many exposures of the upper lithophysal unit. Even there, however, fractures lacking tubular structure but possessing all other characteristics of an origin by cooling--appreciable length, planarity, exceptionally smooth surfaces, and orientations in common with known cooling joints nearby--were noted both by Morgan (1984) and Barton and Larsen (1985). The absence of tubular structure, then, appears not to disprove an origin by cooling. Moreover, the combination of characteristics developed by Morgan (1984) and later workers for recognizing cooling joints was based almost exclusively on studies within the upper lithophysal unit and might not be valid for other units of different lithology, where tubular structures commonly are absent. Because cooling joints are not everywhere obvious as such, much of our early work concentrated on developing field criteria to distinguish them from tectonic joints in the other volcanic units exposed at Yucca Mountain.

Table 1. Median orientations of cooling joint sets in the study area.

Station	Cooling Sets C1	C2	C3	C4
TV1	N14E/84NW	N74W/85SW	--	--
TOB1	N28W/85SW	N80E/89SE	***N62E/10SE***[2]	--
TOB2	N19W/83SW	N60E/67NW	N34W/84SW	--
TR1	N10E/90	N70W/90	***N11W/15NE***[1]	--
TC1	N77E/79NW	N49W/83SW	N26E/83NW	--
TC2	N03E/78NW	N83W/85SW	***N02E/17SE***[1]	--
TC3	N11E/88NW	N50W/89SW	N42E/81NW	N88W/86NW
TC4	N89W/80NE	N13E/87SE	--	--
CC1	--	--	--	--
CH1	N70E/87NW	--	--	--
CH2	--	--	--	--
CH3	--	--	--	--
CH4	--	--	--	--
CH5	--	--	--	--
CH6	***N34E/19SE***[1]	--	--	--
CH7	--	--	--	--
CH8	--	--	--	--
CH9	N69W/83SW	N46E/87NW	***N67W/20NE***[1]	--
CLL1	N70W/73NE	--	--	--
CKS1	--	--	--	--
CKS2	N76E/88SE	N22W/84SW	--	--
CKS3	N35W/79SW	N55E/87NW	--	--
CKS4	N75E/85NW	--	--	--
CRS4	--	--	--	--
CRS5	N70W/83NE	--	--	--
CRS6	N39W/86NE	N53E/81NW	--	--
CRS7	N55W/85SW	--	--	--
CUL1	N76E/87NW	N21W/86SW	--	--
CUL2	N10W/83SW	N76E/89NW	***N79W/21NE***[1]	--
CUL3	N11W/78SW	N80E/88SE	***N48W/10NE***[1]	--
CUL4	N01W/84SW	N90E/90	--	--
CUL5	N45W/83NE	N38E/85NW	--	--
CUL6	--	-	--	--
CUL7	N55E/80NW	N45W/83NE	--	--
CUL8	N34W/89NE	N42E/78NW	--	--
CUL9	N50E/75NW	N51W/79NE	--	--
CUC1	--	--	--	--
CUC2	N38W/86NE	N36E/77NW	N02E/83NW	--
CCR1	N71E/89NW	N20W/87SW	--	--
CCR2	N52E/87SE	N43W/84SW	***N24E/11SE***[1]	--
CCR3	N40E/84NW	N69W/87SW	--	--

[1]Median orientations of gently dipping cooling joint sets.
[2]Two gently dipping sets (C3a, C3b) occur in different parts of the outcrop. Median orientation is given for most prominent set. Refer to field data in Appendix A for more information.

Table 2. Median orientations and regional properties of tectonic joint sets in the study area

Station	Tectonic Sets T1	T2	T3	T4
TV1	--	N30W/88NE	--	--
TOB1	N01E/89NW	--	N50E/86SE	--
TOB2	N05E/79SE	--	--	--
TR1	N10E/86NW	N41W/84SW	--	--
TC1	N05E/77NW	--	--	--
TC2	N02W/81SW	--	N39E/77NW	N87W/89SW
TC3	N11E/80NW	--	--	--
TC4	N04E/86SW	N18W/81NE	--	N88W/87NE
CC1	N04E/85NW	N45W/87SW	N46E/83NW	N86W/89NE
CH1	N12W/84SW	N52W/90[1]	--	N80W/86NE
CH2	N06E/84NW	--	N28E/87NW	N76W/90
CH3	N04W/78SW	N33W/77SW	N36E/87NW	N85W/88NE
CH4	N08E/86NW	N22W/88NE	--	N79W/83SW
CH5	--	--	N35E/90	--
CH6	N04W/88SW	N30W/85SW	N47E/89NW	N82W/86SW
CH7	N09E/85NW	--	N46E/89NW	N86W/88SW
CH8	N03E/89SE	N43W/86SW	--	N87E/88SE
CH9	N04W/82SW	--	--	--
CLL1	N11W/86NE	--	N28E/85SE	--
CKS1	N02W/80SW	--	N44E/85NW	N90E/81S
CKS2	--	--	N26E/84SE	N72W/85SW
CKS3	--	--	--	--
CKS4	N06W/86SW	N31W/77SW	--	--
CRS4	N07W/88SW	--	--	--
CRS5	--	--	--	--
CRS6	N05W/90	--	--	N78W/81NE
CRS7	--	N24W/87SW	--	--
CUL1	--	N32W/84SW	N35E/87NW	N72W/76SW
CUL2	--	--	--	--
CUL3	--	--	--	--
CUL4	--	--	--	--
CUL5	N07W/88NE	--	N18E/86SE	--
CUL6	N09W/83NE	--	N50E/81NW	--
CUL7	--	--	--	--
CUL8	--	--	--	--
CUL9	N10E/86NW	N31W/82SW	--	N75W/81SW
CUC1	--	N21W/85SW	--	--
CUC2	--	--	--	--
CCR1	--	N27W/86SW	--	--
CCR2	--	--	--	--
CCR3	--	--	--	--
Grand median orientation	N01W/86SW	N31W/86SW	N38E/88NW	N82W/88SW
Strike range	N11E-N12W	N18W-N52W	N18E-N50E	N72W-N87E
Strike dispersion	23°	34°	32°	21°

[1]Two subsets of T2 (T2a, T2b) occur in different parts of the outcrop. Median orientation is given for most prominent set. Refer to field data in Apendix A for more information.

Table 3. Median strikes of cooling joints for localities within enclosed area on Figure 11.

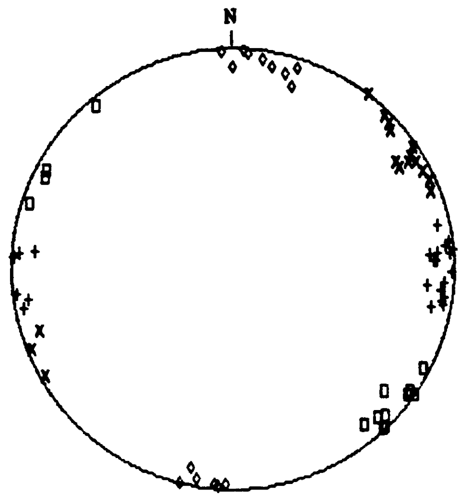
Station	Cooling Sets NE-striking	NW-striking
CH1	N70E[3]	--
CH6	N34E[3]	--
CLL1	--	N70W[3]
CKS4	N75E[3]	--
CRS5	--	N70W[3]
CRS6	N53E	N39W[3]
CRS7	--	N55W[3]
CUL5	N38E	N45W[3]
CUL7	N55E[3]	N45W
CUL8	N42E	N34W[3]
CUL9	N50E[3]	N51W
CUC2	N36E	N38W[3]
CCR1	N71E[3]	N20W
CCR2	N52E[3]	N43W
CCR3	N40E[3]	N69W
Pvmt 100[1]	N48E[3]	N45W
Pvmt 200[1]	N37E[3]	--
Pvmt 300[1]	N36E	N40W[3]
Pvmt 600[2]	N35E[3]	--

1 = Refer to Barton and others (1993)

2 = Pavement 600 was mapped in 1985 by C.K. Throckmorton; C.C. Barton, unpub. data, 1985

3 = Dominant set

n = 69



+	MEDT1	n =	24
x	MEDT2	n =	16
□	MEDT3	n =	14
◇	MEDT4	n =	15

Schmidt net, lower hemisphere projection

MEDT1	MEDT2	MEDT3	MEDT4
N04E85NW	N45W87SW	N46E83NW	N86W89NE
N12W84SW	N27W86SW	N28E87NW	N80W86NE
N06E84NW	N52W90SW[1]	N36E87NW	N76W90NE
N04W78SW	N34W88SW[1]	N35E90NW	N85W88NE
N08E86NW	N33W77SW	N47E89NW	N79W83SW
N04W88SW	N22W88NE	N46E89NW	N82W86SW
N09E85NW	N30W85SW	N44E85NW	N86W88SW
N03E89SE	N43W86SW	N26E84SE	N87E88SE
N04W82SW	N31W77SW	N28E85SE	N90E81SE
N02W80SW	N24W87SW	N35E87NW	N72W85SW
N06W86SW	N21W85SW	N18E86SE	N78W81NE
N11W86NE	N32W84SW	N50E81NW	N72W76SW
N07W88SW	N31W82SW	N39E77NW	N75W81SW
N05W90SW	N18W81NE	N50E86SE	N87W89SW
N07W88NE	N41W84SW		N88W87NE
N09W83NE	N30W88NE		
N10E86NW			
N05E77NW			
N02W81SW			
N11E80NW			
N04E86SE			
N01E89NW			
N05E79SE			
N10E86NW			

[1]Median orientations are given for two subsets of T2 (T2a, T2b), that occur in different parts of the outcrop at station CH1. Refer to field data in Appendix A for more information.

Figure 3.--Stereographic plot showing median orientations of T1-T4 joint sets for all stations.

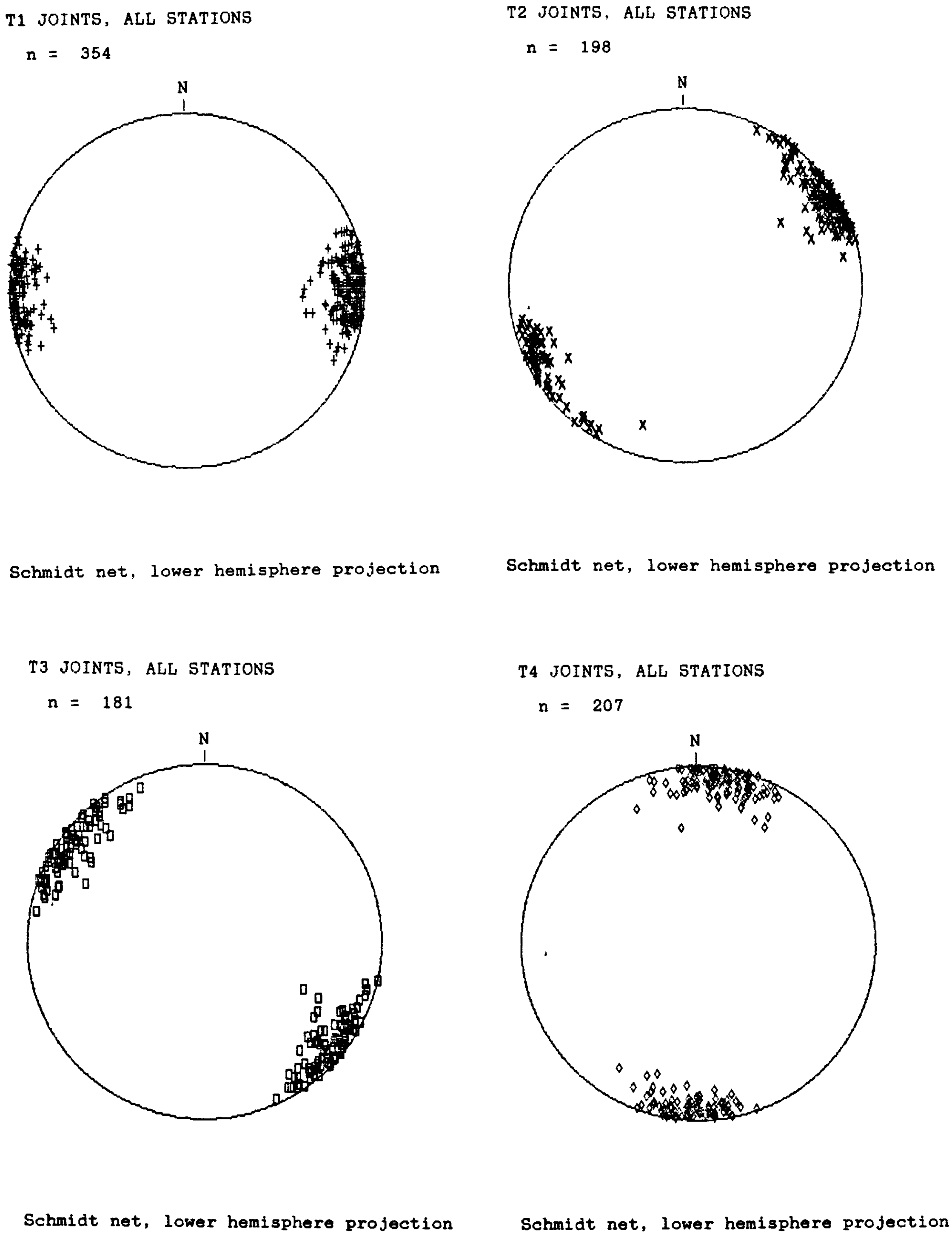


Figure 4.--Stereographic plot showing fracture orientations of T1-T4 joints for all stations. Explanation of symbols shown on figure 3.

Figure 5.--Photograph of reactivated, prominent north-striking cooling joints on east side of Fran Ridge in the Topopah Spring Tuff, just south of station TC3. Joints extend from the caprock unit downward through the thin lithophysal unit into the rounded step unit. One joint (N02W/82SW) is 20 m long and 16 m high. Many joints with similar orientations are of comparable size. View is to north.

Figure 6.--Tubular structures on N27E/89NW cooling joint 6 m north of station CUL5. Exposed joint surface is approximately 2 m in length and 0.7 m in height. Tube diameters range from 0.4 to 1 cm. View is northwest.

Tubular structures proved to be sparse or absent in most volcanic units but were found on some cooling joints within the orange brick unit of the Topopah Spring Tuff and the hackly, lower lithophysal, upper lithophysal, upper cliff, and caprock units of the Tiva Canyon Tuff. These joints provided a starting point to document other properties by which cooling joints might be recognized in the same and possibly other units. A constant property of known cooling joints in all units studied was very low surface roughness. By itself, however, smoothness to the touch is not diagnostic of cooling joints, for the surfaces of undisputed tectonic joints in several units (vitrophyre, orange brick, rounded, hackly, and rounded step) are nearly as smooth as those of cooling joints in the same exposures. Very smooth tectonic joints are nonetheless uncommon, and smoothness remains a prime criterion for recognizing cooling joints in all units studied.

The evident planarity of cooling joints, a property remarked upon by Morgan (1984) for cooling joints within the upper lithophysal unit of the Tiva Canyon Tuff, is characteristic only of areas where they form two well-defined, nearly vertical sets at approximate right angle to each other. Elsewhere, where the pattern of cooling joints is of fundamentally different geometry (see following section), shapes of cooling joints range from gently sinuous to markedly curved. Tectonic joints, as later discussed, generally range in shape from subplanar (gently to moderately sinuous) to nearly planar--thus, gross fracture shape is not often a reliable discriminator between cooling and tectonic fractures. On a finer, decimeter scale, however, the shapes of cooling joints and tectonic fractures exhibit consistent differences in nearly all units studied. The differences are most apparent in their traces on pavement surfaces: traces of cooling joints are smoothly continuous , as if they had been drawn with a French curve, whereas those of tectonic joints in the same exposures are distinctly more irregular. Though some of the surface irregularities on tectonic joints are sufficiently small that they are expressed in the Joint Roughness Coefficient mentioned above, others are of broader wavelength and are best detected visually.

Early in this study, fracture size (primarily length) was recognized as a useful criterion for identifying cooling joints in units where tubular structures are sparse or absent. Our results support and extend the correlation noted earlier by Morgan (1984) for the upper lithophysal unit: the smoothest fractures in most of the exposures studied are among the longest fractures present. At stations TC2, TC4, CRS6, CUL4, and CCR1, for example, most of the cooling joints belonging to the most prominent set (C1) have lengths of 5 m or more, but the later tectonic fractures generally are only 0.5-3 m long. The length difference between cooling and tectonic joints in some exposures is so marked that the cooling joints are recognizable on sight. The commonly shorter length of tectonic fractures resulted in part from their formation in a rock already cut by abundant cooling joints, whose presence impeded lateral growth of later fractures.

All of the above criteria for recognition of cooling joints refer to properties of individual fractures. Their collective network geometry, however, can also aid in their recognition. For example, a large number of triple junctions--three fractures radiating from a common point at approximate 120° interplanar angles--can only signify a crude hexagonal network of cooling joints. Network geometries of cooling joints are discussed in more detail below.

The final criterion for recognition of cooling joints, and in some respects the most powerful one, is relative age: only the oldest fractures in any given exposure can be considered as potential cooling joints. Close attention to abutting and crosscutting relations was paid in our studies to establish relative age of fracture sets wherever possible. The results confirmed that fractures showing the properties mentioned above--very low surface roughness, smooth, continuous traces, appreciable length, and locally marked sinuosity or curvature--consistently are the oldest (fig. 7). We thus interpret them as cooling joints and conclude that a combination of these characteristics, together with demonstration of early relative age, is sufficient to distinguish cooling from tectonic joints in most areas where tubular structures are absent.

Network patterns of steeply dipping cooling joints

Quantitative analysis of the network geometries of steeply dipping cooling joints was to have been one element of our later work at Yucca Mountain, and we have made no special study of them. Reconnaissance field work, however, soon showed that the prominent rectangular pattern documented by Morgan (1984) and Barton and Larsen (1985) for parts of the upper lithophysal unit, though common in other units as well, does not everywhere apply; cooling joints in some places conform instead to crude hexagonal networks or to networks of mudcrack geometry. We here provide a few preliminary observations.

Cooling joints in moderately to densely welded parts of the columnar unit, near the base of the Tiva Canyon Tuff, divide the rock into the abundant, crude, vertical columns for which the unit was named by Scott and Bonk (1984). Brief examination of low, cliff outcrops of the columnar unit in Drill Hole Wash revealed numerous places where three fractures radiate from a common vertical axis, thereby confirming that many of the fractures present are cooling joints and that their pattern is based on an hexagonal motif. Column diameters of 20-100 cm are common. Tectonic joints in the columnar unit are uncommon at Drill Hole Wash, in large part because the sheer abundance of cooling joints inhibited their formation. Hexagonal networks of cooling joints, though possibly common in the columnar unit, were not noted by us in any of the other units studied.

Two sets of steeply dipping cooling joints at approximate right angle to each other were documented at 23 of 41 joint stations in the Topopah Spring and Tiva Canyon Tuffs and comprise the dominant pattern of cooling joints at Yucca Mountain. Map units in which such rectangular networks were found include the vitrophyre, orange brick, rounded, and caprock units of the Topopah Spring Tuff and the hackly, clinkstone, rounded step, upper lithophysal, upper cliff, and caprock units of the Tiva Canyon Tuff. Further work almost certainly will disclose them in other units also. Angles between the two sets, as measured clockwise from the dominant (C1) to the subordinate (C2) cooling set, range from 71° to 115° and have a median value of 89.5° (fig. 8). Departures of more than 10° from true perpendicularity may reflect sparsity of data as much as reality: at five of seven stations showing such departure, only 4-8 cooling joints of the subordinate set were found for measurement. Weak expression of one cooling set relative to the other is common. An extreme example is pavement 100 (fig. 1) of Barton and Larsen (1985), wherein one cooling set is represented by abundant, long, closely spaced joints and the second only by several short joints. At several of our stations, too (CH1, CH6, CLL1, CKS4, CRS5, CRS7), we measured one well-expressed set of cooling joints but were unable to verify the certain presence of a second set. At pavement 600, located in the northern part of the study area, only one, poorly expressed cooling set is present, although two sets at right angles are documented at a nearby station (CUL8). Nearly equal development of the two sets, though uncommon, was noted at stations TOB1, CUL7, and CCR3.

Gentle curvature of rectangular cooling-joint networks over distances of tens to hundreds of meters seemingly is common, but only rarely is the curvature pronounced at that scale. Data from one example are shown in fig. 9 for a set of probable cooling joints at station CUL4, just above the base of the upper lithophysal unit at a locality near the north end of Fran Ridge.

Figure 7.--Cooling joint belonging to C2 set, exposed in trench (locality CKS3), 0.3 km west of Fran Ridge. Joint curves 34° over a length of 2.6 m. Dip change is very gradual. Joint has been reopened, probably during movement on the Paintbrush fault, and is filled with a 13-cm-thick, white, noncalcareous mineral fill (resembling chalcedony or opaline silica). Small, angular pieces of clinkstone are present within the fill.

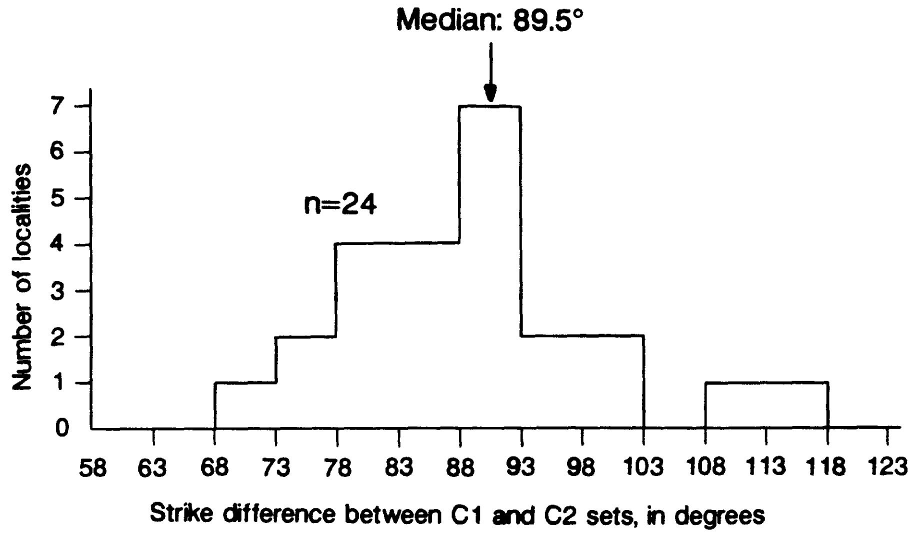


Figure 8.--Linear histogram showing strike difference between pairs of cooling-joint sets on and near Yucca Mountain. The plot reflects the common tendency for cooling-joint sets to form crude rectangular networks. The median angle between sets is 89.5°. At one locality (TC3) near the top of the Topopah Spring Tuff, two cooling episodes resulted in four cooling sets which locally coexist; thus 24 joint-set pairs are represented from 23 localities.
n = total number of joint-set pairs.

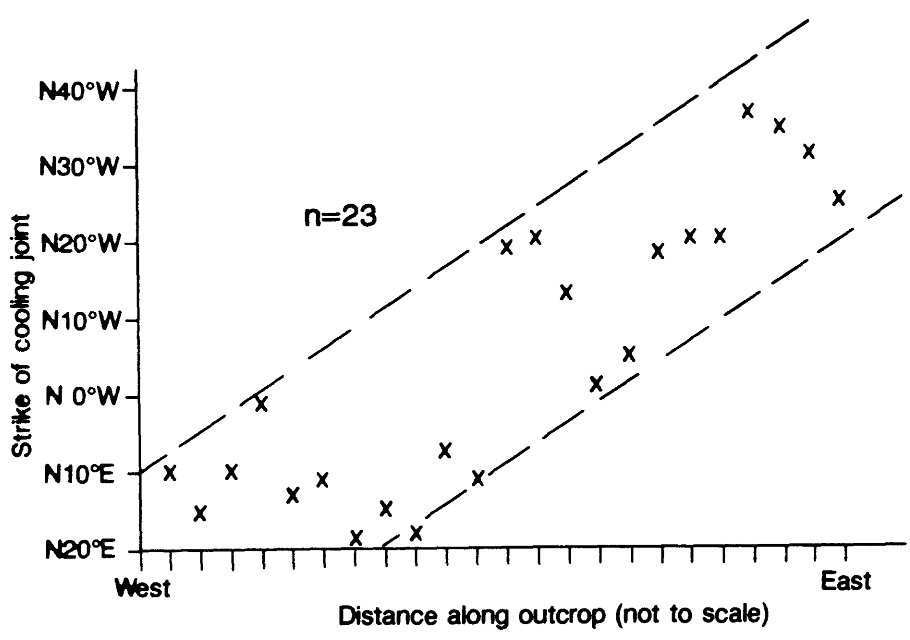


Figure 9.--Strikes of cooling joints at station CUL4, plotted from the west end of the outcrop (left) to the east end (right), showing apparent strong curvature of a cooling-joint set within a horizontal distance of several tens of meters. Distances along horizontal axis not to scale.
n = total number of measurements.

The large (56°) strike dispersion of this set, from N. 19° E. to N. 36° W., at first proved puzzling until the data were plotted in the order in which they were measured from one end of the outcrop to the other. The resultant plot (fig. 9) suggests that the cooling-joint set curves 50° over a lateral distance of only 30 m, from N. 20° E. strikes at the west end of the outcrop to N. 30° W. strikes near the east end.

Cooling joints with a distinctive mudcrack geometry seemingly are rare at Yucca Mountain and are not present at any of our 41 formal joint stations. Nevertheless we noted them in several places, and they may be more common than is generally realized. Characteristics of this pattern include pronounced curvature of some of the fractures, lack of triple junctions (as opposed to their common presence in hexagonal networks), and consistent right-angle terminations of one fracture against another.

Subhorizontal cooling joints

Cooling joints of low dip, parallel to foliation in the tuff or transecting it at low angles, were documented at eight localities on Yucca Mountain and Fran Ridge (table 1). At seven of them the presence of tubular structures on the joint surfaces served as proof of origin (fig. 10). Median dips of these joints range from 8° to 21° to the northeast or southeast, reflecting the generally eastward tilt of the rocks. To date we have found low-dipping cooling joints in the orange brick, rounded, and caprock units of the Topopah Spring Tuff and in the hackly, upper lithophysal, and caprock units of the Tiva Canyon Tuff. Though seemingly widespread there is no mention of them in the previous literature, probably because they often passed unrecognized among the generally much greater numbers of unloading joints of similar orientation. In addition to tubular structures, distinction between the two types of joints is based on the following criteria:

- The cooling joints have smooth, undulatory, subplanar to nonplanar surfaces. Unloading joints commonly are of similar shape but have decidedly rougher surfaces.
- The cooling joints only rarely cut lithophysae, even in units where lithophysal cavities are abundant. The later unloading joints cut through lithophysae indiscriminately and, as later discussed, commonly originated at them.
- Abutting relations at several localities show that the gently dipping cooling joints are either the oldest joints present or formed during the same time period as those of steep dip. At station TR1, for example, numerous, nearly vertical joints of the earliest known tectonic set terminate against smooth joints parallel to foliation; the low-dipping joints are thus interpreted as due to cooling. Similarly, at station CUL3, the continuity of tubular structures on one gently dipping cooling joint intersected by a second, vertical cooling joint demonstrates the early age of the low-dipping joint. Numerous abutting relations at station TC2 show that the gently dipping cooling joints formed later than some of those of steep dip and earlier than others. Foliation-parallel fractures due to unloading, in contrast, are much younger and characteristically terminate against or intersect the steeply dipping tectonic joints.
- At two localities (TC2, CCR2) the cooling joints increase in abundance downward, the opposite of the expected trend for unloading joints.

Figure 10.--Tubular structures on subhorizontal cooling joint at station CUL3 on Fran Ridge. The joint surface is smooth and slightly irregular in shape. Tube diameters range from 1-3 mm and are spaced 4-7 cm apart.

The low-dipping cooling joints thus have several properties in common with those of steep dip: smooth surfaces, early age relative to tectonic joints, tubular structures, common undulatory shape, and, in some localities, large size. Collectively these properties are useful in distinguishing cooling from unloading joints in the much same manner as steeply dipping cooling joints are distinguishable from tectonic fractures.

At all localities but one (CH6) where foliation-parallel cooling joints were found, two sets of steeply dipping cooling joints are present also. In three dimensions these joints form mutually orthogonal fracture arrays, but in most places the joints of all three sets differ markedly in average size, abundance, and spacing. The low-dipping cooling joints invariably are less abundant than those of the other two sets but at some localities are fairly prominent nonetheless.

Preferred orientations of cooling joints

Median orientations of cooling joint sets are shown in figure 11 and listed in Table 1. The data, though too sparse to be definitive, suggest that cooling joints in Tiva Canyon Tuff within the northern part of the Yucca Mountain block--the area enclosed by the dashed line on the figure--are preferentially oriented and thus potentially amenable to realistic characterization. The proposed repository site lies within this area.

Strike data for cooling joints at 15 localities and four pavements within the proposed repository site are listed in Table 3 to show their consistency. Relative prominence of each set is shown. The data are readily interpretable in terms of two sets, one striking N. 20°-70° W. and the other N. 34°-71°E. (grand medians are N. 45° W. and N. 50° E., respectively). The total strike range represented by the two sets is less than half the possible range of 180° and underscores the nonrandom nature of the rectangular cooling-joint pattern at this scale. Preferred orientations of cooling joints over an area of about 0.2 km^2 was demonstrated from the earlier work of Morgan (1984) and Barton and others (1989, 1993). Our results suggest the same is true for most of the northern half of Yucca Mountain within an area of more than 20 km^2 underlain by various units of the Tiva Canyon Tuff.

Tectonic Joints

The term *tectonic joint* is used here in its broadest sense to indicate all natural joints not related to contractional cooling or to surficial processes such as weathering and mass wasting. Tectonic joints thus potentially include joints due to regional crustal extension or compression, volcanism and caldera formation, and unloading due to erosion of overlying rock. Our results suggest that five sets of tectonic joints are present in the field area and that they formed in the order discussed below.

Regional extension joints: T1 through T3 sets

Tectonic joints striking within 40° of due north are present in great numbers on Yucca Mountain. Where well-formed they are divisible into three sets on the basis of orientation and abutting relations. Probably most or all of them are elements of a regionally consistent joint network, but this inference cannot be tested until the nature of that network has been documented over a far larger area than has been studied to date. The tectonic significance of each set remains uncertain for the same reason, though their generally northerly strikes suggest an origin by Basin-and-Range crustal extension, the differing strikes of each set possibly reflecting noncoaxial extension over time.

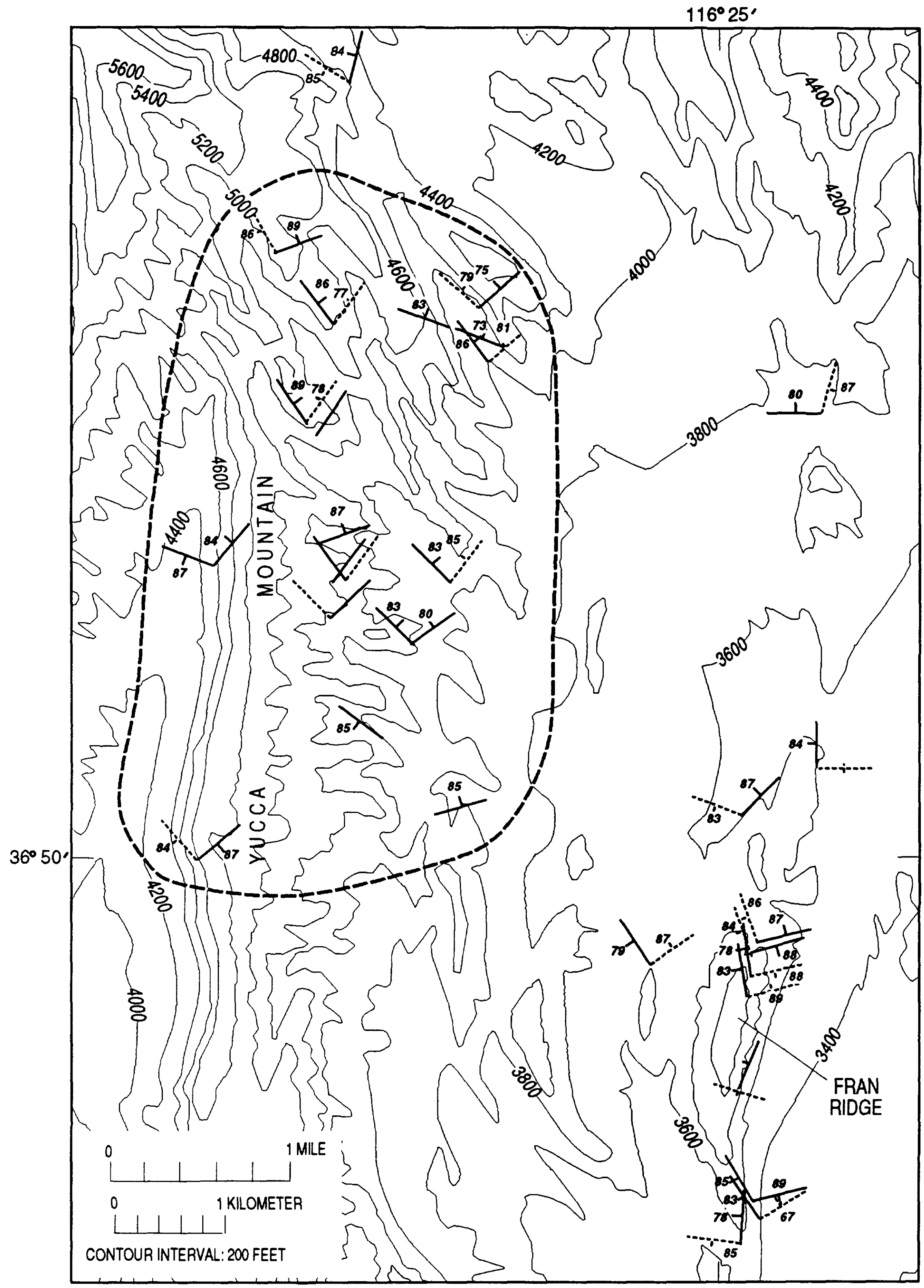


Figure 11.--Map showing median orientations of cooling-joint sets in the Tiva Canyon and Topopah Spring Tuffs. Dashed line encloses area within which cooling-joint sets show preferred NW and NE strikes. Solid and dashed strike symbols indicate dominant and subordinate sets, respectively. Not all stations on Fran Ridge are plotted due to the close proximity of stations.

T1 set: North-striking joints

A set of joints (fig. 12, table 2) with a grand median orientation (median of median orientations calculated for each joint set) of N. 01° W. 86° SW. was documented at nearly 60 percent of all localities studied. These earliest formed tectonic joints show the lowest strike dispersion (23°) from place to place of any regional extension set: their strikes range only from N. 11° E. to N. 12° W. Surface structures on T1 joints typically are inconspicuous, but local arrest lines and twist hackle show that they are extension fractures.

The prominence of the T1 set varies greatly but in general is inversely related to that of the cooling joints. Where cooling joints are few, as in much of the hackly unit, the T1 set reaches its greatest development. The T1 set is present at eight of the nine stations studied within this unit, and at five it is the dominant set. Conversely, where cooling joints are both large and abundant, as in much of the upper lithophysal unit of the Tiva Canyon Tuff, the T1 joints form only a weak set or are absent; we found them, in low numbers, in only three of nine localities. The effect of prominent existing sets of joints in suppressing the development of later sets is well illustrated by the T1 set at Yucca Mountain.

At many localities joints of the T1 set are the largest of all tectonic joints present; only some of the earlier cooling joints are larger. Exposed lengths of 2-5 m are common among T1 joints, and some may be traced for more than 7 m in exposures large enough to permit it. These values likely are close to true lengths in several places (TR1, CH7, CRS4), but in others, where few ends of T1 joints are exposed, their true lengths remain unknown. Exposed heights of 1-3 m are the norm, but some have exposed heights of 4-6 m (CH1) and rarely as much as 12 m (TOB1). In places, however, the presence of abundant lithophysal cavities appears to have inhibited the development of large tectonic joints: T1 joints at station CLL1 in the lower lithophysal unit and at station CUL5 in the upper lithophysal unit are uniformly small, less than a meter in maximum dimension.

Surface properties (gross shape, roughness) of T1 joints differ from unit to unit, but subplanar to locally planar joints with moderately rough to very rough surfaces are characteristic of more than 60 percent of the localities at which the T1 set is present. T1 joints are commonly planar, and those with surfaces as smooth as those of typical cooling joints are rare. Smooth to fairly smooth T1 joints are most common in the hackly unit (eight localities), but even there they are noticeably rougher than cooling joints in the same exposures. Regardless of overall shape or surface roughness, however, the irregular traces of T1 joints on a centimeter to decimeter scale set them apart from cooling joints, with their smoothly continuous traces, at most localities.

T2 set: North-northwest-striking joints

Tectonic joints of the T2 set (fig. 13, table 2) were documented at 15 of 41 (37 percent) of the localities studied and have a grand median orientation of N. 31° W. 86° SW. Local twist hackle and arrest lines show that the T2 joints are extension fractures, as do common hooks of individual T2 joints into joints of the same and older sets.

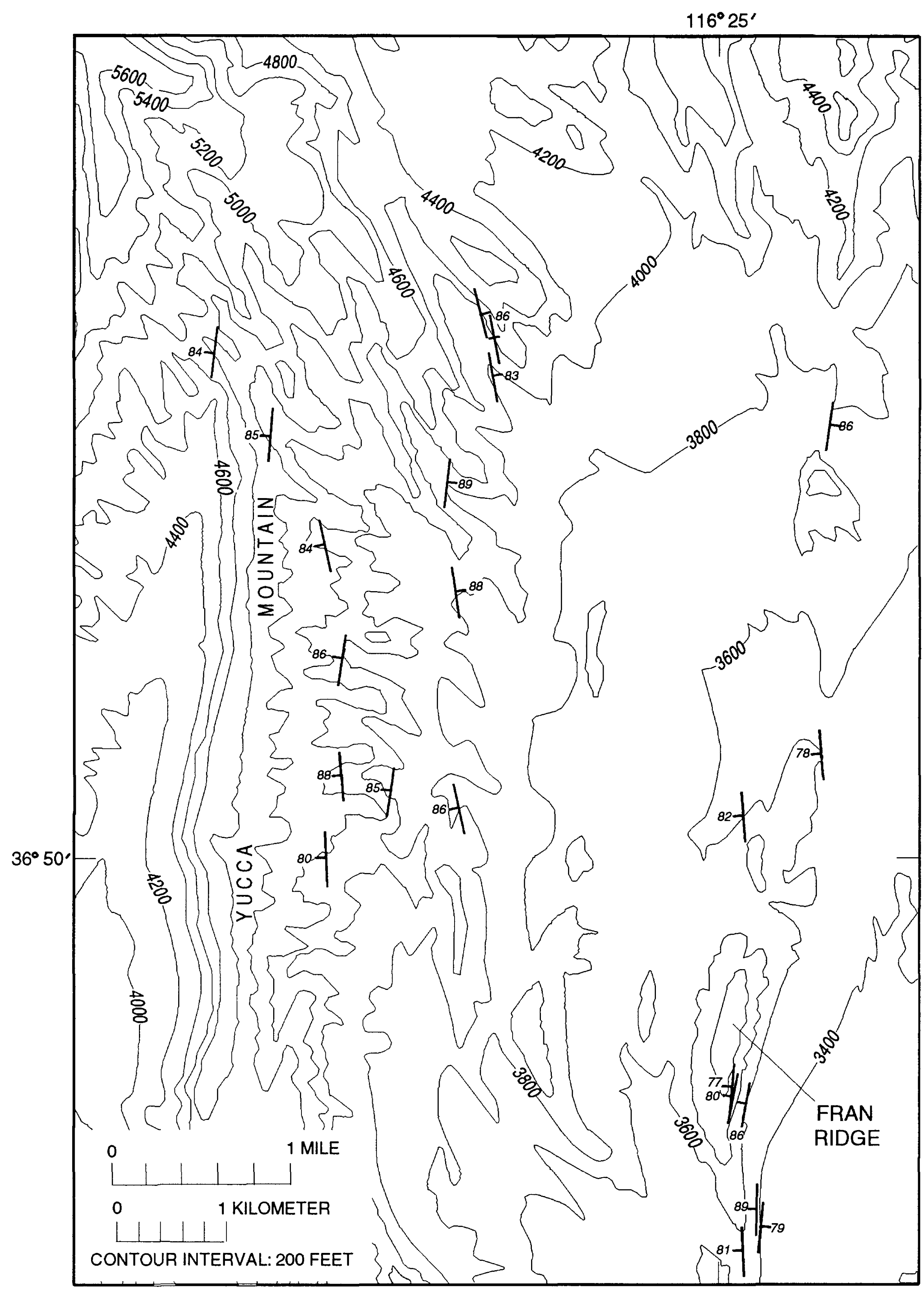


Figure 12.--Map showing median orientations of T1 tectonic joints in the Tiva Canyon and Topopah Spring Tuffs. All stations are not plotted due to the close proximity of stations.

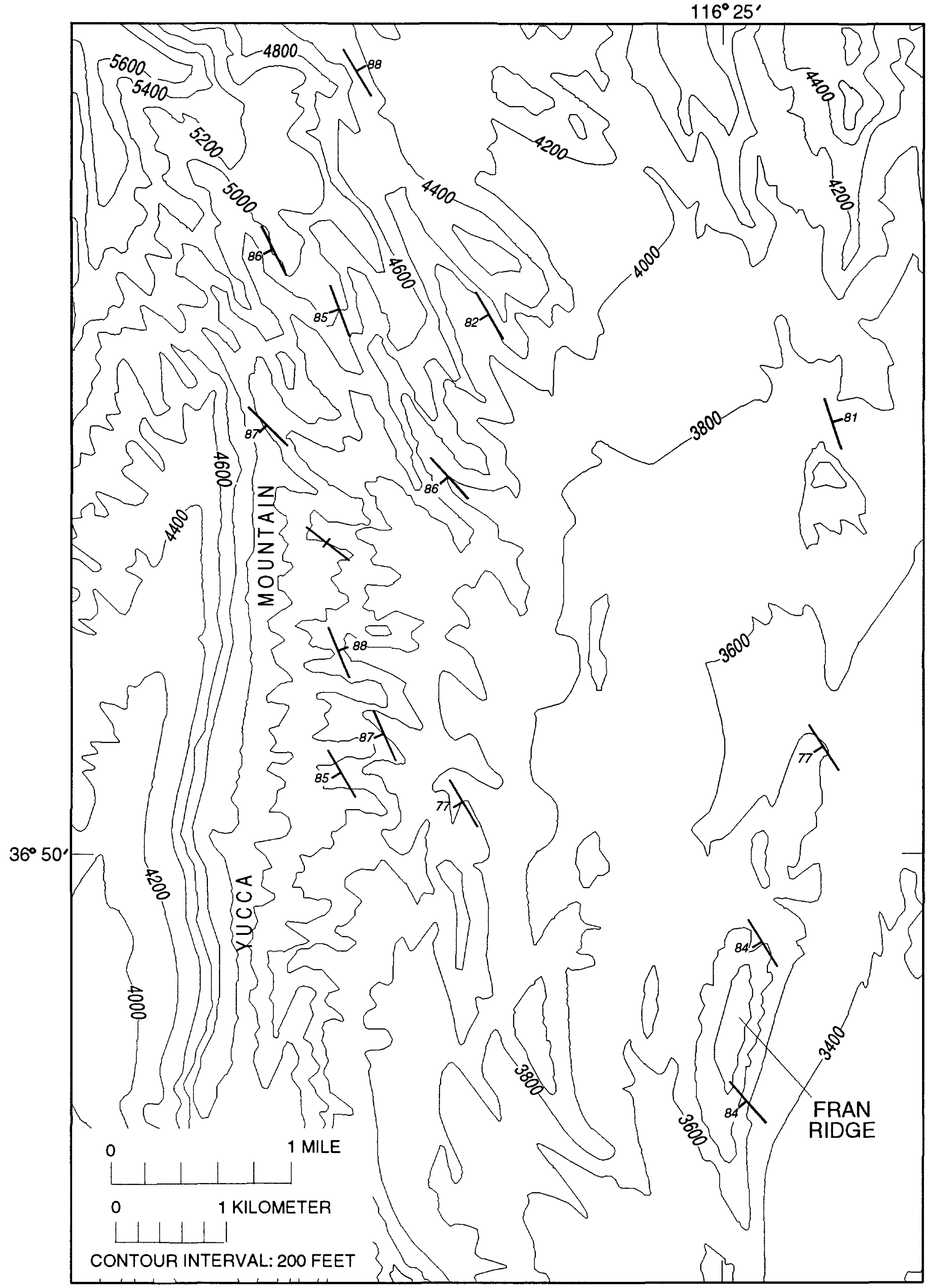


Figure 13.--Map showing median orientations of T2 tectonic joints in the Tiva Canyon and Topopah Spring Tuffs.

Several properties of the T2 set of joints are a direct consequence of their younger age relative to the T1 set:

- At 11 of the 15 stations where the T2 set was documented, its prominence is inversely related to the abundance of older joints in much the same manner as discussed previously for the T1 set. At stations CH6, CRS7, and CCR1, for example, where joints of earlier sets are sparse, abundant T2 joints constitute the *dominant* component of the local fracture network. Conversely, at stations TR1, CC1, CH3, CH4, and CH8, the T2 set is only weakly developed, but at all five stations the T1 set is prominent. At 26 other localities--more than 60 percent of those studied--the T2 joints are absent, in large part because their development was inhibited by abundant joints already present.

- Median orientations of T2 joints are more variable from place to place than those of the T1 set because the T2 joints formed in more-fractured, less isotropic rock. Most T2 joints strike within the range of N. 20° W. to N. 40° W., but the total strike deviation of 34° (N. 18° W. to N. 52° W.) is 12° greater than that of the T1 set.

- T2 joints are shorter on average than those of older sets because, during growth, they commonly terminated against fractures already present. Exposed lengths of 2.5 m or less are typical of most localities, as at station TV1, where closely spaced cooling joints of north-northeast strike constrained lateral growth of the later T2 joints. The only stations where lengthy T2 joints were recorded are CUC1 and CCR1, where the large thickness of the upper cliff unit and the absence of the T1 set allowed joints of exceptional dimension to form.

Traces of T2 joints commonly are gently curved or sinuous along strike, but at a few localities they are very nearly planar. Their surfaces, though everywhere rougher and more irregular than those of cooling joints in the same exposures, seem smoother than those of coexisting T1 joints. Reasons for the different surface morphologies remain obscure, and we have made no special study of them, but it should be noted that tectonic joint sets of different roughness in the same rock are known from many localities worldwide.

Abutting relations between T2 and T1 joints were observed at a sufficient number of localities that the relative age of the two sets seems fairly well established. The tips of T1 joints locally served as origin points for the later propagation of T2 joints, as shown in fig. 14, confirming this age relationship. The resultant structure has the appearance of a single kinked joint but is due to two stages of growth, during the second of which minor left-lateral shear occurred on the T1 joints. Similar structures have recently been described by Cruikshank and others (1991).

T3 set: Northeast-striking joints

The T3 set of joints (fig. 15, table 2), with a grand median orientation (strike and dip) of N. 38° E. 88° NW., was documented at 14 of 41 localities. Surface structures on these joints are sparse, but their origin as extension fractures is indicated by local arrest lines, abundant hooks of T3 joints into older joints, and, at one locality (CC1), by the lack of shear offset along T3 joints where they cut conspicuous pumice fragments within the tuff.

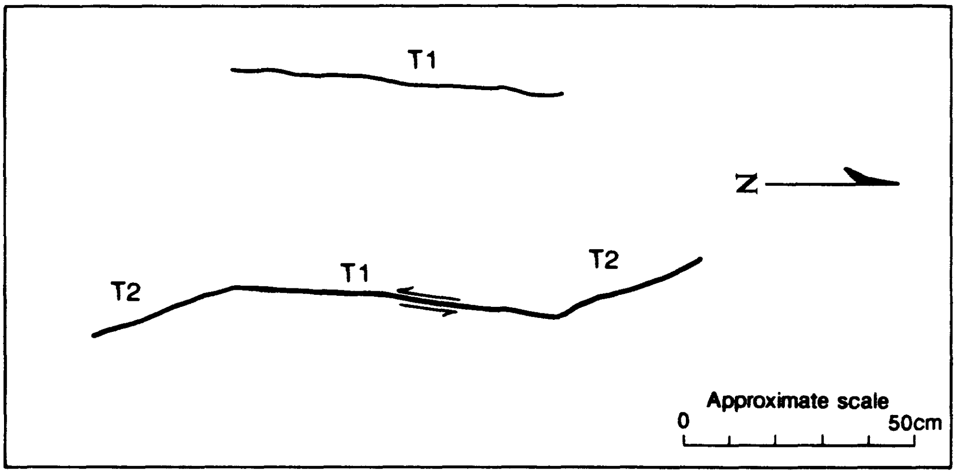


Figure 14.--Sketch showing common appearance of reactivated T1 joints at station TC4. Top, original joint. Bottom, resultant structure after reactivation during formation of the T2 joint set. New growth segments coincide in strike with those of T2 joints in adjacent rock. Opening of T2 joint segments is accompanied by a minute amount of left-lateral shear on the original T1 joint. See Cruikshank and others (1991) for discussion of similar structures.

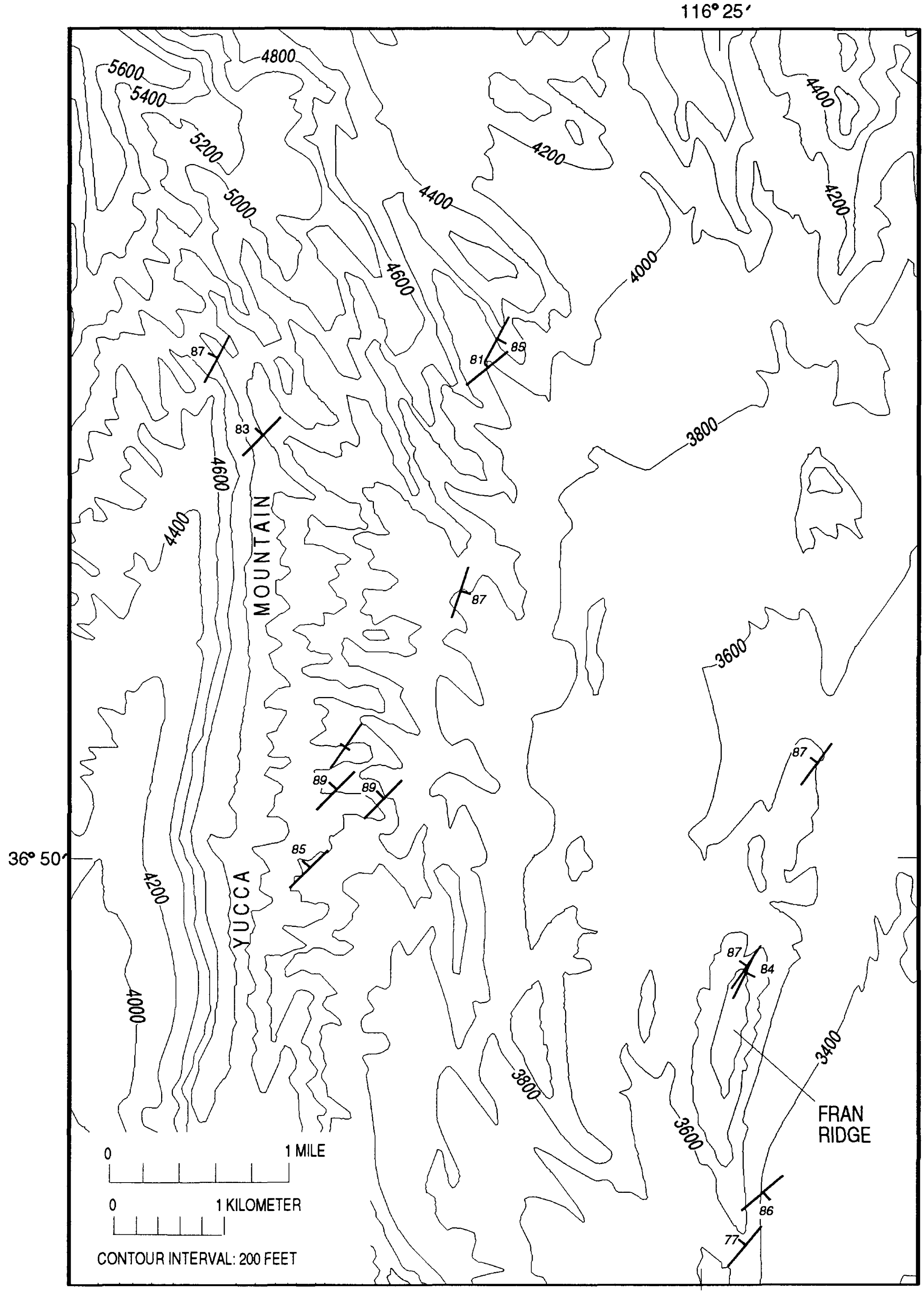


Figure 15.--Map showing median orientations of T3 tectonic joints in the Tiva Canyon and Topopah Spring Tuffs.

To an even greater degree than joints of the T2 set, most properties of the T3 joints reflect their development in rock already abundantly fractured:

- The T3 set, though present at approximately the same number of localities as the T2 set, is subordinate to one or another of the older tectonic sets. The set is absent from station CH4, where abundant T1 joints form the dominant component of the local fracture network.

- T3 joints commonly are shorter than those of earlier sets because their lateral growth was constrained by fractures already present. Joints older than the T3 set in some localities (CC1) are so numerous that the heights of T3 joints exceed their lengths. The marked effect of previous fracture history on T3 joint size is perhaps best illustrated by station CH2. T1 joints in most of this large exposure are so numerous and closely spaced that the later T3 joints are small, only 0.5-1.5 m long and 0.2-0.6 m high, except toward the west end of the outcrop. There, where T1 joints are more widely spaced and locally absent, the T3 joints grew to much larger size: 4-6 m long and 2-3 m high.

- The effect of joint propagation within fractured, anisotropic rock, where local stress directions commonly deviate from the regional (far-field) stresses, is reflected in the subplanar to locally nonplanar shapes of many T3 joints. T3 joints commonly are undulatory along strike, and some are markedly curved, much more so than those of earlier tectonic sets. The only place where planar T3 joints were recorded is the western end of station CH2, where, as noted above, earlier joints are anomalously sparse.

- Hooklike terminations of T3 joints against other joints are more common than among T1 or T2 joints because the T3 joints in most places propagated in rock already well fractured.

Surfaces of T3 joints range from fairly smooth (rare) to rough (common). Even among the most smooth T3 joints, however, their traces are irregular on a centimeter to decimeter scale, much like those of other tectonic joints and distinctly dissimilar to those of cooling joints.

T3 joints hooking toward and terminating against T1 joints were documented at so many localities that the later age of the T3 set seems assured. The T3 and T2 sets, however, are present together at only four of the localities studied, and abutting relations were visible at only two of them (CH3 and CH6). Though the presence of several T3 joints abutting T2 joints at both localities supports the sequence of formation given here, inference that the T3 set is the younger should be regarded as tentative, not proven.

Unloading joints: T4 and SH sets

The two youngest joint sets at Yucca Mountain formed upon reduction of lithostatic load during erosion as the rock adjusted to new, near-surface stress conditions. Both sets, as explained below, have genetic parallels among common types of unloading joints in sedimentary and plutonic rocks.

T4 set: West-northwest-striking joints

Steeply dipping T4 joints (grand median orientation: N. 82° W. 88° SW.; table 2, fig. 16) form a widespread but generally minor component of the fracture network at Yucca Mountain. Among the 15 localities where we documented their properties, the set is weakly to only moderately developed at 12 of them, and nowhere do they constitute the dominant joint set.

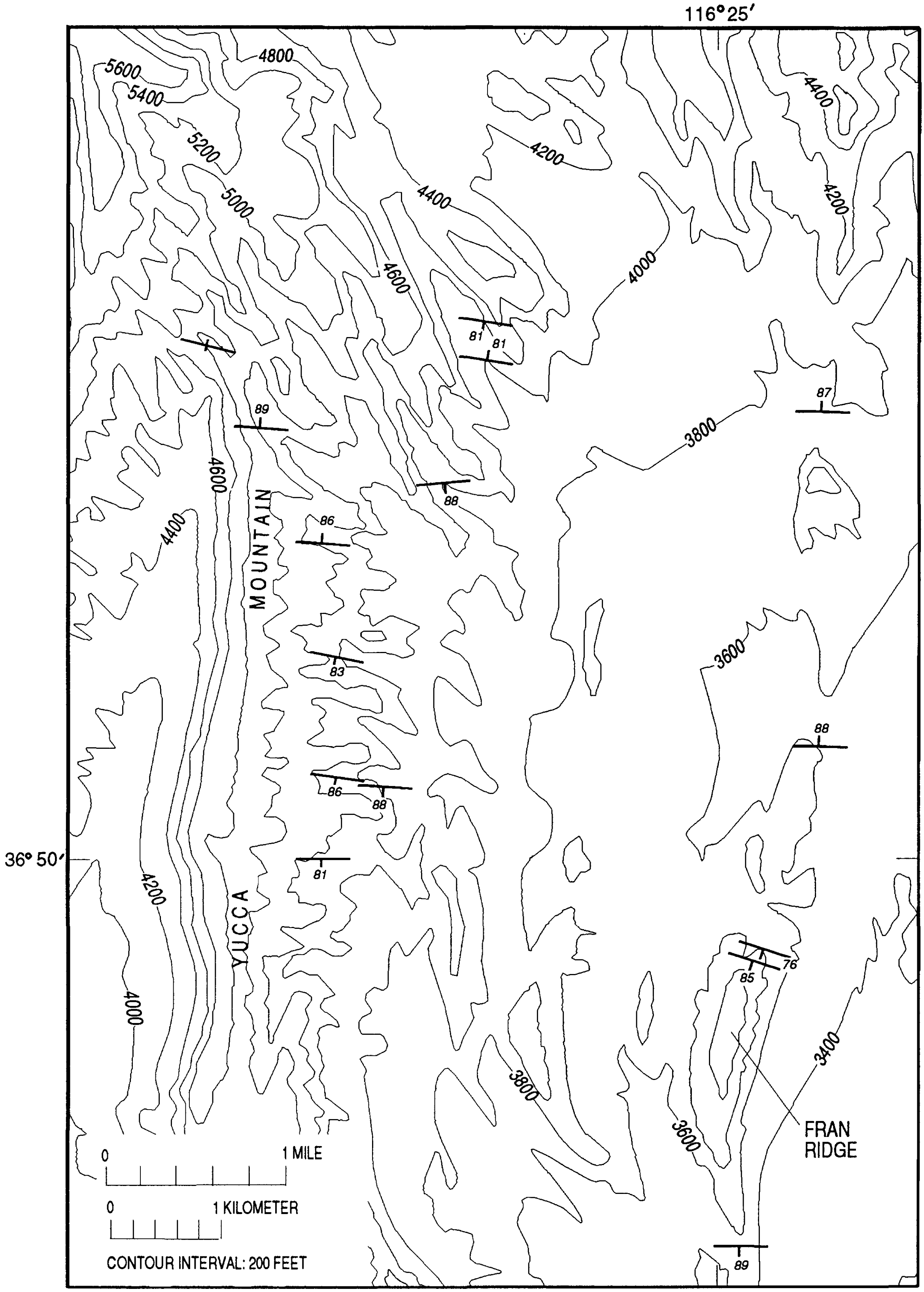


Figure 16.--Map showing median orientations of T4 tectonic joints in the Tiva Canyon and Topopah Spring Tuffs.

In many places, however, the T4 set is visually obvious because its joints strike at high angles to those of all other tectonic sets.

At nearly all localities the T4 joints are short--commonly far shorter, on average, than those of all older sets. Lengths of only 0.2-1.5 m are typical. Sizes of T4 joints in many places were controlled by the spacings between adjacent T1 joints, against which they commonly abut at both ends. Similar terminations against joints of the T2 and T3 sets, as well as against cooling joints, further limited the lengths to which most T4 joints could grow. T4 joints that cross multiple older joints and thereby achieve significant length (3-5 m) were noted at several localities but are common at none of them. The heights, too, of T4 joints tend to be smaller than those of preceding sets, in part because short joints rarely grow to great height, but in larger part because the T4 joints in many places terminate against the foliation-parallel unloading joints described in the next section.

The T4 joints in most places formed in rock already highly fractured and thus mechanically anisotropic. Deviations of local stress directions from the regional (far field) stresses during growth of the T4 joints are reflected in several of their properties, most obviously shape: commonly they are of irregular form, notably more so than those of other sets, and among all tectonic joints they show the greatest tendency to curve along strike. Where T4 joints deviate out-of-plane their surfaces commonly display twist hackle. Multiple arrest lines were also noted in a few localities and, together with twist hackle, show that the T4 joints propagated as extension fractures. Further evidence of extension (mode I) propagation is the presence of inclusion hackle (Kulander and others, 1979), one component of the structure that in aggregate geologists call *plumose structure*. The inclusions in this case are sanidine crystals--mineral grains resistant to fracture, and around which the advancing fracture front commonly split on a microscopic scale. At low light angles these microscopic irregularities of the fracture surface lend a distinctive streaked appearance to the joint face.

Joints of the T4 set commonly strike about perpendicular to those of the T1 or T3 sets and thus form a crude set of *cross joints* with respect to those earlier sets. T4 joints of nearly east-west strike are most common (table 2), reflecting the widespread abundance of the north-striking T1 joints: the two sets are present together at 13 of the 15 localities where T4 joints were measured. At the remaining two localities (CKS2, CUL1), where the north-northeast-striking joints of the T3 set are dominant instead, the T4 joints strike N. 72° W. rather than east-west. A tendency for late unloading joints to form at high angles to whichever earlier set dominates the local fracture network is common to many areas worldwide (Gay, 1973) and reduces the value of such joints as paleostress indicators, as later discussed. The seeming absence of east-northeast-striking T4 joints perpendicular to T2 joints, though puzzling, probably reflects the fact that the T2 set is nowhere dominant over the T1 set at those localities where the late T4 set was measured.

Spacings of T4 joints at the outcrop scale are related to those of earlier sets. The clearest example is station CC1, where a prominent rectangular network of T1 and T4 joints dominates the local fracture network, and joints of other sets are sparse. In most of this exposure the T4 joints are spaced 15-40 cm apart, but their spacings decrease to as little as 10 cm in places where the earlier T1 joints are unusually abundant. The tendency for cross joints to be most abundant where earlier joints perpendicular to them are most closely spaced is related to a similar but more well known effect, the tendency for joints of any particular set to increase in abundance with decreasing bed thickness. Note that this effect is opposite to that of all earlier joints, which tend to be *least* abundant wherever joints of any older set are best developed. The difference lies in the angular relations from one set to another, as later discussed in the section on *Number of Joint Sets*. The mechanics of cross-joint formation and controls on their spacing were discussed recently by Gross (1993).

The T1 and T4 sets are present together at so many localities that their relative age is clear, as revealed by numerous terminations of T4 joints against those of the T1 set. Abutting relations between T4 joints and those of the T2 and T3 sets were visible at fewer localities and are far less numerous, though suggestive of T4 being the youngest set. Relatively short lengths, commonly curved traces, and terminations against older joints are general properties of the T4 set.

SH set: Foliation-parallel joints

A set of joints parallel or nearly so to compaction foliation in the Tiva Canyon and Topopah Spring Tuffs was found at almost half the localities studied (20 of 41 stations). In most of these the set is a prominent one; spacings of 0.3-1.0 m are typical. The SH joints are most abundant in exceptionally brittle rock, such as the orange brick unit of the Topopah Spring Member and the black vitrophyre subunit of the caprock unit of the same member. At the two localities studied in this latter rock type (stations TC1 and TC4) the SH joints are spaced only 5-24 cm and 2-20 cm apart, respectively. The presence of abundant SH joints is responsible for the stepped, ledgelike appearance of many outcrops on and near Yucca Mountain.

The SH joints commonly have a dual nature, depending on whether they parallel foliation or transect it. Most SH joints, though statistically parallel to foliation as a set, do not follow the foliation planes exactly but cut across them at low angles. Such joints generally have subplanar to nonplanar, markedly undulatory shapes and irregular, rough to very rough surfaces. However, where parts of the same joints split along foliation planes, or where entire SH joints opened along those planes in rock where compaction foliation is well developed, the joint surfaces are more nearly planar and conspicuously smoother.

Sizes of SH joints vary widely, depending on whether they cut across or terminate against the steeply dipping joints of older sets. At station CC1, for example, the dimensions of SH joints in an east-west direction were determined by the 2-35 cm spacings between adjacent T1 joints, against which many SH joints terminate. The SH joints likewise terminate against T3 and T4 joints and as a result are small in all directions; maximum dimensions of 0.2-1.3 m are typical of this locality. In other places, however, where joints of preceding sets are more widely spaced or where SH joints more commonly intersect rather than abut older joints, the SH joints grew to much larger size. Maximum exposed dimensions of 2-5 m are common at some localities, but rare individual SH joints 7-8.5 m across were seen at two of them.

Flattened lithophysal cavities commonly served as origin flaws for SH joints, which began growth at cavity edges and propagated radially into the rock. The SH joint geometry is both distinctive and expected: in vertical section the joints bisect the cavities along their greatest diameter rather than intersect them randomly, a result of high induced tensile stress where the radius of curvature of the cavity was least. The theoretical basis for elliptical flaws in rock serving as stress concentrators for fracture initiation is treated in most introductory texts on rock mechanics; many field examples illustrating the process are known.

The late age of the SH set relative to cooling joints and tectonic joints of the T1 through T3 sets is well established through abutting relations at numerous localities. Abutting relations with the T4 set are ambiguous, a probable indication that both sets formed during the same time period to accommodate the minor three-dimensional strains induced during erosion of superincumbent load. We thus view both the T4 and SH joints as unloading joints, the SH joints representing the volcanic equivalents of the more familiar exfoliation (sheeting) joints in massive plutonic rocks.

The late age, rough surfaces, and tendency to intersect numerous lithophysal cavities generally serve to distinguish SH unloading joints from gently dipping cooling joints of much earlier age. In some units, however--notably parts of the hackly unit, where joints of *all* sets have fairly smooth surfaces and lithophysae are sparse to absent--apparent terminations of pre-T4 tectonic joints against SH joints suggest that some cooling joints are included in the SH set. Distinction between the two was most difficult at station CH1, where several terminations of T2 joints against smooth, gently dipping joints parallel to foliation suggest an early age and thus a cooling origin for the latter, but the rough surfaces of portions of the same joints where they cut across compaction foliation instead suggest an origin due to unloading. A likely but unproven possibility is that early, foliation-parallel cooling joints were reactivated and grew larger during later erosional unloading, thereby creating ambiguous abutting relations and variable joint-surface properties.

Evidence of similar reactivation is more clear at station CH2, also in the hackly unit, where smooth, gently dipping joints with discolored surfaces (alteration rinds) are coated with a white to cream-colored, noncalcareous mineral (presumably quartz), but the outermost portions of the same joints are exceedingly rough, not discolored, and unmineralized. The extreme difference in character between inner and outer portions of the same joints is most compatible with an interpretation of reactivated cooling joints. The process of reactivating a gently dipping cooling joint--essentially an extremely flat, elliptical crack--is mechanically analogous to that of propagating a new unloading joint from the margins of a flattened lithophysal cavity, as discussed above.

DISCUSSION

Number of Joint Sets

The joint network at Yucca Mountain, so far as known, consists of three cooling sets followed by five tectonic sets. No exposure examined by us, however, contains all eight sets. Three to five sets are common at most localities and a few contain as few as two or as many as six.

That only about half the total number of known sets are present at most localities is an obvious measure of the tendency for early joint sets to inhibit the development of later ones. The process of joint-set suppression is conceptually simple: the more a given volume of rock is fractured, the more likely any further strain will be accommodated through slight movements on joints already present rather than through development of new fractures.

The degree to which that process is effective is related to several factors, among them the angular relations between existing joints and potential new joints, and the degree of cohesion between opposing faces of the old joints. Where the acute angle between old and potential new joints is 30° or less the suppression of new joints by old commonly is marked, as already noted for the T2 and T3 sets, both of which tend to be weakly developed or absent where great numbers of T1 joints are present. Where the acute angle between sets is instead 70° or more, so that older joints are unfavorably oriented for reactivation, little or no suppression will occur. Such is the case for the T4 set, which formed at high angles to all other tectonic sets and is present at more localities than any other set save T1. Suppression also will not occur where joints of older sets have been effectively "healed" through mineralization so that movement of one joint wall relative to the other no longer is possible.

Early cementation of cooling joints by vapor-phase crystallization is a likely reason that the later T1 set is so common at Yucca Mountain and Fran Ridge and why tectonic sets in general are only slightly underrepresented there. Were all sets developed equally one should find, on average, five tectonic sets for every three cooling sets--a ratio of 3:5. The actual ratio, 3:3.9, indicates a modest overabundance of cooling sets.

Network Patterns of Different Volcanic Units

Joint data currently available suggest that the overall style of the fracture network within each volcanic unit present at Yucca Mountain is characteristic of that unit, but network styles change vertically, and in some cases dramatically, from one unit to another. In a gross sense, then, vertical heterogeneity in the joint network greatly exceeds that in any lateral direction, and each volcanic unit should be modeled for fluid-flow behavior and mechanical stability separately. Data are available from too few localities to specify details of network properties in each of the several dozen volcanic units present, but a few examples are noted here to point out a promising avenue for further work.

The two most studied units at Yucca Mountain and nearby areas are the hackly and the upper lithophysal units. Nine joint stations were established in each--enough to verify the degree of consistency within each unit and reveal some of the major differences between them:

- As suggested by earlier pavement studies (Morgan, 1984; Barton and Larsen, 1985; Barton and others, 1993), joint networks in the upper lithophysal unit are dominated by cooling joints. Among all sets identified by us in that unit, roughly 60 percent are cooling sets and 40 percent are tectonic. In the hackly unit the opposite is true: only 20 percent of the sets measured are due to cooling, and 80 percent are tectonic.

- The numerous cooling joints in the upper lithophysal unit cluster about the N. 45° W. and N. 50° E. strikes noted previously for the northern half of Yucca Mountain (fig. 17A). Joints of similar strike are less common in the hackly unit (fig. 17B), where instead most joints strike within 30° of due north (T1 through T3 sets) or nearly east-west (T4). Frequency distributions of joint strike within the two units are markedly dissimilar.

- Differences in surface roughness between cooling and tectonic joints reach an extreme in the upper lithophysal unit, where roughness coefficients (RC) for each fracture type are normally distributed with peaks of RC = 2 for cooling joints and RC = 10 for tectonic joints (Barton and others, 1993). Our qualitative data confirm these relations for a much larger area; surfaces of cooling joints are smooth to very smooth and those of tectonic joints consistently and obviously rougher. Within the hackly unit, however, the roughness distinction is less conspicuous: though surfaces of cooling joints invariably are described in our notes as "smooth" or "very smooth" (much like those of the upper lithophysal unit), surfaces of more than two-thirds of the tectonic sets were described not as "rough" but as either "fairly smooth" or "smooth". Frequency distributions of surface roughness for cooling and tectonic joints, if measured, likely would show strong overlap in the hackly unit. Fracture-surface roughness thus is related to lithology in a definable and consistent way. As a criterion for distinguishing cooling from tectonic joints, surface roughness is most valuable in the upper lithophysal unit, where earlier fracture studies were concentrated. Elsewhere the distinction is not as straightforward.

Network Connectivity

Connectivity--the extent to which fractures in a given volume of rock are interconnected--is a key property in determining the fluid-flow behavior of fracture networks. Barton and Hsieh (1989) and Barton and others (1993) provided initial data on network connectivity at Yucca Mountain through fracture maps of four pavement exposures (three in the upper lithophysal unit of the Tiva Canyon Tuff and one in the orange brick unit of the Topopah Spring Tuff).

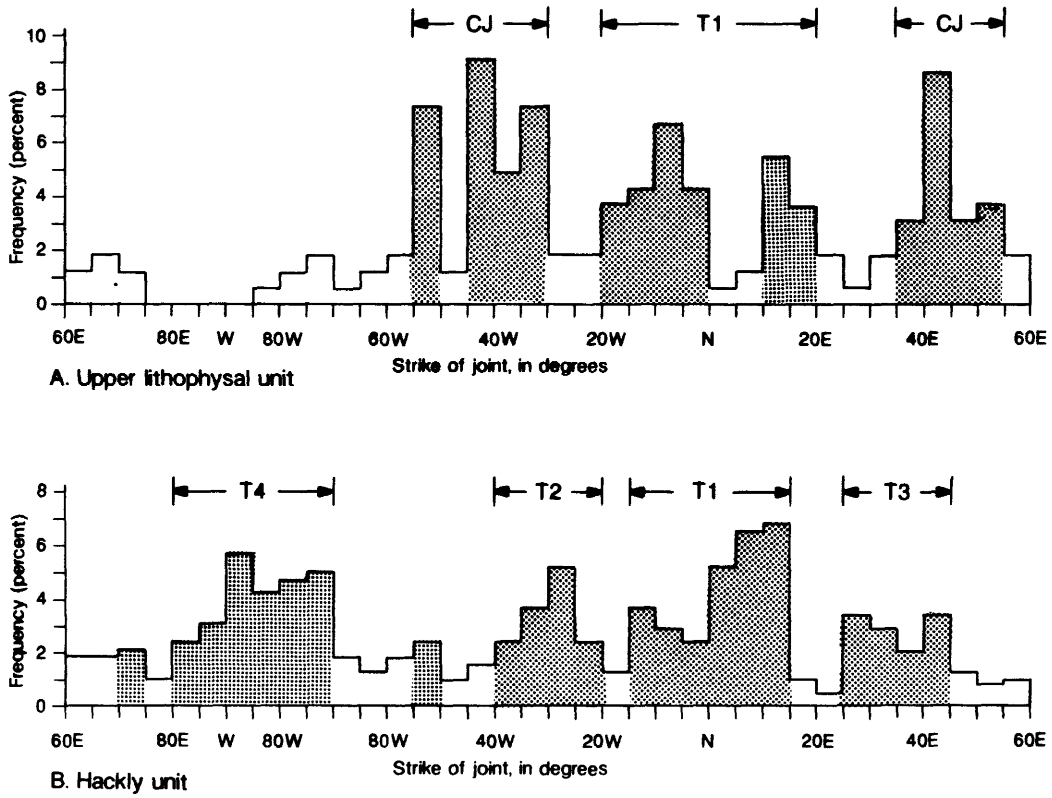


Figure 17.--Linear histograms showing strike-frequency distributions of steeply dipping joints within two volcanic units at Yucca Mountain. A, upper lithophysal unit. B, hackly unit. Note origin point at N. 60° E.; this direction corresponds to minima in both distributions so that positions of the maxima can more clearly be compared. Strike data are plotted with 5° class interval; classes containing 2 percent or more of the data are shaded. CJ = cooling-joint set; T = tectonic set.

Nearly all fractures measured on these four pavements dip steeply, 65° or more. The discussion below briefly addresses connectivity in these and other volcanic units at Yucca Mountain and stresses the importance of gently dipping fractures to fluid flow.

Connectivity due to steeply dipping joints

Barton and others (1993) published a ternary diagram for four pavement exposures in which they reported the relative proportions of blind fracture endings (fractures dying out as hairline cracks in the rock), intersections (crossing fractures), and terminations (one fracture ending against another). The proportions for all three pavements in the upper lithophysal unit are closely similar and plot within a narrow area on the diagram, indicating 40-51 percent terminations, 26-33 percent blind endings, and 21-27 percent intersections. The pattern of connectivity within this unit thus appears relatively constant, at least within the small portion of Yucca Mountain from which the data were obtained. Data for a fourth pavement in the nonlithophysal unit, however, reveal a much different pattern--a dearth of blind endings and a ratio of terminations to intersections of about 60:40. Full statistical treatment of the results for all four pavements is difficult because no provision was made to separate data for fractures with two, one, or no ends exposed; the necessary information must be recaptured from the fracture maps. Nonetheless it has been firmly established that the measured fracture networks in the two units studied are well interconnected at the outcrop, and that pavement studies provide an effective means of assessing map-view patterns of fracture connectivity for models of fluid flow.

Outcrop studies in incompletely exposed bedrock are more poorly suited to study of fracture connectivity because details of fracture terminations and intersections frequently are obscured by surface debris and vegetation. Our observations are thus necessarily qualitative in nature. Nevertheless, joint networks at almost all of our stations, and in numerous other exposures inspected casually, are well interconnected. The high degree of connectivity is due in part to the complexity of the joint history; the development through time of three or more joint sets at nearly all places within the Tiva Canyon and Topopah Spring Tuffs provided ample opportunity for fracture interaction to occur. The sheer abundance of early formed cooling and T1 joints in many places further increased the odds of fracture interaction because subsequent joints could not grow to any appreciable length before encountering other fractures. And finally, mineral precipitation effectively bonded the opposing walls of numerous fractures into stress-transmitting contact, thereby commonly allowing new fractures to cut across many of those already present. Together these three factors resulted in abundant fracture intersections and terminations in most of the volcanic units at Yucca Mountain and Fran Ridge, with the possible exception of some weakly welded tuffs that have not yet been studied extensively, but within which the joints are more widely spaced. The degree of fracture connectivity demonstrated through the pavement studies of Barton and Hsieh (1989) and Barton and others (1993) probably is not unusual for the region.

Connectivity due to gently dipping joints

Patterns of fracture connectivity as documented through pavement studies reveal two-dimensional views through networks that are interconnected in three dimensions. The connectivity of fractures dipping at high angles to compaction foliation in the tuff is accurately represented, but network linkages due to fractures dipping at low angles or parallel to foliation are obscured. For this reason, probably, the occurrence and significance to fluid flow of foliation-parallel joints at Yucca Mountain seems scarcely to have been recognized.

Foliation-parallel joints at Yucca Mountain, as previously discussed, are of two types, cooling (early) and unloading (late). The cooling joints are only sporadically abundant but the unloading joints widespread and common. Terminations and intersections of both types of joint with steeply dipping joints of other sets are common. Also common on joints of both sets are alteration rinds, discolored surfaces, and remnant coatings of a white to cream-colored, fine-grained, noncalcareous, presumably siliceous mineral. The field relations thus show that gently dipping cooling and unloading joints were conductive elements of an interconnected fracture network and long served as conduits for subsurface fluid flow. Some remain conductive, as at stations TC-1, TC-3, and TC4, where mineral coatings 1-3 mm thick with botryoidal outer surfaces attest to large original apertures and incomplete closure of the gently dipping fractures by mineralization. The significance of such fractures at repository depths remains uncertain; the unloading joints, in particular, should wane in abundance with depth. They should not, however, be regarded as purely surficial, for analogous joints in some areas persist to depths of 300 m or more (Verbeek and Grout, 1983), and the common presence of continuous mineral coatings on them at Yucca Mountain shows that they also were conduits for subsurface fluid flow. Inspection of drill cores and data from the recently excavated decline ramp into the proposed repository should provide the needed information. Regardless, the contribution of foliation-parallel joints to past and present fluid flow at Yucca Mountain should not be underestimated.

Paleostress History

Extension joints are excellent and sensitive recorders of paleostress history because they commonly form at lower levels of differential stress than do faults. Moreover, their abundance in most exposures affords essentially unlimited opportunity to document regional stress histories from integration of data from many closely spaced localities, each of which provides a partial record of a more complex whole.

The fractures of all eight sets discussed in this report are extension joints, as shown both by surface structures on the joint faces and, in areas undisturbed by later faulting, by common lack of visible shear offset where the fractures transect lumps of pumice embedded in the tuff. The orientations of three components of the stress field can be read from extension joints. Sigma 3 (σ_3), the minimum principal compressive stress, is the perpendicular to the fracture plane. Within the horizontal plane, the maximum horizontal compressive stress (σ_{hmax}) and the minimum horizontal compressive stress (σ_{hmin}) are parallel and perpendicular, respectively, to joint strike, regardless of the dip of the joint. Note that only one of the *principal* stress axes of the stress tensor can readily be determined from extension joints and that none of the principal stresses need be horizontal. The phrase "maximum (or minimum) principal horizontal stress", found in some of the literature on Yucca Mountain and surroundings, is meaningless. The stress components σ_{hmax} and σ_{hmin}, when discussed for areas of appreciable size, can be viewed as roughly equivalent to the directions of tectonic crustal compression and extension, respectively.

Cooling joints

The stress significance of consistently oriented rectangular sets of cooling joints in the Tiva Canyon Tuff on Yucca Mountain is problematic in that the cause of the consistent orientations is unknown. Barton and others (1993) suggested that the rectangular pattern reflects eruption of the tuff onto a tilted surface in much the same way that mudcracks (which, like cooling joints, are contraction fractures) on a sloping surface commonly form one set of long cracks oriented parallel to the slope and a second set of shorter cracks downdip. A downdip component of layer-parallel extension due to gravity is responsible for the preferred orientation of the dominant set. Observation of mudcracks along the sloping shorelines of lakes (Allen, 1982) and experiments in drying tilted pans of mud (Kindle, 1917) lend credence to this view. If true, the cooling-joint orientations reflect underlying topography and have no regional paleostress significance. Left unexplained, however, is why the northeast-striking set of cooling joints on Yucca Mountain is dominant in some places and the northwest-striking set in others (fig. 11; table 3). Careful measurement of the orientations of the dominant cooling set and of compaction foliation of the tuff in the same outcrops should help resolve the problem.

Older cooling joints within the Topopah Spring Tuff generally show much different orientations. With only eight joint stations in this unit it is too early to define areal patterns, but we draw attention here to the east flank of Fran Ridge, where geologic relations at two stations (TC2, TR1) and at additional outcrops between them are consistent with tectonic extension during cooling of the ash-flow sheet. Median strikes of the dominant (C1) cooling set in this area range from N. 03° E. to N. 11° E. along a 6-km length of the ridge. A second, more weakly expressed set (C2) is present at right angles to the first, as is a third set of gently westward-dipping, foliation-parallel cooling joints. Also present in the same exposures are common joints of the T1 set, which strike N. 02° W. to N. 11° E., nearly parallel to the C1 joints. The T1 joints, however, are much smaller and rougher, and they consistently abut the C2 and foliation-parallel cooling joints. Strong differences in joint style and consistent abutting relations establish that two parallel sets are present. The parallelism between the two sets could be mere coincidence, but inasmuch as normal faulting in the region began prior to volcanism and continued as the ash flows were emplaced (Scott and others, 1983), it could equally well reflect tectonic extension of the ash-flow sheet while it was cooling. North-striking cooling joints in the overlying Tiva Canyon Tuff in the same area (stations CUL2 through CUL4) support the latter interpretation. If true, (a) crustal extension with σ_3 oriented nearly east-west was already active during emplacement of the Topopah Spring and Tiva Canyon Tuffs, (b) tectonic extension of the cooling ash-flow sheets controlled the orientation of the dominant set of cooling joints in both units, and (c) continuing extension in the same direction later led to formation of the T1 tectonic joints in the same rocks. This interpretation raises anew the question of the significance of cooling joints in the Tiva Canyon Tuff on Yucca Mountain: if their orientations reflect crustal stress rather than paleotopography, directions of crustal extension during Tiva Canyon time were different in different structural blocks, implying decoupling along major interblock faults. Much more data than are available at present will be required for confident interpretation.

Tectonic joints

The paleostress significance of tectonic joints at Yucca Mountain is more straightforward than that of cooling joints; regionally consistent tectonic joints can only imply a regionally consistent stress field. Evidence that normal faulting began prior to volcanism and continued during and after it (Scott and others, 1983) necessitates that the T1 through T3 sets be viewed within the context of Basin-and-Range extensional tectonism. So viewed, the orientations of the T1 through T3 joint sets (figs. 12, 13, 15) imply noncoaxial crustal extension through time, with extension directions shifting from nearly due east (T1) to east-northeast (T2) and thence to southeast (T3). As noted above, stresses compatible with the T1 extension direction may have existed well before T1 time, during and perhaps before emplacement of the Paintbrush Group. How long that stress state persisted is unknown because the age of the T1 joint set is not well constrained by stratigraphic evidence; nor is the age of the T2 set that succeeded it. The T3 set may be of Quaternary age because its strike (median N. 38° E.) is almost exactly perpendicular to the N. 50° W. direction of σ_{hmin} inferred by Carr (1974) from his regional studies of Quaternary faulting. Similar directions of contemporary σ_{hmin} have been inferred for the region from hydrofracture tests and orientations of borehole breakouts (Haimson and others, 1974; Rogers and others, 1983; Springer and others, 1984; Stock and others, 1985; Stock and Healy, 1988).

Directions of σ_{hmin} as read from the joint history at Yucca Mountain are very nearly equivalent to orientations of σ_3 because the joints of all three sets have near-vertical dips (table 2). The orientations of the other two principal stresses for each fracture episode must lie within the plane representing the median orientation of each set, but without further evidence their plunges cannot be given--that is, one cannot tell from the mere presence of a set of joints whether those joints formed in a normal-slip stress field (σ_1 vertical), a strike-slip stress field (σ_1 horizontal), or an oblique-slip stress field. Thus, the relation of the jointing history to the complex record of normal and strike-slip faulting events at Yucca Mountain and nearby areas (Scott and others, 1984; Minor, 1989, in press; O'Neill and others, 1991; Spengler and others, 1994) is incompletely known. Further evidence might take the form of propagation directions of joints as read from surface structures (plumose structure, arrest lines), senses of slip on faulted joints (not uncommon on Yucca Mountain) as determined from slickenside striations and the geometry of subsequent growth segments (Cruikshank and others, 1991), and integration of the results obtained with data from fault-slip studies. The latter are underway (S.J. Minor, oral commun., 1994).

No special paleostress significance should be attached to the T4 and SH joints because they formed as the tuff was being decoupled from the regional crustal stress field as the rocks were brought to increasingly shallow crustal levels through erosion. Both sets of joints record decreasing confining pressure and stress release in directions not readily accommodated by fractures already present.

SUMMARY

The fracture network at Yucca Mountain includes three sets of cooling joints that formed during cooling of the Tiva Canyon and Topopah Spring Tuffs, followed by five sets of tectonic joints. Three sets of tectonic joints formed during regional crustal extension, and two younger tectonic sets, strikingly different in style, are due to unloading and erosion of overlying rock. These joint sets are present in different combinations and to varying degrees of expression at 41 localities studied. The character of the local fracture network thus differs, sometimes markedly, from one locality to another, but a strongly defined regional pattern nonetheless exists.

Cooling Joint Sets

Two sets of steeply dipping cooling joints at approximate right angles were documented throughout much of the study area, in a total of ten units. Weak expression of one cooling set relative to the other is common. In the northern half of Yucca Mountain, joints of one set strike N. 34°-75° E., while the other set ranges in strike from N. 20°-70° W. (grand medians are N. 45° W. and N. 50° E., respectively).

At several localities these two sets comprise the dominant component of the fracture network. Distinguishing characteristics of these sets in the upper lithophysal unit of the Tiva Canyon Tuff include tubular structures, appreciable length, exceptionally smooth surfaces, and abutting relation indicating early age. In other units, where tubular structures commonly are lacking, a combination of the remaining characteristics, together with demonstration of early relative age, is sufficient to distinguish cooling from tectonic joints.

A third, subhorizontal-cooling joint set is present in six units of the Topopah Spring and Tiva Canyon Tuffs. These gently dipping joints parallel the foliation in the tuff or transect it at low angles. Smooth, undulatory, subplanar to nonplanar surfaces, and absence of lithophysae on the joint surfaces, and demonstrated early age, separate these joints from unloading joints of similar orientation. Abutting relations at several localities show that the gently dipping cooling joints are either the oldest joints present or formed during the same time period as those of steep dip. Both the low-dipping cooling joints and the steeply dipping cooling joints have properties in common, including smooth surfaces, early age relative to tectonic joints, tubular structures, common undulatory shape, and in some localities, large size.

Tectonic Joint Sets

Three regional extension joint sets (T1 through T3) were identified and their order of formation determined. Grand median orientations (strike and dip) of T1, T2, and T3 joint sets are N. 01° W. 86° SW.; N. 31° W. 86° SW.; and N. 38° E. 88° NW. (table 2), respectively. The order of formation of each set (T1 earliest, T2 next, T3 later) has been determined on the basis of abutting relations.

The earliest formed set (T1) is present at 24 of the field stations and, as expected, has the lowest strike dispersion (23°) of the three sets. Development of T1 joints is inversely related to that of the cooling joints. Where cooling joints are both large and abundant, as in much of the upper lithophysal unit of the Tiva Canyon Tuff, the T1 joints are present in low numbers or are absent. Conversely, where cooling joints are few, as in much of the hackly unit, the T1 set reaches it greatest development. Joint size of the T1 set varies from unit to unit; lengths as great as 7 m may be traced where T1 growth was not confined by earlier cooling joints. Subplanar to locally planar joints and moderately rough to very rough surfaces characterize T1 joints in most of the units at which the set is present. Where T1 joints occur in the hackly unit, however, the joint surfaces are smooth to fairly smooth.

The north-northwest-striking T2 set was documented at 15 field stations. Their later age relative to the T1 set is evident from several properties. (1) The prominence of the T2 set is inversely related to that of older joints in much the same manner as discussed previously for the T1 set. (2) Median orientations of T2 joints are more variable than those of the T1 set because the T2 joints formed in more-fractured, less isotropic rock. (3) T2 joints are shorter on average than those of older sets because, during growth, they commonly terminated against fractures already present.

The T3 set of joints was documented at about the same number (14) of field stations as the T2 set. Abutting relationships show that the T3 set is younger than T1, but its age relative to the T2 set remains tentative. The T3 set has many properties characteristic of sets developed in rock already abundantly fractured: (1) T3 joints are subordinate (lower numbers) to one or another of the older tectonic sets. (2) In general, T3 joints are shorter because their growth was constrained by fractures already present. (3) The subplanar to locally nonplanar T3 joint shapes are indicative of joint propagation within fractured, anisotropic rock, where local stress directions commonly deviate from the regional (far-field) stresses. (4) Hooklike terminations of T3 joints against other joints are common. (5) Strike dispersion (32°) is high, as would be expected of jointing in anisotropic rock.

Unloading joints of the T4 set (grand median orientation: N. 82° W. 88° SW.), constitute a minor component of the fracture network; they are widespread but their size and spacings are restricted by earlier sets. Joints of the T4 set commonly strike at high angles to other tectonic sets, most commonly joints of the T1 or T3 sets. Numerous T4 joints terminate against those of the T1 set; thus they are unquestionably younger than the T1 set. Abutting relations with joints of the T2 and T3 set are scarce, but the relations observed suggest a younger age for T4.

Foliation-parallel joints (SH) occur at 20 stations, where the joints are conspicuous. Abutting relations at numerous localities establish the late age of the SH set relative to cooling joints and the tectonic joints of the T1, T2, and T3 sets. Abutting relations with the T4 set are ambiguous, a probable indication that both sets formed during the same time period to accommodate the minor three-dimensional strains induced during erosion of superincumbent load. The late age, rough surfaces, and tendency to intersect numerous lithophysal cavities serve to distinguish SH unloading joints from gently dipping cooling joints of much earlier age.

Joint data currently available suggest that the overall style of the fracture network within each volcanic unit present at Yucca Mountain is characteristic of that unit, but that network style changes vertically, and in some cases dramatically, from one unit to another. Each volcanic unit should be modeled for hydrologic flow and mechanical stability separately.

Paleostress History

The T1 through T3 sets of tectonic joints on and near Yucca Mountain record changing directions of σ_{hmin} through time, from nearly east-west (T1) to east-northeast (T2) and then to southeast (T3). The latter direction is compatible both with paleostresses inferred from the regional record of Quaternary faulting and with the contemporary stress state as measured from borehole data. The changing stress directions are interpreted to reflect noncoaxial extension directions during Basin-and Range crustal extension in the region.

The possible paleostress significance of the earlier cooling joints remains uncertain because the cause of their preferred orientations has not yet been established. The most likely cause, that the preferred orientations reflect cooling of a tilted ash-flow sheet deposited on a nonhorizontal surface, suggests that the cooling-joint sets reflect underlying paleotopography more than regional stress.

ACKNOWLEDGMENTS

This study was partly supported by the Nevada Nuclear Waste Storage Investigations Project of the Civilian Radioactive Waste Management Program. The authors wish to thank the following personnel at the Mercury, Nevada facility: Jerry Magner and Dan Blout assisted the authors in the field and Ron Martin provided vehicles and equipment. We wish also to thank Michael Chornack for suggesting several exceptional exposures for study. The authors gratefully acknowledge Ramon E. Sabala and Mike Duncan for their computer graphics and drafting assistance and Sharon Rosema for formatting and proofing the text. This report benefited from a careful review by John C. Lorenz of Sandia National Laboratories, New Mexico.

REFERENCES CITED

Allen, J.R.L, 1982, Sedimentary structures--their character and physical basis, v. II: Amsterdam, Netherlands, Elsevier Scientific Publishing Company, 679 p.

Barton, C.C., 1984, Tectonic significance of fractures in welded tuff, Yucca Mountain, southwest Nevada {abs}: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 438-439.

Barton, C.C., and Hsieh, P.A., 1989, Physical and hydrologic flow properties of fractures: 28th International Geological Congress Field Trip Guidebook T385, American Geophysical Union, Washington, D.C., 36 p.

Barton, C.C., and Larsen, Eric, 1985, Fractal geometry of two-dimensional fracture networks at Yucca Mountain, southwestern Nevada: International Symposium on Fundamentals of Rock Joints, Bjorkliden, Lapland, Sweden, September 15-20, 1985, Proceedings, p. 77-84.

Barton, C.C., Larsen, Eric, Page, W.R., and Howard, T.M., 1993, Characterizing fractured rock for fluid-flow, geomechanical, and paleostress modeling: Methods and preliminary results from Yucca Mountain, Nevada: U.S. Geological Survey Open-File Report 93-269, 62 p., 1 plate.

Barton, C.C., Page, W.R., and Morgan, T.L., 1989, Fractures in outcrops in the vicinity of drill hole USW G-4, Yucca Mountain, Nevada--Data analysis and compilation: U.S. Geological Survey Open-File Report 89-92, 133 p.

Barton, Nick, and Choubey, Vishnu, 1977, The shear strength of rock joints in theory and practice: Rock Mechanics, v. 10, p. 1-54.

Carr, W.J., 1984, Summary of tectonic and structural evidence for stress orientation at the Nevada Test Site: U.S. Geological Survey Open-File Report 74-176, 53 p.

Cruikshank, K.M, Zhao, Guozhu, and Johnson, A.M., 1991, Analysis of minor fractures associated with joints and faulted joints: Journal of Structural Geology, v. 13, no. 8, p. 865-886.

Gay, S.P., Jr., 1973, Pervasive orthogonal fracturing in Earth's continental crust: Salt Lake City, Utah, American Stereo Map Company Technical Publication 2, 121 p.

Gross, M.R., 1993, The origin and spacing of cross joints--Examples from the Monterey Formation, Santa Barbara coastline, California: Journal of Structural Geology, v. 15, no. 6, p. 737-751.

Haimson, B.C., Lacomb, J., Jones, A.H., and Green, S.J., 1974, Deep stress measurement in tuff at the Nevada Test Site: Advances in Rock Mechanics, v. IIa; Washington D.C., National Academy of Sciences, p. 557-561.

Hudson, M.R., and Sawyer, D.A., 1994, Paleomagnetism and rotation constraints for the middle Miocene southwestern Nevada volcanic field: Tectonics, v. 13, no. 2, p. 258-277.

Kindle, E.M., 1917, Some factors affecting the development of mudcracks: Journal of Geology, v. 25, no. 2, p. 135-144.

Kulander, B.R., Barton, C.C., and Dean, S.L., 1979, Applications of fractography to core and outcrop fracture investigations: U.S. Department of Energy Report METC/SP-79/3, 179 p.

Lorenz, J.C., and Finley, S.J., 1991, Regional fractures II--Fracturing of Mesaverde reservoirs in the Piceance basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 75, no. 11, p. 1738-1757.

Minor, S.A., 1989, Paleostress investigation near Rainier Mesa, Nevada Test Site, *in* Olsen, C.W., and Carter, J.A. eds., Fifth Symposium on Containment of Underground Nuclear Explosions, Proceedings: Lawrence Livermore National Laboratory Report CONF-8909163, v. 2, p. 457-482.

____in press, Superimposed local and regional paleostresses--fault-slip analysis of Neogene Basin-and Range faulting near a middle Miocene caldera complex, Yucca Flat, southern Nevada: Journal of Geophysical Research.

Morgan, T.L., 1984, Fracture characterization in the Tiva Canyon Member, Paintbrush Tuff, Yucca Mountain, Nevada: Ft. Collins, Colorado State University, M.S. thesis, 126 p.
O'Neill, J.M., Whitney, J.W., and Hudson, M.R., 1991, Photogeologic and kinematic analysis of lineaments at Yucca Mountain, Nevada: Implications for strike-slip faulting and oroclinal bending: U.S. Geological Survey Open-File Report 91-623, 24 p., 1 plate.
Rogers, A.M., Harmsen, S.C., Carr, W.J., and Spence, William, 1983, Southern Great Basin seismological data report for 1981 and preliminary data analysis: U.S. Geological Survey Open-File Report 83-669, 243 p.
Rosenbaum, J.G., 1986, Paleomagnetic directional dispersion produced by plastic deformation in a thick Miocene welded tuff, southern Nevada: Implications for welding temperatures: Journal of Geophysical Research, v. 91, no. B12, p. 12,817-12,834.
Rosenbaum, J.G., Hudson, M.R., and Scott, R.B., 1991, Paleomagnetic constraints on the geometry and timing of deformation at Yucca Mountain, Nevada: Journal of Geophysical Research, v. 96, no. B2, p. 1963-1979.
Scott, R.B., Bath, G.D., Flanigan, V.J., Hoover, D.B., Rosenbaum, J.G., and Spengler, R.W., 1984, Geological and geophysical evidence of structures in northwest-trending washes, Yucca Mountain, southern Nevada, and their possible significance to a nuclear waste repository in the unsaturated zone: U.S. Geological Survey Open-File Report 84-567, 23 p.
Scott, R.B., and Bonk, Jerry, 1984, Preliminary geologic map of Yucca Mountain, Nye County, Nevada, with geologic sections: U.S. Geological Survey Open-File Report 84-494, scale 1:12,000.
Scott, R.B., Spengler, R.W., Diehl, Sharon, Lappin, A.R., and Chornack, M.P., 1983, Geologic character of tuffs in the unsaturated zone at Yucca Mountain, southern Nevada, *in* Mercer, J.W., Rao, P.S.C., and Marine, I.W., eds., Role of the unsaturated zone in radioactive and hazardous waste disposal: Ann Arbor Science, Ann Arbor, Michigan, p. 289-335.
Snyder, D.B., and Carr, W.J., 1982, Preliminary results of gravity investigations at Yucca Mountain and vicinity, southern Nye County, Nevada: U.S. Geological Survey Open-File Report 82-701, 36 p.
Spengler, R.W., Braun, C.A., Martin, L.G., and Weisenberg, C.W., 1994: The Sundance fault: A newly recognized shear zone at Yucca Mountain, Nevada: U.S. Geological Survey Open-File Report 94-49, 11 p.
Spengler, R.W., and Fox, K.F., Jr., 1989, Stratigraphic and structural framework of Yucca Mountain, Nevada, *in* Nuclear Waste management 1988; Perspectives on national and international programs and technology, Part II: Radioactive Waste Management and the Nuclear Fuel Cycle Journal, v. 13 (1-4), p. 21-36.
Springer, J.E., Thorpe, R.K., and McKague, H.L., 1984, Borehole elongation and its relation to tectonic stress at the Nevada Test Site: Lawrence Livermore National Laboratory Report UCRL-53528, 43 p.
Stock, J.M., and Healy, J.H., 1988, Stress field at Yucca Mountain, Nevada, *in* Carr, M.D., and Yount, J.C. eds., Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada: U.S. Geological Survey Bulletin 1790, p. 87-94.
Stock, J.M., Healy, J.H., Hickman, S.H., and Zoback, M.D., 1985, Hydraulic fracturing stress measurements at Yucca Mountain, Nevada, and relationship to the regional stress field: Journal of Geophysical Research, v. 90, no. B10, p. 8691-8706.
Verbeek, E.R., and Grout, M.A., 1983, Fracture studies at C-a mine, Piceance Creek basin, Colorado: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 375.

APPENDIX A

Station Number	TV1
Quadrangle	Topopah Spring NW, 7.5', lat 36°53'54" N., long 116°27'05" W.
Location	Northernmost flank of Castle Point, almost at valley floor
Exposure Description	Station is at base of gentle NE-facing slope at the northern end of Castle Point, just west of and above instrument station that is accessed by short road off dirt road in Yucca Wash. A natural pavement exposes about 50 percent of the vitrophyre over an area 16 m across slope by 10 m upslope.
Stratigraphic Unit	Topopah Spring Tuff, vitrophyre zone of Scott and Bonk (1984)
C1	
Median Orientation	N14E/84NW (n=36)
Expression	Very well; most obvious set on outcrop
Shape	Most are planar; few are gently curviplanar
Roughness	Smooth, fairly uniform along dip, changing slightly along strike
Exposed Length	Commonly 1-2 m; as great as 4 m observed; true lengths greater
Exposed Height	Commonly 1-1.5 m; some greater; many shorter, true heights greater than exposed heights for most
Structures	None seen; most C1 joint surfaces are filled
Spacing	Variable; observed range is 0.1-1.1 m
Mineralization	Most filled with a white, translucent, noncalcareous mineral up to 1 cm thick. Fill is of variable thickness along single joints; some fills are layered. Three joints have residual voids of botryoidal "chalcedony" which in some joints forms multiple, overlapping, discontinuous veinlets with devitrification rinds, indicating healing and reopening of joint. Orange devitrification rinds, 0-6 cm thick (but most < 1 cm), are present on most joints.
Remarks	Many smaller (< 0.3 m) C1 joints not measured. The devitrification rind is discontinuous along many joints, so absence of rind cannot be used with confidence to distinguish cooling C1 joints from possible tectonic joints with same orientations.
C2	
Median Orientation	N74W/85SW (n=18)
Expression	Moderate to weak
Shape	Planar, some gently curviplanar
Roughness	Smooth
Exposed Length	0.3-1 m; close to true lengths, as C2 lengths are controlled by C1
Exposed Height	0.1-0.5 m; true heights indet.
Structures	None seen
Spacing	Indet., but variable; appear to be widely spaced, as great as 2 m; some are spaced between 0.8-1.5 m
Mineralization	Many are mineralized with a very thin, noncalcareous film; one C2 joint has a translucent, noncalcareous mineral fill 3 mm thick. Suspect all C2 joints are mineralized but uncertain as set is very tight and most joint surfaces are not exposed. Two joints have alteration rinds 1-2 cm thick, but most rinds are less than 3 mm thick and are discontinuous along the joint.

Station Number	TV1
Remarks	A tectonic set parallel to C2 may be present, but cannot separate from C2 set.
Terminations	Short T2 abuts C1; T2 and C1 intersect; T2 hooks into and abuts C1
T2	
Median Orientation	N30W/88NE. (n=21)
Expression	Moderate; second most prominent set, but not conspicuous
Shape	Planar to curviplanar
Roughness	Smooth; some undulatory along strike and dip, others fairly uniform along strike and dip
Exposed Length	0.2-0.6 m; true lengths very close to exposed lengths. T2 lengths are controlled by C1 spacing.
Exposed Height	0.1-0.6 m; true heights indet.
Structures	Twist hackle noted on two joints
Spacing	Commonly 1-1.5 m; locally greater and smaller
Mineralization	Many T2 have white, platy, noncalcareous fill < 0.5 mm thick. Some short T2 joints have orange devitrification rinds ranging in thickness from 0-8 mm. Most rinds are thin (< 2 mm).
Remarks	T2 joints are fairly tight to tight.
Miscellaneous Remarks	Horizontal sets are not apparent here. Other sets probably exist, but are too weakly expressed to be accurately defined.
Summary	The oldest and most well expressed set (C1), clearly dominant in the outcrop, consists of smooth, north-northeast-striking joints bordered by prominent orange devitrification rinds. The rinds are of variable thickness and discontinuous presence along the length of many C1 joints, and some lack them altogether. Most of the rinds are < 1cm in thickness, but some are as thick as 6 cm, and on average they are thicker than those of any other set. These joints we interpret as a cooling set, primarily because of the strength of the associated devitrification effects and because their orientations (median: N. 14° E.) lie just beyond the normal range of the T1 tectonic set.

Joints nearly perpendicular to the C1 set (C2) are interpreted as the complimentary set of a rectangular cooling system. We base this conclusion primarily on analogy to those other localities where rectangular cooling systems have been documented with considerably greater certainty. More than half of the C2 joints are bordered by devitrification rinds similar to those along C1 but generally thinner, 3 mm or less but locally 1-2 cm.

The third joint set, well defined by measurements but not prominent visually, is known from abutting and hooking relations to be younger than the C1 set. Its age relative to C2 joints is unknown. Devitrification effects along these joints are minimal: two-thirds of them lack visibly altered wall rock, and devitrification rinds bordering the others generally are less than 2 mm in thickness. These joints we interpret as the T2 set, based principally on their orientation, their obliquity to both other sets in the outcrop, and their young age relative to the C1 set.

Evidence for reactivation of the C1 cooling set is abundant at this locality. Many of the C1 joints are mineral-filled, but the fill varies in thickness along the length of the joint and in some places "wanders" from the original joint trace into the wall rock, indicating reopening of a previously sealed fracture. Multiple, overlapping, discontinuous veinlets cutting devitrification rinds adjacent to the original joints are additional evidence of secondary extension. Thicknesses of the mineral fill along C1 joints are highly variable, from a fraction of a millimeter to nearly 1 cm. Joints of the C2 cooling and T2 tectonic sets are mineralized also but show no evidence of reactivation.

Station Number	TOB1
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'19" N., long 116°24'45" W.
Location	Test pit #1 and pavement bordering test pit at the south end and east side of Fran Ridge
Exposure Description	Measurements from nearly vertical exposure in test pit and pavement bordering pit. Pavement area is on a 10-22° slope with nearly 100 percent exposure. Measurements were taken from west and southwest sides of pavement area bordering the test pit, over an area 12 m across slope and 5 m upslope.
Stratigraphic Unit	Topopah Spring Tuff, orange brick zone of Scott and Bonk (1984)
C1	
Median Orientation	N28W/85SW (n=8)
Expression	Moderate, about as obvious as C2 set; most prominent on east side of pavement and in test pit.
Shape	Nonplanar; sinuous along strike and dip; trace is fairly irregular
Roughness	Indet.; most coated or filled with caliche. One joint in test pit has a smooth surface
Exposed Length	Variable, observed range from 0.1-2.5 m; true lengths greater. Most joints extend to edge of pit and may cross pit
Exposed Height	Commonly 1 m; observed from 0.5-2 m
Structures	None seen (caliche coats most surfaces). Joint surfaces do not cut lithophysae.
Spacing	Very variable; on pavement surface commonly 1.5-3 m; elsewhere as close as 0.1 m
Mineralization	All surfaces are coated or filled with caliche up to 3 cm thick. Long C1 joint in pit is stained black and has a thin, white, spotty, noncalcareous mineral coating. Breccia with clasts up to 8 cm long occurs in caliche fill, in places (reactivated joint). A dark reddish-brown alteration rind 2-3 mm thick is present.
Remarks	On C1 joint in test pit, west side, are few horizontal striations resembling slickenside striations, on the alteration rind surface. These appear to be man-made and not true slickenside striations.
C2	
Median Orientation	N80E/89SE (n=8)
Expression	Moderate overall; best expressed on west and south side of pavement and on west side of test pit
Shape	Subplanar; sinuous along strike and dip; a few are curviplanar
Roughness	Smooth, very undulatory along strike and dip
Exposed Length	Commonly 6-10 m; true lengths very close to exposed lengths
Exposed Height	Commonly 1-3.5 m; joints extend to bottom of test pit
Structures	None seen (most covered with caliche). Two joints with alteration rinds cut a few lithophysae. Other joints belonging to this set do not cut lithophysae.
Spacing	Observed spacings in pit range from 0.6-1 m; on pavement surfaces spacings are commonly 0.75 m. Spacings as great as 3 m observed.
Mineralization	Surfaces are caliche coated. A dirty white, sugary, noncalcareous mineral is present on one C2 joint. In test pit, joint surfaces lightly stained black. Two joints have a 2 mm-thick alteration rind.
Remarks	One C2 joint in test pit curves from N80E to N58E. Many short (< 8 cm) C2 end blindly (both ends) and were not measured.
C3a	
Median Orientation	N62E/10SE (n=9)
Expression	Poor; locally developed; with one exception, all are located on west side of test pit. All seen were measured.
Shape	Planar, some curve slightly along strike

Station Number	TOB1
Roughness	Very smooth. Small angular chips on surfaces cause pitted surfaces, but original surfaces are very smooth. Pitting appears to be below the alteration rind and is present where rind has weathered away.
Exposed Dimension	0.15-2.3 m; true dimensions very close to exposed dimensions
Structures	Tubular structures with diameters ranging from less than 1-3 mm are present on all surfaces. Joint surfaces do not cut lithophysae.
Spacing	Closely spaced; those dipping NE are spaced 3-9 cm apart; those dipping SE or SW are spaced from 0.3-3 m apart.
Mineralization	Surfaces coated with caliche. Dark red alteration rinds are present on some and rinds border tubes. Rinds are < 1 mm thick on joint surfaces and are 0.5-2.5 mm thick where the rinds border the tubes. A few patches of white to cream-colored, granular, sparkly, noncalcareous mineral was noted on some surfaces; mineral weathers to light-orangish tan.
Remarks	Definite cooling joints based on presence of tubular structures. Joint surfaces are weathered, some badly. A large, 9 cm long pumice fragment is cut by one joint. C3a joints have same characteristics as C3b set, except dips are steeper on C3a joints. C3a set is missing below the top 0.3 m of test pit and does not extend far laterally. This set appears to be only locally developed and present only on a small area on the pavement surface.

C3b

Median Orientation	N20E/08SE (n=6)
Expression	Poor
Shape	Planar to subplanar
Roughness	Smooth
Exposed Dimension	Indet.; possibly < 2 m
Structures	All C3b joint surfaces have very weakly developed tubular structures with diameters < 1 mm. Joint surfaces do not cut lithophysae.
Spacing	Commonly 0.3-1 m
Mineralization	Many joint surfaces are coated with caliche. Underlying the caliche is a cream-colored to yellow, granular, noncalcareous mineral coating. Surfaces are altered to light purplish gray color, overlain by a dark purplish gray color, overlain by the cream-colored mineral and finally caliche.
Remarks	Definite cooling joints, due to presence of tubular structures. Joint surfaces are weathered. All C3b joints are located in an area about 20 m south of test pit; none were seen in the test pit or on the pavement surface surrounding the test pit. C3b set is separated from C3a set due to their near-horizontal dips. C3b and C3B sets appear to be analogous sets of cooling joints. SH joints of similarly gentle dip but different character are interpreted as younger unloading joints.

T1

Median Orientation	N01E/89NW (n=10)
Expression	Very well; most prominent set on outcrop
Shape	Subplanar; sinuous along strike and dip
Roughness	Very rough; irregular along strike and dip
Exposed Length	Commonly 2-5 m; true lengths may be much greater if joints cross pit
Exposed Height	Commonly 0.2-5 m, but as great as 12 m. True heights vary greatly
Structures	None seen. Joint surfaces are mostly completed filled with caliche. Few joint surfaces cut lithophysae
Spacing	Commonly 0.3-1 m; but also spaced 2-4 cm apart in 10-cm- wide zones
Mineralization	Surfaces coated with caliche up to 2 mm thick. Many T1 joints have dark reddish brown alteration rinds 2-3 mm thick. In places, a 1 mm-thick, white, probably noncalcareous, mineral coating is present under the caliche.

Station Number	TOB1
Remarks	Possible mixed tectonic and cooling set. Longer T1 with alteration rinds may be cooling joints and shorter joints tectonic in origin. Needs further evaluation.
T3	
Median Orientation	N50E/86SE (n=11)
Expression	Moderate overall, but locally developed. Fairly obvious on east side of pavement where most were measured.
Shape	Subplanar and very sinuous along strike and dip; changes in strike within 10 cm of trace length
Roughness	Fairly smooth, very irregular along strike and dip
Exposed Length	Variable, commonly 0.3-2 m; true lengths indet. but variable
Exposed Height	Indet.; as great as 0.5 m; true heights indet., but variable
Structures	None seen. Joint surfaces cut lithophysae.
Spacing	Indet., but variable. Two joints are spaced 0.3 m apart; T3 joints are spaced as close as 2-9 cm in shear zone.
Mineralization	Surfaces partly coated with caliche. Brecciated fill is present, and is interpreted to be a small shear zone, coinciding with reactivation along T3.
Remarks	Joint surfaces weathered. Abutting relationships evident on west side of pavement document that T3 and C2 are not the same set. Here T3 and C2 intersect, and T3 abuts C2.
SH	
Median Orientation	N49W/05NE (n=14)
Expression	Well on pavement surface; very poor in test pit where very few SH joints were seen
Shape	Nonplanar to subplanar; very undulatory along strike and dip. Two SH joints change in dip from 0° to 26°.
Roughness	Fairly smooth to smooth
Exposed Dimension	Exposed dimensions range from 0.04-5 m; true dimensions are greater
Structures	SH joints on pavement surface cut a few lithophysae. In test pit, rock is nonlithophysal.
Spacing	Commonly 0.5 m; observed range of 0.05-1 m
Mineralization	Most joint surfaces are coated with caliche. All surfaces are partially stained black. Underlying the caliche is a white to cream-colored, sugary, noncalcareous mineral.
Remarks	SH set is distinguished from C3a and C3b due to the absence of tubular structures. However, it is remotely possible some SH surfaces could have tubes, obscured by caliche which covers most SH joint surfaces. Where SH joint surfaces were visible, no tubes were present. SH joints nowhere approach a planar shape, as do C3a and C3b joints.
Terminations	C3a and T1 intersect; (2) T3 abut T1, one T1 abuts T3; most T1 and C2 intersect; several T1 and C3a intersect; T1 and T3 intersect; T1 abuts C1; some T1 and C1 intersect; several C3a terminate just before reaching C2; some C2 terminate just before reaching T1; C2 and C1 intersect; several C2 and T3 intersect; one C1 and T3 intersect; C2 and T3 intersect.
Miscellaneous Remarks	Low-confidence locality; complex and needs further work.
M	
Orientation	N55W/85SW, N78E/83SE
Summary	The fracture network at this locality was studied both within a recently excavated test pit about 4-5 m deep and on natural pavement surfaces bordering the pit to the west and southwest. Fractures interpreted as cooling joints form three mutually perpendicular sets, two nearly vertical and the third of gentle southeast dip. Superimposed on this network are at least three additional joint sets interpreted as tectonic.

Station Number TOB1

The fracture network remains incompletely--perhaps even poorly--understood and deserving of further study. Many C1 fractures in the pit are bordered by prominent, dark reddish-brown alteration rinds that at first were taken to be an indicator of cooling joints. That many younger fractures lack such rinds strengthened the supposition. However, closer inspection of those relatively few cooling joints with tubular structures revealed that although some possess visible alteration rinds, others of the same set do not. The same is true of the C2 set, whose properties strongly suggest an origin by cooling, and of rough-surfaced joints of nearly N-S strike that almost certainly are tectonic. Moreover, alteration rinds at some other localities in the study area are present on all joint sets, cooling and tectonic, old and young alike (see, for example, station TV1). Additional factors besides joint age--such as aperture, joint size, and degree of interconnection with other fractures--likely influence alteration-rind development, necessitating that further study of these features in thin section be made before their significance in the field can be fully interpreted. At locality TOB1, inspection of additional outcrops and laboratory study of mineral coatings and alteration rinds on joints of different sets likely will prove necessary to satisfactory understanding of the evolution of the fracture system there. Abutting relations and fracture characteristics nevertheless help to constrain possible interpretations.

The set most readily demonstrable as due to cooling is the C3 set, all measured members of which bear tubular structures upon their surfaces. These joints dip gently, 16° and less. Joints of the other two cooling sets, C1 and C2, dip steeply at 80° or more and have median strikes of N. 28° W. and N. 80° E., respectively. Evidence that joints of the C2 set are due to cooling includes their large size (lengths of 6-10 m are common), their smooth and undulatory surfaces, and the fact that they do not generally cut lithophysal cavities in the rock. Joints of the C1 set are of overall similar character, though smaller, and are known through abutting relations to predate joints interpreted as the earliest (T1) tectonic set.

Joints striking within 10°-15° of due north are the most well expressed joint set (T1), of the area. Their rough, irregular surfaces suggest the set is dominantly tectonic. We note, however, that the strike range of the T1 and C1 sets is nearly continuous, that a few joints of T1 orientation are enormous (heights up to 12 m), and that among them are some joints that cut no lithophysae and others that do. For these reasons we infer as likely possibilities that (1) the true strike range of the early C1 set is broader than given here and includes some joints of more northerly strike, overlapping in orientation those of the T1 set; (2) the T1 set as recorded in the field notes probably includes a few joints more properly assigned to the C1 set; and thus (3) the true median strike of the C1 set is somewhat more northerly than N. 28° W., and thus more nearly perpendicular to the joints of the C2 cooling set. Abutting relations and joint characteristics at this locality do not permit for all joints a clear distinction between a cooling or tectonic origin.

Two additional sets of joints offer fewer problems of interpretation. Joints of the T3 set are demonstrably young relative to those described above and are characterized by their small size, markedly irregular traces, and the fact that they cut through lithophysal cavities; there seems little doubt that these joints are tectonic. Also present are numerous, gently dipping joints nearly parallel to foliation (SH) that are distinguished from joints of the early C3 set by the absence of tubular structures, their transection of lithophysal cavities, more irregular shape, and somewhat rougher surfaces. These we interpret as late unloading joints similar to those recorded at numerous other localities.

Station Number	TOB2
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'21" N., long 116°24'45" W.
Location	Test pit #2 and pavement bordering test pit at south end and east side of Fran Ridge
Exposure Description	Station is located in completely exposed, vertical exposures within the test pit and on pavement surfaces bordering the north, west, and south sides of the pit. A gently dipping 10° slope forms the pavement surfaces and provides about 90 percent exposure. The pavements bordering the pit include a 4 m^2 area on the south side, a 4 x 12 m area on the west side, and a 4 m^2 area on the north side. A small fault is exposed on the north side of the test pit.
Stratigraphic Unit	Topopah Spring Tuff, orange brick zone of Scott and Bonk (1984)
C1	
Median Orientation	N19W/83SW (n=21)
Expression	Well; most prominent set and obvious in pit
Shape	Subplanar; long, gentle curves along strike; dip is consistently to SW
Roughness	Appears fairly smooth, but most surfaces are mineralized; somewhat undulatory along strike
Exposed Length	Commonly 0.5-1 m; in pit observed to range from 0.15-3.3 m; true lengths indet.
Exposed Height	Commonly 1-2 m; 2 m heights are exposed in pit; true heights indet. but greater than those observed
Structures	One arrest line 0.6 m long
Spacing	Longer joints are spaced from 0.2-0.8 m; shorter ones are spaced as close as 5 cm
Mineralization	Joint surfaces are heavily coated with caliche. A cream colored, sugary, noncalcareous mineral is present on some surfaces, and a white, fine-grained, powdery, noncalcareous mineral is present (these may be the same mineral, observed in different states of weathering). Black stains are visible underneath the mineral coating. No visible alterations rinds were noted.
Remarks	C1 joints appear to be open in the pit. C1 is interpreted as a cooling joint.
C2	
Median Orientation	N60E/67NW (n=17)
Expression	Moderately well, second most prominent set; like C1, is obvious in pit, and less obvious on pavement surface
Shape	Planar to nonplanar, curve along strike, very undulatory along strike and dip on a 1 m-scale, although dips remain NW.
Roughness	Fairly smooth, but more irregular than C1; locally very undulatory on a 15-30 cm-scale along strike and dip.
Exposed Length	Commonly 3-5 m; true lengths greater
Exposed Height	Commonly 0.5-3 m; true heights greater
Structures	Arrest line
Spacing	Long joints are spaced 0.4-4 m apart; shorter joints spaced as close as 0.5 cm; many shorter joints pinch into longer joints.
Mineralization	Caliche coats surfaces. Minerals present are same as described in C1 set. Dark reddish brown, 1-2 mm-thick alteration rinds are present on all C2 joints.
Remarks	Most C2 joints were measured in the pit. Alteration rinds appear thinner (1 mm) on shorter C2 joints, and thicker (2 mm) on longer C2 joints.
C3	
Median Orientation	N34W/84SW (n=16)
Expression	Very poor to poor, locally developed on outcrop; five joints are located on the NE wall of pit, near the bottom.
Shape	Planar to subplanar, sinuous along strike and dip, many curve gently along strike and dip, even over lengths as short as 1-2 m.

Station Number	TOB2
Roughness	Indet.; caliche coats most joint surfaces; possibly fairly smooth but some appear to be fairly rough with infrequent, small (2-4 cm scale) undulations
Exposed Length	0.2-4 m; true lengths indet., but greater
Exposed Height	0.05-3 m; true heights indet.
Structures	None seen; caliche covers most surfaces
Spacing	Variable, observed range of 0.1-1 m
Mineralization	Small, thin patches of white, noncalcareous mineral are present on many joints. Thin (0.5-1 mm thick), dark reddish brown alteration rinds are present on all joints. Small, black microcracks with alteration rinds extend at an angle from some joints belonging to this set.
Remarks	Presence of alteration rinds on C3 differentiates this set from C1.

T1

Median Orientation	N05E/79SE (n=9)
Expression	Poor overall; moderate on surface
Shape	Most are subplanar to nonplanar and irregular along strike and dip. Some very irregular along strike and dip. Some curve gently along strike
Roughness	Rough with large (0.3 m) bumps on joint surfaces
Exposed Length	Variable, as great as 4 m observed; true lengths greater
Exposed Height	Observed to 1 m; true heights greater
Structures	Some joints cut a few lithophysae. Small, sheared zones are abundant in this set.
Spacing	Variable; observed range of 2-20 cm
Mineralization	A thin, dirty white, platy, noncalcareous mineral coating is present on some joints. Dark reddish brown, 4-mm-thick alteration rinds are present on longest joints. Rind thickness decreases as joint lengths decrease. Rinds are absent on very short joints.
Remarks	T1 joints are much rougher than joints belonging to sets C1 or CM; T1 set is very difficult to distinguish from CM; most T1 joints have alteration rinds, but rinds are absent on CM joints. T1 strikes are variable, especially for shorter T1 joints.

SH

Median Orientation	N52W/05NE (n=10)
Expression	Well; obvious on pavement surface; extend only 1 m below pavement surface
Shape	Subplanar to nonplanar
Roughness	Irregular surfaces; caused primarily by pumice fragments and few lithophysal cavities which are cut by the joint surfaces
Exposed Dimension	Variable, observed as great as 5 m; true dimensions greater, perhaps as much as 7 m for some
Structures	None seen
Spacing	Commonly 0.05-0.3 m; observed range of 0.05-0.5 m
Mineralization	None seen, but joint surfaces mostly concealed by caliche
Remarks	SH joints are parallel to rock foliation and form ledges on the pavement surface. Joints from this set are probably caused by unloading.

Terminations	One C1 abuts C2; C1 and C2 intersect (C1 traces just barely cross C2); C2 and T1 intersect; C2 and C3 intersect; T1 and C3 intersect; two T1 hook and abut C3.

M

Orientation	N84W/71SW, N27E/77SE
Miscellaneous Remarks	Low- confidence locality. Sets may be mixed, or over separated. Presence or absence of alteration rinds may not be a significant criterion for separating sets. More work and mineralogical analyses are needed.

Station Number TOB2

Summary

A 4-5 m pit exposes relatively fresh rock and is bordered by natural pavement exposures where additional readings were taken to document the fracture network summarized below.

Some degree of similarity of the fracture network between station TOB1, to the south and this locality, is indicated.

At both localities the observed properties of C2 joints--large, smooth, commonly sinuous, and with orientations unlike those of known tectonic sets--collectively provide strong evidence that these joints formed during cooling. Joints of the C3 set are more problematical in that their orientations are equally compatible with a tectonic or cooling interpretation, but observation that T1 joints--those of the earliest tectonic set--hook toward and abut C3 joints establishes C3 as the older set. The sinuosity of many C3 joints is another property more suggestive of a cooling than a tectonic origin.

The T1 set is much more weakly developed at this station than at TOB1, but the character of its joints--rough-surfaced and irregular--is identical between the two localities. So too are properties of the SH joints, which in both places are interpreted to be late joints due to erosional unloading.

The C1 joint set is the most prominent but difficult-to-interpret set exposed in the pit. Its joints lack visible alteration rinds and initially were separated from those of the C3 set on that basis, but lessons learned at TOB1 and other localities show that presence or absence of alteration rinds is not a reliable guide to cooling versus tectonic joints. At TOB1, for example, some C1 joints with tubular structures lack visible alteration rinds, whereas others have them. The C1 joints are described in field notes as "fairly smooth" and only gently curving to undulatory along strike--properties insufficiently diagnostic of either a cooling or tectonic origin. That the C1 joints are not as rough as those of the T1 set constitutes at present our sole criterion for labeling them as cooling joints. If so, probably they should be grouped with the C3 set, giving an overall median orientation for the combined set of N. 24° W./84° S. W. Alternatively, the 15° strike difference between the C1 and C3 set, if regarded as significant, suggests instead that the C1 joints correspond to the T2 tectonic set. Abutting suggest only that the C1 joints postdate those of the C2 set. As at station TOB1, the complex fracture network of the local area is poorly understood and deserving of additional study.

Station Number	TR1
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'53" N., long 116°24'45" W.
Location	East side of Fran Ridge, on north side of gully on the SE-facing slope
Exposure Description	Outcrop is a rounded and exfoliated slope, dipping 22° SE. Foliation (measured on flattened pumice) is 24°. Station is located just below the thin lithophysal zone. The lower part of the rounded step zone at station TR1 is barely fractured. Exposure is 60 percent.
Stratigraphic Unit	Topopah Spring Tuff, rounded zone of Scott and Bonk (1984)
C1	
Median Orientation	N10E/90 (n=6)
Expression	Poorly expressed
Shape	Planar
Roughness	Smooth; uniform along strike and dip
Exposed Length	1-6 m, true lengths greater
Exposed Height	0.3-1.7 m, true heights greater
Structures	None seen
Spacing	Indet., two joints are spaced 0.8 m apart
Mineralization	Slight darkening of joint surface inward for a distance of 2-3 mm. White, opaque, noncalcareous fill 1.5 cm thick, enclosing breccia fragments averaging 0.5-4 cm in greatest dimension.
Remarks	Probable cooling joints based on roughness and shape.
C2	
Median Orientation	N70W/90 (n=12)
Expression	Poor; all seen were measured
Shape	Curviplanar; undulatory along strike and dip
Roughness	Indet. due to weathering; undulatory along strike and dip
Exposed Length	0.6-4 m, true lengths greater
Exposed Height	0.3-0.5 m, true heights greater
Structures	None seen
Spacing	Indet.
Mineralization	None seen; because C2 set forms the risers of rounded ledges, weathering may have removed mineralization
Remarks	C2 set is also present in the lower part of the zone.
C3	
Median Orientation	N11W/15NE (n=6)
Expression	Poor
Shape	Subplanar
Roughness	Indet., due to weathering, appears fairly smooth in places
Exposed Dimension	0.2-5 m; true dimension of one joint is 1 m.
Structures	None observed
Spacing	Commonly 0.1-0.4m; as wide as 2 m locally
Mineralization	Surfaces badly weathered to a gray color. Small patches of caliche are present on some surfaces
Remarks	C3 set is parallel to rock foliation.
T1	
Median Orientation	N10E/86NW (n=9)
Expression	Very well expressed; most obvious set at outcrop
Shape	Planar to curviplanar; small irregularities along strike and dip. One joint curves from N. 03E-N. 08E and extends through the entire 5 m stratigraphic thickness of outcrop.
Roughness	Fairly smooth; traces are irregular unlike the sharp, smooth C1 traces
Exposed Length	0.4-4 m; true lengths greater
Exposed Height	0.2-2 m; true heights greater, but possibly not by much

Station Number	TR1
Structures	None observed
Spacing	Common range = 1-2 m; also occur in closely spaced zones 0.3-0.8 m apart
Mineralization	All joints were once filled; some are filled with caliche while only patches of caliche remain on other surfaces. One T1 has caliche fill 3.3 cm thick. No visible alteration rinds were noted.
Remarks	Many shorter T1 joints are present between longer more prominent T1 joints. Only most prominent T1 joints measured. T1 set is very weakly expressed in the lower part of the station, where this and other joint sets appear to be dying out. True lengths of T1 joints approximate 5 m. Some T1 joints pinch towards the NW.

T2

Median Orientation	N41W/84SW (n=5)
Expression	Poor; all observed were measured
Shape	Curviplanar, gently curving along strike; one joint curves from N44-63W over a length of 1.5 m
Roughness	Smooth, similar to T1, with very small irregularities along strike and dip
Exposed Length	0.5-2 m
Exposed Height	0.4-0.6 m
Structures	None seen
Spacing	Indet., three joints are spaced 0.3-0.4 m apart
Mineralization	Caliche fills two joints
Remarks	None
Terminations	T1 and C2 intersect; T2 hooks into and abuts T1; two T2 abut T1; some T1 and C3 intersect; many T1 abut C3; cannot determine relationship between C2 and T2
Miscellaneous Remarks	Small (1-3 cm) lithophysal cavities are present, but not abundant

M

Orientation	N50E/69SE
Summary	The fracture network at this locality is similar to that at nearby station TC2 to the south: three sets of cooling joints (two vertical, one subhorizontal) nearly at right angles, one set of which is parallel to the T1 tectonic joints. Here, however, the tectonic joints dominate the network, and all three cooling sets are weakly expressed. The rock over much of the outcrop is sufficiently weathered, but the smoothness of C1 joints in protected areas of the outcrop is strongly suggestive of cooling joints. The same is true to a lesser extent of the gently dipping C3 joints, whose origin as a cooling set seems well established from the additional evidence that many T1 tectonic joints terminate against them. The identity of C2 as a cooling set is based principally on analogy to nearby exposures where evidence for their origin is better preserved; at this station no abutting relations of C2 with other fractures were seen. The T1 tectonic set and C1 cooling set are almost exactly parallel, as is typical of most outcrops in this general area. Among these joints collectively, however, some in outcrop have smooth, continuous traces whereas others, far more numerous, are distinctly irregular. Further, it is only the irregular joints that terminate against the gently dipping fractures of the C3 cooling set. Two sets rather than one thus seem indicated from the field observations, with the relatively younger T1 tectonic set dominant. The wide range in height of the T1 joints is attributable to their common failure to cut across pre-existing fractures: the T1 joints are short in those places where C3 surfaces are abundant but are much larger, locally cutting more than 2 m of section, where the C3 joints are absent. The dimensional control exerted by one joint set on a later set is well expressed in this outcrop. Also present at this locality are scattered joints of the T2 tectonic set. Terminations of several of them against nearby T1 joints confirm the relative age of the two sets.

Station Number	TC1
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'59" N., long 116°24'48" W.
Location	East side of Fran Ridge, at northernmost exposure of Topopah Spring Tuff at Fran Ridge, on flat surface formed by Topopah Spring Tuff
Exposure Description	Station is located in black vitrophyre above the caprock zone. Measurements were taken from two exposures located 6 m apart along slope. One outcrop, (larger one) is located 11 m upslope from the smaller exposure. Area of large exposure is 7 m across slope and 7 m upslope; smaller area is 3 m across slope and 3 m upslope. Exposure is 60 percent on a 12-17° slope.
Stratigraphic Unit	Topopah Spring Tuff, caprock zone, black vitrophyre subzone of Scott and Bonk (1984)

C1

Median Orientation	N77E/79NW (n=10)
Expression	Moderately well
Shape	Most are curviplanar. One joint is very sinuous along strike and dip over a 0.5 m scale, curving from N74E to N56W and back to N75E.
Roughness	Very smooth, in spite of weathered surfaces
Exposed Length	0.18-2.3 m; true lengths greater for most
Exposed Height	0.04-0.3 m; true heights greater for most
Structures	Possible arrest line
Spacing	Commonly 0.5-0.8 m. Two C1 joints are spaced 0.2 m apart
Mineralization	All have medium-red colored joint surfaces (probable alteration rinds). One C1 joint has a thin, white, opaque, noncalcareous film.
Remarks	Probable cooling set based on same criteria as C2 set. Cl joint are open < 1 mm.

C2

Median Orientation	N49W/83SW (n=12)
Expression	Moderately well
Shape	Most are curviplanar, few are planar; many are sinuous along strike but dip is consistently SW. Some observed to curve 30°
Roughness	Very smooth, in spite of weathered surfaces
Exposed Length	0.4-1.3 m; true lengths greater for most
Exposed Height	0.04-0.3 m; true heights greater for most
Structures	None seen
Spacing	Commonly 0.5 m; few are 0.8-1 m apart
Mineralization	All have medium-red colored joint surfaces (probable alteration rinds)
Remarks	Probable cooling set based on shape, roughness, orientation, red surfaces. The point where one C2 joint abuts a C1 joint acted as an origin point for small T1 joints that curve 35° in 0.25 m.

C3

Median Orientation	N26E/83NW (n=6)
Expression	Poor, not many seen
Shape	Planar to gently curviplanar
Roughness	Very smooth, very slightly sinuous on a 1-cm scale along strike
Exposed Length	0.2-1.7 m; true lengths mostly much greater
Exposed Height	0.02-1 m; true heights greater
Structures	None seen
Spacing	0.5-1 m (based on 3 joints, where spacings could be determined)
Mineralization	All have medium-red colored joint surfaces (interpreted to be alteration rinds).
Remarks	Probable cooling set based on same criteria as C2 set.

Station Number	TC1
T1	
Median Orientation	N05E/77NW (n=15)
Expression	Moderate to poor
Shape	Subplanar to planar; irregular along strike and dip
Roughness	Indet. due to weathering, but rougher than C1, C2, or C3
Exposed Length	0.3-1.6 m; lengths are variable; some true lengths greater
Exposed Height	0.01-0.8 m; heights are variable; some true heights greater
Structures	None seen
Spacing	Commonly 0.1-0.2 m; probably wider than observed
Mineralization	Caliche fills some T1 joints. No other mineralization seen
Remarks	Many minor T1 joints are present but were not measured. Many T1 joints pinch northwards. Several joints appear to have offset C1 joints left laterally by 1-1.5 cm (some C1 joints offset 3 times, all left laterally). T1 joints are distinguished from C3 by lack of red-colored surfaces, more irregular shapes, and abutting relationships.
SH	
Median Orientation	N18E/13SE (n=10)
Expression	Well
Shape	Subplanar, variable along strike and dip; possibly undulatory
Roughness	Indet. due to weathering but appear to be fairly smooth
Exposed Dimension	Greatest exposed dimension is 2.5 m; true dimensions greater
Structures	None seen
Spacing	Variable; commonly 0.05-0.24 m; some < 0.05 m
Mineralization	A few SH joint surfaces are altered to a medium-red color. Most surfaces are stained black. A few surfaces have a white to gray, translucent, botryoidal, noncalcareous, chalcedony (?) mineral coating up to 3 mm thick.
Remarks	SH set forms rounded, gentle, east-dipping exposures. All SH surfaces may have been mineralized but weathering is sufficient to have removed mineral coatings.
Terminations	Many C2 abut C1; C1 and SH intersect; C1 abuts C3; few C2 abut C3; C2 and SH intersect; T1 and SH intersect; T1 abuts C1; T1 abuts C3; one C1 barely crosses C3; T1 abuts SH; some minor SH abut C2; many T1 and C1 intersect.
Miscellaneous Remarks	Medium red color on C1, C2, and C3 surfaces may be the result of vapor phase alteration. Directly below the station, in the pale-red caprock subzone are two joints with orientations of N50W/80 SW and N32E/79NW. These two joints are interpreted as cooling joints.
Summary	The fracture network is dominated by cooling joints, which form a complex network of several sets. Properties shared by all of the cooling sets include smooth surfaces and joint walls discolored medium red, in sharp contrast to the black of the original rock. Many of these joints also show marked sinuosity, some as much as 20°-30° along strike. The later T1 joints, in contrast, are planar to subplanar, have distinctly rougher surfaces, and have black rather than red walls. A clear distinction can be made between tectonic and cooling joints, as based both on multiple fracture characteristics and on abutting relations. Most of the cooling joints are members of two moderately well expressed sets (C1 and C2) having an obtuse angle between them of 126°. Joints of the third and apparently earliest set (C3), few in number at the outcrop and represented here by only six readings, remain unexplained. In addition to the steeply dipping cooling and tectonic (T1) joints at this locality are other, fairly numerous joints of gentle (9°-22°) eastward dip (SH set). These appear to be a mixed set of early cooling and late unloading joints. A few of the gently dipping joints have reddened surfaces similar to those of the steeply dipping cooling joints and are interpreted accordingly. The termination of several T1 tectonic joints against members of the subhorizontal set likewise suggests that early cooling joints of low dip are present. The majority of the SH joints, however, have black surfaces, and some clearly postdate the T1 set; these we interpret as unloading joints similar to those documented at numerous other outcrops.

Station Number	TC2
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'14" N., long 116°24'52" W.
Location	East side of Fran Ridge, at southernmost exposure of the caprock zone of the Topopah Spring Tuff on Fran Ridge
Exposure Description	Station is a cliff exposure located at the south nose and along the east side of Fran Ridge. Area covered extends from south nose of ridge northward across the slope for 35 m, covering a stratigraphic thickness of 18 m. A few measurements were also taken around the tip of the ridge nose, on the west side of Fran Ridge. Vertical cliff faces are formed by C1 and subhorizontal ledges are formed by C3. Exposure is 80 percent. The outcrop has a few lithophysae in the top 8 m, while the lower 4 m of outcrop contains almost no lithophysae.
Stratigraphic Unit	Topopah Spring Tuff, caprock zone, pale red, devitrified subzone of Scott and Bonk (1984)
C1	
Median Orientation	N03E/78NW (n=24)
Expression	Very well, most prominent set
Shape	Gently curviplanar, most dip NW, some joints change dip along strike but curvature is gentle and not sinuous
Roughness	Smooth where surface is only mildly weathered. Some joints are undulatory along strike and dip; others appear fairly uniform along strike and dip
Exposed Length	1-18 m; many true lengths greater than 11 m
Exposed Height	0.2-9 m; many true heights greater than 4 m
Structures	2 m long, northward propagating arrest line. Joint surfaces cut few lithophysal cavities
Spacing	Commonly 0.3-1 m; at ridge nose spaced 3 m apart; few observed as closely spaced as 0.06 m
Mineralization	Most surfaces are badly weathered and in places stained black and orange. Patches of caliche observed on some surfaces. In some places, breccia is present in the caliche. One joint surface has thin (0.5 mm), white to pale gray, opaque, noncalcareous mineral coating
Remarks	Very probable cooling set (roughness, length, height, shape). Only most prominent C1 joints measured. At ridge nose are few joints with C1 orientations; these joints have rough, irregular surfaces and abut C2 in locations where prominent C1 and C2 intersect. These may be C1 joints reactivated to abut already formed C2. Rock readily spalls parallel to C1 inward to distances of up to 10 cm. Small (3 cm) angular, granitic xenolith observed on C1 joint surface about 4.5 m from top of the caprock zone.
C2	
Median Orientation	N83W/85SW (n=23)
Expression	Moderately well
Shape	Curviplanar, few observed to change dip direction within 2 m height
Roughness	Smooth, gently undulatory along strike and dip
Exposed Length	0.4-3 m; many true lengths probably greater
Exposed Height	0.4-3 m; many true heights probably greater
Structures	Arrest lines, left stepping en echelon (propagating to east)
Spacing	Indet. but variable and wider than C1 set. Major joints are spaced 1-3 m apart; three joints are spaced 0.2-0.3 m apart
Mineralization	Patches of caliche are present on some C2 joints. Black and orange stains are present on some joint surfaces
Remarks	Very probable cooling set (roughness, shape). Most apertures are < 2 mm.
C3	
Median Orientation	N02E/17SE (n=14)
Expression	Well
Shape	Planar, some may be slightly curviplanar
Roughness	Fairly smooth and uniform along strike and dip

Station Number	TC2
Exposed Dimension	Greatest observed dimension is 7 m; smallest dimension observed is 0.2 m. True dimensions variable; many probably as great as 1-5 m, but some also probably greater than 7 m.
Structures	None seen
Spacing	Extremely variable. Near the top of section, major C3 are spaced 0.3-2 m apart, and some spacings are greater than 3 m; Near the top of sections spacing commonly ranges from 1.3-2 m. Below the top 5 m; spacings are closer where 0.2-0.3 m is more common.
Mineralization	Patches of white, opaque, noncalcareous mineral on one joint
Remarks	C3 joints are parallel to rock foliation. Interpreted as probable cooling joints. One indication that these are probably cooling joints is the downward diminishing of spacings. C3 joints are very tight and are uniformly sharply formed planar joints often of large size. Also present are generally smaller joints which are very rough, highly irregular, and about parallel to the foliation; these probably are late unloading joints.

T1

Median Orientation	N02W/81SW (n=6)
Expression	Poor
Shape	Subplanar, irregular trace
Roughness	Indet., irregular along strike and dip
Exposed Length	0.5-3 m; true lengths unknown, but greater than range of exposed lengths
Exposed Height	0.2-3 m; true heights unknown, but greater than range of exposed lengths
Structures	Northward propagating arrest lines on one joint
Spacing	Indet.; as close as 10 cm
Mineralization	All surfaces weathered; many surfaces stained orange and black
Remarks	Probable tectonic set. Difficult to distinguish from C1 joints and suspected weathering fractures that occur on the outside edge of outcrop. Southernmost edge of outcrop is badly weathered and/or buggered up with small fractures. Look for other localities away from faults.

T3

Median Orientation	N39E/77NW (n=4)
Expression	Poor
Shape	Subplanar
Roughness	Indet.
Exposed Length	0.5-3.0 m seen
Exposed Height	0.2-3.0 seen
Structures	None seen
Spacing	Indet.
Mineralization	Surfaces stained black and orange
Remarks	Probable tectonic set.

T4

Median Orientation	N87W/89SW (n=15)
Expression	Poor
Shape	Most are subplanar; some are planar
Roughness	Rough
Exposed Length	0.3-1.5 m; many true lengths range from 0.3-0.7 m, and are controlled by C1 spacing
Exposed Height	0.2-0.7 m; true heights indet., but one was observed to be 0.5 m; heights constrained by C3, but not all terminate against it.
Structures	None seen
Spacing	0.8-2 m where set is best expressed at south end of exposure; much greater elsewhere
Mineralization	Surfaces stained black and orange

Station Number TC2

Remarks

Crudely expressed set of cross joints with respect to C1. Style of T4 set is very different from C2; joints belonging to T4 set are uniformly rough and irregular along strike and dip.

M

Orientation

N03E/72SE, N09E/69SE, N83W/22SW

Terminations

Many C2 abut C1; C1 and C2 intersect; many C1 and C3 intersect; T1 abuts C2; one C2 ends blind before reaching C1; one C2 abuts C3; some C3 abut C1; C2 and C3 intersect; one C1 hooks into another C1; some C3 abut C2; T4 and C3 intersect; one T4 abuts C3; many T4 abut C1

Summary

Three well-defined sets of fractures interpreted as cooling joints dominate the fracture network of this outcrop. Members of the most prominent cooling set (C1) strike nearly north, and are notable for their large size: exposed lengths of 6-11 m are common. Nearly at right angles to them, and generally younger as established through abutting relations, are shorter cooling joints of a second (C2) set. Among these, exposed lengths of 1-3 m and heights of 2-3 m are common, the shorter lengths having been determined in part by the spacings between adjacent C1 joints. Joints of both sets have smooth walls and commonly are undulatory along both strike and dip.

The third (C3) set of cooling joints consists of large, fairly smooth, planar to gently undulatory surfaces about parallel to foliation, and thus dipping at low angles (median 17°) to the east. Abutting relations suggest these postdate C1 and are roughly synchronous with the later, C2 cooling set. Their spacings are erratic but generally are greatest near the top of the exposure and decrease toward its base, the opposite of the expected trend for unloading joints, but not inconsistent with a set of cooling joints. One of these surfaces in the underlying thin lithophysal zone, about 2.5 m below the caprock zone at this locality, displays tubular structures as proof of an origin due to cooling. Tubular structures on cooling-joint surfaces within the largely nonlithophysal caprock zone, however, are absent at this locality, as expected for the lithology.

Two and possibly three sets of steeply dipping tectonic joints, all weakly expressed, add complexity to the fracture network. The complexity is compounded by the near-parallelism of two of these sets (T1 and T4) to the earlier-formed C1 and C2 cooling sets, respectively. The tectonic joints, however, differ markedly from the cooling joints in size, overall style, and perhaps more importantly in their demonstrated young age as revealed by abundant abutting relations. The T4 joints, for example, are uniformly small, crudely formed, rough-surfaced joints totally different in style from the associated C2 cooling joints, and their heights are constrained by the perpendicular distance between adjacent C3 cooling joints. Alone among the tectonic joints, only those of the T3 set are distinguishable from cooling joints solely on the basis of orientation; nonetheless so few were observed that the presence of this set is considerably less certain than the others.

Unloading joints parallel to rock foliation, and thus to the C3 cooling set, were noted only in passing and did not record by measurement. Again, however, the generally small size, irregular shape, rough surfaces, and young age of the unloading joints collectively provide sufficient means to distinguish them from the earlier cooling fractures.

See also the notes for nearby station TR1, where a similar fracture network is exposed in a lower stratigraphic unit.

Station Number	TC3
Quadrangle	Topopah Spring SW, 7.5', lat 36°48'53" N., long 116°24'51" W.
Location	East side of Fran Ridge, near northernmost exposure of Topopah Spring Tuff
Exposure Description	TC3 is a near vertical cliff exposure located at the top of a gully and a small, nearly horizontal area encompassing 2 m across slope by 4 m upslope, located 60 m SW of the top of the gully where the rock outcrops on a flat ridgetop. SH set forms the ledges and C1 forms the cliff faces in the gully. Most measurements taken from the gully exposure spanning an area 50 m across slope and 15 m upslope. Stratigraphic thickness covered is approximately 8 m. Exposure is 70 percent. Uppermost section contains a few lithophysal cavities. Blocks of rocks have shifted from freezing and thawing. A N44E joint on south side of station deflects compass. All orientation measurements were checked for compass deflection.
Stratigraphic Unit	Topopah Spring Tuff, caprock unit; pale red densely welded subzone of Scott and Bonk (1984)

C1

Median Orientation	N11E/88NW (n=17)
Expression	Very well; most prominent set
Shape	Planar to gently curviplanar
Roughness	Weathered, appears very smooth; uniform along strike and dip
Exposed Length	0.5-8 m; true lengths greater
Exposed Height	0.1-3 m; true heights greater
Structures	None seen
Spacing	Commonly 0.5-2 m
Mineralization	Some surfaces have noncalcareous, white, botryoidal patches 0.5-1 cm thick. Pockets observed where botryoidal surfaces never filled.
Remarks	Probable cooling set. Probable reactivation along C1.

C2

Median Orientation	N50W/89SW (n=16)
Expression	Moderately well
Shape	Curviplanar, many sinuous along strike (0.5-1 m scale); most dip SW
Roughness	Surfaces weathered but appear very smooth and uniform along strike
Exposed Length	0.5-7 m; true lengths greater
Exposed Height	0.15-5 m; true heights greater
Structures	Arrest line one joint
Spacing	Commonly 0.3-1 m; some as close as 0.15 m; two are spaced 1.5 m apart
Mineralization	All surfaces are weathered. Some surfaces have noncalcareous, white, botryoidal patches. A black stain coats portions of most C2 surfaces. No alteration rinds seen.
Remarks	Very probable cooling set. Apertures are 1-3 mm on area exposed on flat ridgetop. Abutting relationships for C2, C3, and T1 sets can most easily be discerned on the flat ridgetop. C2 orientations may be extremely variable. Several C2 joints form wedges.

C3

Median Orientation	N42E/81NW (n=9)
Expression	Poor
Shape	Curviplanar to planar; some sinuous along strike (0.2-1 m scale), but all joints dip NW
Roughness	Surfaces weathered, but appear to be very smooth and uniform along strike and dip
Exposed Length	0.5-7 m; true lengths greater
Exposed Height	0.07-2 m; true heights greater
Structures	Surfaces cut a few lithophysal cavities
Spacing	1-3 m common

Station Number	TC3
Mineralization	Some surfaces have noncalcareous, white botryoidal patches. C3 joints exposed on flat ridgetop are completely filled with siliceous material. Mixed chalcedony and calcite filling 5-7 mm thick observed on one joint
Remarks	Probable cooling set. Aperture of C3 joint on ridgetop is 12 mm. C3 set is parallel to slope and is open more than C2 joints.

C4

Median Orientation	N88W/86NW (n=4)
Expression	Poor
Shape	Curviplanar
Roughness	Smooth
Exposed Length	0.8-3.5 m, true lengths greater
Exposed Height	0.1-0.6 m, true heights greater
Structures	None seen
Spacing	Indet.
Mineralization	None seen
Remarks	Probable cooling set.

T1

Median Orientation	N11E/80NW (n=16)
Expression	Moderately well
Shape	Subplanar, irregular traces
Roughness	Indet. but probably undulatory along strike and dip based on irregular trace
Exposed Length	0.5-5 m; true lengths some greater than 5 m
Exposed Height	0.01-0.4 m; true heights greater
Structures	None seen; most surfaces not visible or badly weathered
Spacing	Variable, commonly 0.2-0.3 m; as close as 0.1 m
Mineralization	White-to-gray, translucent, noncalcareous, botryoidal fill 1 mm thick
Remarks	Many T1 joints abut N76W-71E oriented joints that cannot be defined as a set at this locality.

SH

Median Orientation	N04W/14NE (n=15)
Expression	Very well expressed, almost as well as C1
Shape	Subplanar
Roughness	Indet. due to weathering, fairly rough along strike
Exposed Dimension	0.3-4 m observed, true dimensions greater
Structures	None seen
Spacing	0.5-0.8 m common for major SH joints, others spaced 0.15-0.5 m
Remarks	SH joints are parallel to foliation
Mineralization	Same as C1, C2, C3, T1

M

Orientation	N62W/85NE, N64W/90NE, N90E/85SE, N04W/79SW
Terminations	Major SH abut C2; some C2 abut C1; SH and C1 intersect; C2 and C1 intersect; T1 abuts C3; one C3 abuts C2; C2 and C3 intersect; one C3 abuts C1; C4 and SH intersect; some SH abut C4; many T1 abut C4; two C4 abut C1

Station Number TC3

Summary

Here, as at nearby station TC1 to the north, the fracture network is dominated by cooling joints. Orientations of the cooling joints, all of which dip steeply and have very smooth surfaces where unweathered, define two strong and two weak groups. Properties of the four sets are as follows:

Set	Orientation	Expression	Angular Relations
C1	N. 11° E.	Very well	
C4	N. 88° W.	Poor	C1 to C4=81°
C2	N. 50° W.	Mod. well	
C3	N. 42° E.	Poor	C2 to C3=88°

Within this grouping the sets are listed in probable order from oldest to youngest as established through abutting relations, with only the position of the C4 set being somewhat in doubt. The cooling sets thus appear to define two rectangular systems, each with one dominant and one subordinate set of joints, similar to many such systems documented elsewhere. Possible explanations for the presence of four steeply dipping cooling sets, rather than the usual two, include (a) tilting of the rocks during cooling, so that downdip gravitational stresses became reoriented, (b) vertical growth of cooling sets from one unit into another, overlying or underlying unit where cooling sets of different orientation had already formed, resulting in superposed cooling systems of somewhat different age, and (c) two-stage cooling, the first following emplacement of the Topopah Spring Tuff and the second following emplacement of the overlying Tiva Canyon Tuff just above. Further work in this area, including close attention to vertical sequences of cooling joints and tilt directions of the rocks, is needed to decide among the possibilities.

Tectonic joints of the T1 set are nearly parallel to those of the oldest (C1) cooling set but are distinguished from them by their demonstrated young age, their irregular rather than smooth surfaces, and their generally smaller size (exposed heights of T1 joints are uniformly small, 0.4 m or less, and few T1 joints attain lengths approaching those of the larger C1 joints). A further difference, repeated at other localities, is the greater variation in dip among the cooling joints--41°, as opposed to only 24° for the later tectonic set. Both sets at this locality are represented by abundant joints.

Irregular, shallow-dipping joints parallel to rock foliation are second in prominence at this locality only to the C1 cooling set. Abutting relations suggest they are the last-formed set and thus that they are unloading joints.

Station Number	TC4
Quadrangle	Topopah Spring SW, 7.5', lat 36°52'07" N., long 116°24'19" W.
Location	Yucca Wash, directly north of the northern tip of Alice Hill
Exposure Description	Station TC4 is located in the bottom of Yucca wash, in an isolated exposure 6 x 8 m in size. Here, a completely exposed, nearly horizontal pavement exposes a densely welded brick red vitrophyre with a black vitrophyre beneath.
Stratigraphic Unit	Topopah Spring Tuff, caprock zone. Station TC4 is located in the black vitrophyre subzone mapped by Scott and Bonk (1984).
C1	
Median Orientation	N89W/80NE (n=6)
Expression	Moderate to well; an obvious set but widely spaced
Shape	Nearly planar to gently curving along strike, gentle changes along dip
Roughness	Smooth
Exposed Length	0.4-5.5 m; true lengths greater
Exposed Height	0.1-0.6 m; true heights probably much greater
Structures	None seen
Spacing	Observed range of 2.5-4 m
Mineralization	Dark, blackish gray, altered surface noted on one C1 joint; white, scaly, noncalcareous mineral on C1 joint with altered surface; colorless film of noncalcareous mineral (not gypsum) on one joint
Remarks	One long C1 joint is discontinuous along strike; both right and left stepping with minor overlap segments.
C2	
Median Orientation	N13E/87SE (n=5)
Expression	Moderate
Shape	Curviplanar, some curving markedly in dip and to a lesser extent in strike
Roughness	Smooth, like C1
Exposed Length	2-6.5 m; true lengths greater
Exposed Height	0.2-1.5 m; true lengths much greater
Structures	Possible arrest line indicating downward propagation of joint
Spacing	Range of observed spacings is 0.3-2.5 m
Mineralization	Hint of dark, blackish gray altered surface. Translucent to opaque, noncalcareous mineral coating up to 1.5 mm thick
Remarks	C2 set is distinguished from T1 set on the basis of smoothness, size, shape, and to a lesser extent, spacing. C2 set is not as well-developed as C1.
T1	
Median Orientation	N04E/86SE (n=15)
Expression	Well
Shape	Relatively planar, some are irregular along strike
Roughness	Fairly rough, irregular surfaces
Exposed Length	0.4-2.5 m; true lengths probably not much greater; many small T1 (0.1 to <1 m) pervade the outcrop.
Exposed Height	0.1-0.6 m; true heights unknown
Structures	None seen
Spacing	Variable, from 0.06-1 m, commonly 0.2-0.4 m in the SE corner of outcrop where set is best expressed, increasing to 0.3-0.6 m elsewhere
Mineralization	White, translucent to opaque, noncalcareous fill up to 1 mm thick. T1 joints in the black vitrophyre are bordered by medium orange-brown altered zones, commonly 0.5-1 mm thick.
Remarks	Only the longest T1 joints were measured. One short, overlapping and dominantly right-stepping zone of T1 joints strongly suggests that these are tectonic rather than cooling joints. This set extends into the black vitrophyre.

Station Number	TC4
T2	
Median Orientation	N18W/81NE (n=14)
Expression	Moderately well
Shape	Subplanar, many somewhat irregular along strike
Roughness	Moderately rough; surfaces slightly irregular; appear smoother than T2
Exposed Length	0.4-1.5 m; Commonly spaced at 0.4-0.8 m; True lengths of most T2 joints are < 1 m.
Exposed Height	0.05-0.1 m; true heights unknown but presumably small
Structures	None seen
Spacing	Variable; observed range is 0.01 to 1 m; common range is 0.2-0.4 cm over half of outcrop
Mineralization	None seen; possible thin, noncalcareous, white coating on one joint; T2 joint surfaces are not well exposed
Remarks	Only larger T2 joints measured. T2 is a very tight set. Tips of T1 joints served as origin points for later T2; commonly see one curving or hooking into another. From this can verify, along with abutting relationships, that T2 is the younger set.
T4	
Median Orientation	N88W/87NE (n=12)
Expression	Moderate to poor
Shape	Subplanar
Roughness	Fairly rough
Exposed Length	0.2-1 m; true lengths are very close to exposed lengths
Exposed Height	0.1-0.3 m; true heights are very close to exposed heights
Structures	None observed
Spacing	Variable; 0.2-0.5 m where set is best expressed; spacing increases to 1 m locally
Mineralization	Mineralization is same as SH set, except coating is thinner (<1 mm-thick)
Remarks	T4 set is probably uplift related and is a set of stress-release joints perpendicular to T1.
SH	
Median Orientation	N82W/10SW (n=12)
Expression	Well
Shape	Subplanar, commonly gently undulatory
Roughness	Fairly smooth
Exposed Dimension	1.4 m; true dimensions unknown, but variable. Observed range of dimension is 0.4-1.4 m
Structures	None seen
Spacing	Closely spaced, as close as 1 cm, as much as 0.6 m. Commonly spaced from 2-20 cm.
Mineralization	Most surfaces weathered and mineral coatings presumably eroded off. Several joints have a 1-2 mm-thick, translucent, white to gray, noncalcareous (probably chalcedony) mineral coating with botryoidal outer surfaces. This demonstrates SH joints were open at least this much and were conductive.
Remarks	SH is parallel to foliation. Interpreted as unloading joints, although not purely superficial.
Terminations	Many T2 abut T1; multiple T4 abut SH; multiple T4 abut T1; many T4 and T1 intersect; multiple T2 abut C2; several T4 abut C2; multiple T2 abut C1; several T2 and C1 intersect; multiple T1 abut C1; multiple T1 and C1 intersect; multiple SH abuts T1; multiple SH and T1 intersect; multiple T2 hooks into T1.

Station Number TC4

Summary

This exposure is among the most critical of those described in this report. The fracture network, though complex (six sets), is completely exposed on a pavement surface along the floor of a wash and is developed on a sufficiently compact scale that interrelationships among the sets are readily documented. Abutting relations are numerous, clear, and consistent, leaving no doubt as to relative age of sets. Moreover, major style differences between cooling and tectonic joints allow confident distinction between them, even though orientations of the cooling sets strongly overlap those of two of the tectonic sets. The joints of all six sets are mineralized.

The cooling joints define two sets nearly at right angles (median strikes are N. 89° W. and N. 13° E.) and differ from the later tectonic joints in their large size, smooth surfaces, early age, and wider spacings. Lengths of 2.5 m or more are common among these joints but decidedly rare among the later tectonic joints. The cooling joints are the most prominent fractures in the outcrop and in their visual properties clearly stand apart from the rest.

The T1 tectonic set is represented by abundant joints spaced 20-60 cm apart across much of the outcrop. Many abut the cooling joints. Later joints of the T2 set, almost equally abundant, commonly abut and hook into T1 joints, confirming the relative age of these two sets as inferred from other outcrops. Also common here are fractures showing an abrupt change in strike, with one segment parallel to T1 and the other, later one parallel to T2, showing that the tips of some T1 joints served as origin points for the younger fractures. Such "kinked" fractures, though continuous breaks in the rock, represent not one fracture event but two.

Foliation-parallel fractures interpreted as unloading joints are abundant in this exposure and divide the rock into crude, overlapping, subhorizontal plates commonly 2-20 cm thick. Botryoidal coatings 1-2 mm thick of a hard, noncalcareous, presumably siliceous mineral (opal or chalcedony) are preserved on some of these joints and show that they served as conduits for groundwater flow; they are not merely superficial joints that developed upon exposure.

The youngest joints in this outcrop are those of the T4 set, multiple members of which abut the subhorizontal SH joints. Though coincident in orientation with the C1 cooling set, the T4 joints are uniformly small (<1m length), irregular, fairly rough-surfaced fractures of demonstrated young age. We interpret them as a stress-relaxation set at high angles to the dominant T1 and T2 sets; here, as elsewhere, they form a recognizable but weakly expressed set of late joints. They too are mineralized.

Station Number	CC1
Quadrangle	Topopah Spring SW, 7.5', lat 36°52'07" N., long 116°27'38" W.
Location	Drill Hole Wash, SSW of drill hole USW UZ-1
Exposure Description	Station is located in a manmade shallow trench on the ENE-facing hillslope of Diabolus Ridge. The trench is 4-5 m wide and about 30 m long. Measurements were taken over an area of 6 m x 4 m.
Stratigraphic Unit	Tiva Canyon Tuff, columnar unit, nonwelded basal zone (shardy base) of Scott and Bonk (1984)
Lithology	Medium-gray-brown tuff, prominent slightly flattened pumice fragments; low-density rock. Pumice fragments are pale flesh colored, subangular, and constitute approximately 10 percent of rock. Matrix is vitric.
T1	
Median Orientation	N04E/85NW (n=14)
Expression	Very well
Shape	Planar to subplanar; many show rectilinear traces along strike but others are gently sinuous. Many split and merge where T1 joints are spaced only 2-3 cm apart. Some are slightly sinuous in dip, but not as variably as along strike
Roughness	Fairly smooth, with low relief
Exposed Length	Variable, commonly 0.8-2 m; observed to range from 0.2 m to at least 3 m
Exposed Height	Commonly 0.1-0.5 m; maximum observed height is 1 m; heights are minimized by exposure configuration
Structures	None seen
Spacing	Variable, most T1 are spaced 2-5 cm apart, longest T1 are spaced 20-35 cm apart. Interspersed between them are small T1 joints spaced 1-5 cm apart. Set appears to converge slightly to closer spacings to the south.
Mineralization	Surfaces are discolored dark brown to black with thin films of an unidentified mineral. Many are caliche filled
Remarks	No evidence of shear along T1 surfaces. Wall separations of T1 from near zero to approximately 5 mm; many are 1-2 mm. T1 appears to be the oldest set here, as joints of all other sets terminate against them.
T2	N45W/87SW (n=4)
Median Orientation	
Expression	Very poor, all four joints are located in a small, 1 m^2 area at north end of exposure
Shape	Planar
Roughness	Fairly smooth to slightly rough
Exposed Length	Minimal, up to 0.5 m
Exposed Height	Up to 0.3 m
Structures	None seen
Mineralization	Caliche filled
Remarks	Low confidence set; all seen were measured.
T3	
Median Orientation	N46E/83NW (n=15)
Expression	Poor; fairly ill-defined, although recognizable
Shape	Most subplanar; not as planar as those of T1 and T4
Roughness	Few surfaces not covered with caliche are noticeably rougher than T1 and T4 surfaces
Exposed Length	Uniformly small, commonly 0.15-0.3 m; true lengths of 0.35 m or less
Exposed Height	Commonly 0.2-0.4 m; some T3 heights are greater than lengths
Structures	None seen
Spacing	Very variable; no meaningful average can be given
Mineralization	Most surfaces filled with caliche.

Station Number	CC1
Remarks	A poorly developed set. All T3 seen were measured. No evidence of shear where T3 joints cut through lumps of pumice.
T4	
Median Orientation	N86W/89NE (n=20)
Expression	Moderate to well
Shape	Most planar to subplanar
Roughness	Fairly smooth, similar to T1 surfaces
Exposed Length	Many true lengths are 0.2-0.35 m long; others much shorter, as short as 5 cm where T1 joints are closely spaced. A few T4 cut across one or more T1 joints and thus have lengths greater than T1 spacing; one is 0.5 m long and one approaches 2 m in length.
Exposed Height	20-50 cm; one T4 joint height is 1.5 m
Structures	None seen
Spacing	Variable, most are 15-40 cm; locally as close as 10 cm where T1 is closely spaced
Mineralization	Many T4 surfaces appear fresh and are not discolored; a few surfaces have a faint black to brown discoloration like T1 surfaces, but less pronounced; many are caliche filled
Remarks	Wall separations variable; 0.5-2 m for many, but rarely as much as 5 mm locally. No evidence of shear where T4 joints cut through pumice lumps.
SH	
Median Orientation	N79E/05SE (n=17)
Expression	Poor to moderate
Shape	SH joints have dual characteristics: some are planar and parallel to the tuff foliation; others are inclined to foliation at a low angle and are considerably more irregular
Roughness	Fairly rough, much more so T1 and T4 surfaces
Exposed Dimensions	Those parallel to the foliation are larger, with exposed dimensions of 0.7-1.3 m. Those inclined are smaller, with exposed maximum dimensions of 0.2-0.7 m. Dimensions of SH joints perpendicular to T1 joints are determined by T1 spacing; largest is 35 cm and T1 spacing is as small as 2 cm.
Structures	None seen
Spacing	SH joints are spaced about 10-25 cm apart
Mineralization	Most surfaces are caliche filled
Remarks	Although SH with respect to T3 terminating relationships are rarely exposed, SH appears to be the youngest set.
Terminations	Both ends of nearly all T4 joints abut T1 joints; several T4 intersect one or more T1; multiple T3 abut T1; few small T3 abut T4; few T3 and T1 intersect; few T3 and T4 intersect; many SH abut T1; SH abuts T4; a few SH abut T3. Almost certainly T3 postdates T1.
Summary	Joints of all five tectonic sets are present in this exposure, though to markedly varying degree. The oldest (T1) set, of nearly N-S strike, is by far the best expressed of the five and is represented by great numbers of closely spaced joints. Next in prominence are the T4 set, whose joints strike nearly perpendicular to the T1 surfaces, and the SH set, whose joints are conspicuous by virtue of their gentle dips. Recorded abutting relations among these three sets are clear and consistent. Two additional sets (T2 and T3) are present but not as well defined here. Joints of the T3 set are small, widely scattered, and inconspicuous as a set; nevertheless their orientations fall within a relatively narrow range and match those from other localities where the set is better defined. The T2 joints, few in number (4) and confined to one small area of the exposure, constitute a set of dubious validity, though the set is a common one at other localities on Yucca Mountain. The placement of both sets within the overall fracture chronology is based principally on analogy with other outcrops where abutting relations are better defined; the evidence here is sufficient to show only that T3 is the younger set relative to T1. No abutting relations of T2 surfaces with joints of other sets were observed.

Station Number	CH1
Quadrangle	Topopah Spring SW 7.5', lat 36°51'36" N., long 116°27'17" W.
Location	SE-facing outcrop at base of slope in Wren Wash, at USW UZ-N98 and USW UZ-N24 drill holes
Exposure Description	Exposure is 30 ft high and 150 ft long, extending to floor of wash; 80 percent exposed; moderately to highly fractured. Slope is 30-45°.
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
C1	
Median Orientation	N70E/87NW (n=17)
Expression	Fairly well, obvious because of joint lengths
Shape	Planar to gently curving along strike
Roughness	Smooth
Exposed Length	Commonly 3-5 m, observed up to 8 m
Exposed Height	Commonly 0.3-0.6 m, largest exposed height is 3.5 m
Structures	None seen; surfaces are smooth and nearly featureless
Spacing	Variable; 1-3.5 m common; locally 0.6-1 m where abundant
Mineralization	Ivory to gray colored alteration rinds 1 mm or less are common; mineral coatings common and visually similar to those on T1.
Remarks	Set is unevenly distributed throughout outcrop. Although lacking tubular structures, this set is interpreted as an early cooling set based on roughness, length, and shape characteristics.
T1	
Median Orientation	N12W/84SW (n=16)
Expression	Moderately well expressed overall, locally strongly expressed
Shape	Subplanar, gently sinuous along strike and dip
Roughness	Variable, some fairly smooth but others considerably less so, with a subdued bumpy surface
Exposed Length	Most 1.5 m or less; observed to 2.5 m; minimized by exposure orientation
Exposed Height	Commonly 4-6 m; probably close to true heights
Structures	None seen
Spacing	0.2- 1 m; most are spaced 0.4-0.7 m where set was measured; less abundant elsewhere. T1 joints occur locally in small swarms 10-15 cm wide, where 3-4 joints are spaced 1-5 cm apart. These tend to be small (0.6-1 m in length and height)
Mineralization	Thin alteration rinds, 1 mm or less along some T1. Surfaces bleached to an ivory color. Thin film of smooth, milky white to cream colored cryptocrystalline chalky mineral with a cream-colored, fine granular mineral (tiny euhedral crystals in thin lenticular vugs), probably quartz
Remarks	None
T2a	
Median Orientation	N52W/90 (n=20)
Expression	Very well expressed locally; most prominent set on outcrop
Shape	Planar to gently sinuous along strike; most are very nearly planar
Roughness	Smooth to very gently irregular on a small scale
Exposed Length	Commonly 2-4 m; true lengths indet.
Exposed Height	Commonly 1-2 m; probably close to true heights as many upward and downward terminations are seen
Structures	Hook of one T2 into another T2; prominent hook with twist hackle where T2 curves markedly out of original plane
Spacing	Commonly 0.3-0.6 m; wider locally
Mineralization	Thin, gray alteration rinds on joint surfaces; rock is purple on fresh surfaces; Thin films of white to pale tan, chalky, noncalcareous mineral

Station Number	CH1
Remarks	Set is located primarily in lower part of station.
T2b	
Median Orientation	N34W/88SW (n=22)
Expression	Locally well developed over outcrop and quite prominent
Shape	Planar; some gently sinuous along strike
Roughness	Moderately rough; surfaces bumpy on a cm scale
Exposed Length	Commonly 2-3 m; some up to 4 m and possibly greater
Exposed Height	Commonly 1-1.5 m; probably close to true heights. Some a little smaller, down to 0.5 m
Structures	Arrest lines; hooks of one T2 into another; multiple hooks of this T2 set abut early T2 set
Spacing	Commonly 5-15 cm, dividing the rock into thin vertical slabs
Mineralization	No mineral coatings noted. Surfaces only slightly discolored to gray
Remarks	Set is located primarily in the upper part of the unit at this station. T2b joints cut through rare lithophysal cavities.
T4	
Median Orientation	N80W/86NE (n=13)
Expression	Weak, nearly parallel to trend of hillslope, more common in the lower part of the outcrop
Shape	Subplanar, gently sinuous along strike and dip; some curving
Roughness	Fairly smooth except where weathered
Exposed Length	Commonly 0.3-0.6 m; exposed lengths range from 0.3-5 m; true lengths are generally short
Exposed Height	Commonly 0.3-0.6 m; maximum exposed height observed is 1 m, but most true heights are less than 1 m
Structures	Multiple arrest lines (lateral propagation evidence by inclusion hackle from sanidine crystals
Spacing	Erratic; T4 is not recognizable as a set over most of outcrop, but is locally obvious; no characteristic spacings can be given. Set is most common in lower part of outcrop where spacing locally is 0.2-0.7 m
Mineralization	Fine granular, milky white (probably siliceous) mineral on one joint; tan, silicious mineral on another; no mineralization on most surfaces
Remarks	None
SH	
Median Orientation	N49W/04SW (n=22)
Expression	Moderate overall, much more abundant in upper part of outcrop where they constitute a visually prominent set not readily recognized in the lower part of the outcrop
Shape	Subplanar to nonplanar; many curved and irregular
Roughness	Fairly smooth where parallel to foliation, but very rough to rough where at an angle to foliation
Exposed Dimension	Extremely variable: commonly 0.2-1 m laterally; some areas as great as 3 x 2 m; many are smaller than 0.2 m
Structures	None seen
Spacing	Erratic and variably distributed both laterally and vertically: larger ones spaced 1-2 m, but smaller ones interspersed and locally spaced only 0.3-0.5 m apart
Mineralization	Surfaces strongly discolored to pale orange tan to gray; alteration rinds 0.5 mm or less; granular mineral (probably quartz) coatings are abundant on SH surfaces
Remarks	Subhorizontal joint set nearly parallel to compaction foliation in the tuff.
Terminations	Multiple T1 abut C1; SH abut C1; multiple T1 and C1 intersections; multiple late T2b hook into and abut early T2a; T2a and T1 intersect; multiple T2b and SH intersect; multiple T2b abut and intersect SH; two T2a abut T1; T4 abut T1; two T2b abut C1; two T2a abut SH (dubious); T4 abuts T1; T1 and SH intersect.

Station Number CH1

Summary

The hackly zone at this locality is notable for the complexity of its fracture network. Orientation measurements alone would be powerless to define sets here, but close attention to joint style, abutting relations, and the vertical distribution of the various sets permits their recognition and documentation. The exceptionally smooth surfaces, length, and demonstrated early age of the C1 set suggest they are cooling joints; the others are dominantly tectonic.

In this outcrop the hackly zone is divisible into two subtle subunits marked by vertical differences in the fracture network and by a slight topographic break about midway up the exposure. Observed differences in fracture distribution between the subunits are as follows: (1) Joints of the T1 tectonic set are found throughout the exposure but appear to be more common in the lower subunit, where locally they form a strongly expressed set. (2) Joints of the T2b set are abundant in the upper subunit but rare in the rocks below. In several parts of the upper subunit they form by far the most visually prominent set, with spacings of only 5-15 cm. (3) Joints of the T2a set are abundant in the lower subunit but few in number in the rocks above, (the antithesis of the T2b set). The set is exceptionally well expressed locally, where spacings of 30-60 cm are common. This set is discussed in more detail below. (4) The SH joints in the upper subunit form a visually prominent set not readily recognized below. (5) Joints of the T4 set are present in both subunits but are most common in the lower. (6) The early (C1) cooling joints, though unevenly distributed, are found throughout the exposure in both subunits.

Joints of the T1 set are of variable roughness, some fairly smooth but most considerably less so, with irregular surfaces on the decimetric scale. The rough, irregular joints undoubtedly are tectonic and are present in abundance, but those few of anomalous smoothness for the set could instead be cooling joints of the set complementary to C1.

Joints of the T2a set, though not markedly different from those of the T2b set in orientation, nevertheless have more westerly strikes, a different distribution within the exposure, and appear from abutting relations to be older. Tentatively we regard them as early products of the same general period of fracture that later gave rise to the more familiar and widespread T2b set. Progressive fracture during a period of rotational stress perhaps can best explain the observed geometry, with the earliest T2a joints having formed when the maximum horizontal compressive stress (σ_{hmax}) was oriented northwest and the more northerly T2b joints slightly later, in parts of the rock not previously cut by the earlier joints, when σ_{hmax} rotated about 20° to a north-northwest trend. Median strikes of the T2 set at other localities within the study area commonly range from N. 45° W. to about N. 20° W., not much different from the implied range of the set here (N. 40° W.).

In addition to the joints documented here are others, not measured but widely distributed and centered on N. 30°-40° E. strikes, that probably correspond to the T3 tectonic set.

Station Number	CH2
Quadrangle	Topopah Spring SW, 7.5', lat 36°52'24" N., long 116°27'23" W.
Location	Yucca Mountain, on ridge directly north of the Little Prow, where Drill Hole Wash splits.
Exposure Description	S to SSW-facing hillslope exposure. Slope is approximately 30° where area is 70-80 percent exposed over an area of hundreds of square meters
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
T1	
Median Orientation	N06E/84NW (n=20)
Expression	Well, obvious and most dominant set in outcrop
Shape	Subplanar, gently undulatory along strike and dip
Roughness	Smooth, but bumpy on a 10 cm scale, with minor irregularities elongated parallel to foliation of several mm amplitude and several cm wavelength
Exposed Length	Commonly 2-5 m, some longer and at least as great as 7 m. Many subsidiary T1 are smaller, with lengths from 0.2-1 m, but those of moderate lengths (2-5 m) are most abundant
Exposed Height	Commonly 1-2 m; some up to 3 m;, T1 joints are present over a wide range of size; many are smaller than 1 m
Structures	None seen
Spacing	Variable, 30-60 cm over large areas, locally as small as 10-15 cm for smaller T1. Spacings increase westward as the set becomes more weakly expressed; there spacings of 1-2 m are common
Mineralization	None seen
Remarks	None
T3	
Median Orientation	N28E/87NW (n=14)
Expression	Weak and sporadically expressed overall; locally moderately expressed and fairly obvious
Shape	Subplanar and gently undulatory; especially along strike
Roughness	Smooth
Exposed Length	Commonly 0.5-1.5 m, probably close to true lengths. To the west of outcrop, where T1 joints did not form, T3 joints grew to large size (exposed lengths of 4-6 m)
Exposed Height	Commonly 0.2-0.6 m; to the west of outcrop, where T1 joints did not form, T3 grew to large size (exposed heights of 2-3 m)
Structures	Well-defined hooks into T1
Spacing	Uncertain as few T3 are exposed in same area; rare and locally spaced 0.2-0.5 m apart. To west of outcrop, where T1 joints did not form, T3 joints are spaced 0.3-0.6 m apart
Mineralization	None seen
Remarks	T3 joints to the west of the outcrop have an appearance very similar to T1--a common effect among extension joints.
T4	
Median Orientation	N76W/90 (n=21)
Expression	Poor to moderate; widely scattered over outcrop and not abundant, but because they are the only large joints at high angles to both T1 and T3, the set is not difficult to recognize
Shape	Some are moderately curved and thus vary considerably in strike along their length
Roughness	Most surfaces rough and very irregular on a small (10 cm) scale along strike and dip
Exposed Length	Commonly 1-2 m; locally decreasing to 0.3-0.5 m where T4 abuts T1; few T4 joints are 3-4 m long
Exposed Height	Commonly 0.2-0.5 m
Structures	Twist hackle on one joint

Station Number	CH2
Spacing	Uncertain due to wide spacing; overall widely scattered over outcrop; in one small area spaced 0.5-1 m, but this is abnormal
Mineralization	None seen
Remarks	None

SH

Median Orientation	N85E/10SE (n=18)
Expression	Moderate, well expressed locally
Shape	Variable, some nearly planar; most subplanar and even nonplanar due to gentle curvature along strike and dip
Roughness	Very smooth
Exposed Dimension	Commonly 0.3-0.6 m; as great as 2.5 m
Structures	None seen
Spacing	Extremely variable. Locally 8-20 cm, but in places much greater, at least 2 m, and probably even greater
Mineralization	Common remnant patches of 0.1-2 mm thick, white to cream-colored, very fine granular, noncalcareous, microsaccharoidal coating; surfaces discolored light gray (probable alteration rind)
Remarks	SH set is interpreted to be early cooling or unloading joints, or maybe both. Some SH surfaces have been reactivated. The new portions of these surfaces are unmineralized and extremely rough and irregular, identical in form to the thousands of late fractures which give this rock its hackly appearance.
Terminations	Multiple T4 abut T1; multiple T1 and T4 intersect; multiple T3 abut and hook into T1; multiple T4 and T3 intersect; multiple T1 and SH intersect; two N30W joints abut T4.

M

Orientation	N69E/85NW, N71E/75NW, N59E/92NW, N66E/73SE

A single N49W/86SW joint, a possible cooling joint, is extremely smooth, is 0.8 m long, and cuts lithophysae.

Summary

Of the four joint sets defined at this outcrop, the T1 set is by far the best expressed. Separation of the T1 and T3 sets over much of the outcrop, however, is difficult due to the low angular separation between them (median strikes are N. 6° E. and N. 28° E. respectively) and because of the curving strikes of many T3 joints. The T3 joints of most northerly strike are similar in orientation to those T1 joints of most easterly strike, and the strike distributions of the two sets probably overlap in part. That these joints define two sets rather than one of exceptionally broad strike distribution is demonstrated in three ways. First, local swarms of T1 joints and multiple T3 joints coexist in some parts of the outcrop with a consistent angular difference of about 20° between them; in such areas the separate existence of two sets is visually evident. Second, consistent abutting relations of NNE-striking T3 joints against the nearly N-striking T1 joints confirm that two sets exist. And third, within other outcrops both sets are well expressed and the angular separation between them is larger; see, for example, station CH3.

The wide strike distribution of the late-formed T4 set is typical; its joints are recognizable principally because they occur at moderate to high angles to those of all other sets. The T4 joints are widely scattered across the outcrop and are nowhere abundant.

A few joints coincident in orientation with the T1 and T4 sets are sufficiently smooth that they resemble cooling joints. Unlike known cooling joints, however, their surfaces on a decimetric scale are irregular rather than uniform and nearly featureless, and so the presence at this locality of a weakly expressed rectangular system of cooling joints is uncertain at best. Parallel cooling and tectonic sets nevertheless are known from other localities (e.g. stations TC2 through TC4), at some of which the morphologic differences between tectonic and possible cooling joints are much more pronounced than at this station.

Station Number CH2

The SH joints have very smooth, gently curved, mineralized surfaces and more resemble cooling joints than those of any other set. However, insufficient proof of an early age--at this outcrop one sees only common intersections of SH and T1 joints rather than terminations of one against the other--and the lack of tubular structures on their surfaces preclude certainty of their origin. Cooling joints of low dip and form similar to those described here nevertheless are known from other localities within the hackly unit; see, for example, locality CH6. Reactivation of many SH joints (during unloading?) resulted in renewed growth of their surfaces, but the younger portions differ completely from the old in their exceedingly rough and unmineralized surfaces and are identical in character to the thousands of other young, irregular fractures which upon exposure give this unit its hackly appearance.

Station Number	CH3
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'33" N., long 116°24'24" W.
Location	North end of Fran Ridge
Exposure Description	Steeply outcropping ledge at base of NNE-facing slope. Ledge is 2-4 m high and about 30 m long. Slope is 35-40°, but locally steeper About 70 percent exposed.
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
CM	
Median Orientation	No median calculated; not a definable set. (n=5) Orientations are N85E/64SE, N70E/81NW, N58E/87NW, N78W/75SW, N40W/66SW
Expression	Very weak
Shape	Locally planar, but some curve broadly along their length
Roughness	Very smooth, much more so than all other sets at this locality
Exposed Length	1-3 m or less; true lengths unknown
Exposed Height	0.3 m or less; true heights unknown
Structures	None seen; surfaces are smooth and featureless
Spacing	Wide; very few at the outcrop and widely scattered
Mineralization	Cream colored, scaly, noncalcareous coating; surfaces discolored to pale gray
Remarks	All seen were measured.
T1	
Median Orientation	N04W/78SW (n=23)
Expression	Very well, dominant set at this outcrop
Shape	Subplanar, gently sinuous along strike and somewhat less so in dip. Some are planar
Roughness	Smooth but slightly irregular on a mm scale; most surfaces very weathered
Exposed Length	Commonly 1-3 m, one joint is 4 m; exposed lengths minimized by steep exposure; true lengths unknown
Exposed Height	Commonly 0.6-2.5 m; true heights unknown
Structures	None seen
Spacing	Commonly 0.5-1.5 m for larger T1; locally less where smaller, minor T1 are interspersed
Mineralization	Pale orange-cream siliceous coating of probable surficial origin on some T1. Surfaces discolored pale gray
Remarks	T1 joints are present over a large range of size; the largest joints are the most prominent at this outcrop, but many smaller T1 are present also, down to 0.5-1 m in height. Major T1 have a fairly tight orientation range, while minor T1 show considerably more dispersion. Few minor T1 joints are arranged en echelon.
T2	
Median Orientation	N33W/77SW (n=7)
Expression	Weak
Shape	Subplanar, some curve along strike
Roughness	Fairly rough; very irregular on a cm scale
Exposed Length	0.6-1.5 m
Exposed Height	0.15-0.4 m
Structures	None seen
Spacing	Uncertain, but T2 joints are absent in most places
Mineralization	No mineral coatings seen. Joint surfaces are discolored pale gray.
Remarks	Four T2 joints are located immediately below the clinkstone contact, in a 2 m^2 area.
T3	
Median Orientation	N36E/87NW (n=15)
Expression	Overall weak, but apparent; locally fairly prominent

Station Number	CH3
Shape	Subplanar, some curve gently in dip
Roughness	Similar to T1; most surfaces are badly weathered
Exposed Length	0.5-2 m; true lengths unknown
Exposed Height	0.5-2 m; true heights unknown for largest T3
Structures	Hooks into T1 and C
Spacing	0.3-0.6 m locally, but rare; generally much wider and indeterminate. Joints of this set are not abundant and are widely scattered
Mineralization	Unweathered surfaces are discolored to pale gray and coated with a pale cream-colored granular, noncalcareous mineral (probably quartz)
Remarks	All seen were measured.

T4

Median Orientation	N85W/88NE (n=17)
Expression	Moderate; scattered set, about parallel to hillslope, but obviously different in style from other sets and thus readily recognizable
Shape	Subplanar, locally nonplanar; distinctly more irregular than other sets
Roughness	Fairly rough, more so than other sets
Exposed Length	0.3-0.8 m; true lengths are same as exposed lengths for most; a few approach 1 m
Exposed Height	0.15-0.4 m, uniformly small, and probably close to true heights
Structures	None seen
Spacing	Moderately abundant and therefore probably fairly closely spaced (probably < 2 m), but uncertain because set is oriented nearly parallel to hillslope
Mineralization	No mineral coatings seen; surfaces not altered
Remarks	Small height of set is probably due to termination against foliation-parallel parting joints, but these partings cannot be distinguished from those due to weathering.
Terminations	Multiple T3 hook into and abut T1; multiple T4 abuts T1; T4 abuts T3; probable T1 and CM intersection, with CM apparently older; T1 hooks into and abuts CM; T1 and T3 intersect; two T3 hook into and abut T1; two probable T3 abut T2; one T2 abuts T1; two T3 abut T2; multiple T3 hook into and abut CM.
Summary	Abutting relations at this outcrop are clear and consistent and help to establish the regional chronology of sets. Joints interpreted here as cooling joints are few in number but stand apart from the others in their exceptionally smooth surfaces; abutting relations confirm them as the oldest joints present. The other four sets are variably expressed, from strong to very weak, but all correlate in orientation and relative age to sets found at other outcrops.

Station Number	CH4
Quadrangle	Topopah Spring SW, 7.5', lat 36°51'00" N., long 116°27'10" W.
Location	SSE-facing slope of Live Yucca Ridge, at base of Split Wash, east of trench
Exposure Description	Exposure extends 25 m across a 20-25° slope and 4 m upslope; area 40 percent exposed
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
CM	
Median Orientation	No median calculated; not a definable set (n=4) N18E/64NW, N27E/86NW, N67E/90, N72W/57SW
Expression	Very poor, only four seen
Shape	Planar to gently and broadly curving along strike and dip
Roughness	Very smooth; surfaces are featureless
Exposed Length	2-4 m; true lengths unknown
Exposed Height	0.2-0.5 m; true heights unknown
Structures	Broad, vertical arrest line indicating horizontal propagation
Spacing	Indet., but very wide
Mineralization	Film of cream-colored, fine-grained quartz (?) on two CM joints. Film is thicker than those of T1 and T2. Pale gray discolored surface (probable alteration rind).
Remarks	Smoothness and early age suggest these are cooling joints, but they are not definable as a set.
T1	
Median Orientation	N08E/86NW (n=15)
Expression	Well, most dominant set at outcrop
Shape	Most are nearly planar; some gently curved along strike and dip. Some are more strongly curved
Roughness	Fairly smooth with slight irregularities. Small, rounded pits seen on some surfaces
Exposed Length	Commonly 1-2 m; rarely approaching 3 m; true lengths unknown
Exposed Height	Commonly 0.5-1.5; true heights unknown
Structures	Hooks of T1 into T1; probable arrest line
Spacing	Variable, 0.5-1.5 common, but locally wider
Mineralization	Very thin, white, fine-grained (presumably quartz) mineral. Surfaces of many T1 altered to pale gray (probable alteration rind) up to 1.5 mm thick
Remarks	Several T1 surfaces are very smooth; one at west edge of outcrop has abundant fine-grained, cream colored quartz (?).
T2	
Median Orientation	N22W/88NE (n=11)
Expression	Poor, not visually obvious
Shape	Subplanar
Roughness	Slightly to moderately rough
Exposed Length	Commonly 0.5-1.5 m; true lengths unknown
Exposed Height	Commonly 0.5-1 m; true heights unknown
Structures	Possible T2 hook into CM; twist hackle
Spacing	Indet., but widely spaced; all seen were measured
Mineralization	Surfaces discolored as T1. Very thin film of white, fine-grained quartz (?)
Remarks	A few T2 are fighting to cross T1 joints. One major T2 surface breaks into several small and irregular T2 joints, some of which cross and abut T1. One T2 appears to have propagated from the pre-existing tip of a T1. The initial increments of growth are marked by coarse twist hackle and then by bending of the joint into a normal T2 orientation.

Station Number	CH4
T4	
Median Orientation	N79W/83SW (n=23)
Expression	Fairly well expressed and apparent
Shape	Subplanar; some nonplanar; distinctly more irregular than T2
Roughness	Fairly smooth, but with irregular surfaces
Exposed Length	Commonly 0.5-1 m; longest seen approaches 1.5 m; true lengths close to exposed lengths
Exposed Height	Commonly 0.15-0.4 m; probably close to true heights
Structures	Twist hackle on hooks of one T4 into another T4. Possible arrest line
Spacing	True spacings unobtainable because joints are nearly parallel to hillslope. Average spacings certainly greater than 1 m.
Mineralization	Very thin film of very finely crystalline cream-colored quartz (?) on one T4. Surfaces discolored gray like those of T1 and T2, but discoloration is mottled and not as uniform
Remarks	The limited heights of T4 joints are apparently attributable to their termination against subhorizontal joints
SH	
Median Orientation	N18W/07NE (n=13)
Expression	Poor
Shape	Planar for those few exactly planar to foliation. Most others are subplanar and irregular
Roughness	Rough
Exposed Dimension	Variable, most from 0.5-1.5 m; several are 2-4 m
Structures	None seen
Spacing	Locally 0.4-1 m, but generally much greater
Mineralization	Surfaces discolored pale gray to orangish tan (paler color than fresh rock). No mineral coatings seen
Remarks	All seen were measured.
Terminations	Multiple T4 abuts T1; T1 and T2 intersect; several probable T2 abut T1; probable T2 abuts CM; several T2 hook into CM; T1 and SH intersect; SH abuts T1; multiple T4 abut SH.
Miscellaneous Remarks	Set T3 at station CH5 across wash not picked up at station CH4.
Summary	The T1 set of nearly N-striking joints dominates the fracture network here, followed in prominence by a later (T4) set nearly at right angles. Scattered cooling joints, some of them with orientations similar to and locally coincident with joints of both the T1 and T4 sets, complicate the fracture network but generally are distinguishable from the tectonic joints by their exceedingly smooth, featureless surfaces. Observed abutting relations at this outcrop suggest that the smooth joints are the oldest fractures present, consistent with their interpretation as cooling joints. Joints of demonstrated later age are fairly smooth at best. In the absence of abutting relations, however, joints with weathered surfaces cannot be assigned with certainty to any set. See also station CH5 for notes on an additional fracture set only poorly developed here; the two stations are on opposite sides of the same small wash.

Station Number	CH5
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'58" N., long 116°27'08" W.
Location	On base of N-facing slope of Antler Ridge, opposite side of Split Wash from CH4
Exposure Description	Exposure is at base of Split Wash on a 25° slope. Area encompassed by station is 25 m across slope and 4 m upslope. Exposure is about 15 percent.
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
T3	
Median Orientation	N35E/90 (n=24)
Expression	Well expressed locally; elsewhere poor to moderately expressed, and in some places absent
Shape	Planar, some gently curve along strike
Roughness	Fairly smooth
Exposed Length	1-2 m; few are 3 m; true lengths unknown
Exposed Height	Commonly 0.5-1.5 m; true heights unknown
Structures	None seen
Spacing	Erratic, locally 0.2-0.5 m, but rare
Mineralization	One T3 surface has pale amber, subtranslucent calcite (not resembling caliche); one surface has thin, pale gray discolored surface
Remarks	None
Terminations	T3 abuts T1 of CH4; T4 abuts T3; T4 and T3 intersect
Miscellaneous Remarks	Several cooling joints (about N47E/89NW) with tubular structures are present in the lower lithophysal zone, exposed below station CH5, at bottom of wash and near east end of CH5

Summary

The fracture network at this locality is similar to that at nearby station CH4, but with the addition of the NE-striking T3 set. Sets common to the two outcrops were not remeasured here. The T3 set here is variably expressed across the outcrop, well-defined in some places and all but absent in others, but on the whole is fairly obvious to the eye. At station CH4, however, too few of its joints were seen to merit measurement.

Station Number	CH6
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'24" N., long 116°27'13" W.
Location	South slope of Whale Back Ridge directly east of and about 8 m from Ghost Dance fault
Exposure Description	At base of wash at drill hole USW UZ-N48 and a small exposure 16 m east of USW UZ-N48. Both exposures are at base of wash where exposure is nearly continuous for 15 m across slope and 1-2 m upslope. Slope is gentle (20-25°) at the base of the wash. Exposure is 80 percent.
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)

C1

Median Orientation	N34E/19SE (n=13)
Expression	Poor at drill hole, well to very well expressed at small exposure east of drill hole
Shape	Subplanar to nonplanar
Roughness	Very smooth, surfaces are continuous
Exposed Dimension	Observed range of 0.1-2.6 m; true dimensions probably not much greater than the largest observed dimension
Structures	Tubular structures noted on 5 C1 surfaces. Inclusion hackle from phenocrysts; joints for the most part, do not cut lithophysae
Spacing	Variable, but indeterminate because overlaps not exposed due to joint orientations with respect to outcrop. If they overlap, spacings would range from 0.5-1 m
Mineralization	Very fine-grained, white to cream colored, granular, noncalcareous mineral fill 0.2 mm thick commonly remains in patches. Top of mineral coating is smooth and was in contact with opposing joint face, so thickness of fill equals original fill of aperture. An obvious pale gray alteration rind is present.
Remarks	Subhorizontal cooling joints based on presence of tubular structures. C1 joints cut foliation at various low angles.

CM

Orientation	N74E/85NW

T1

Median Orientation	N04W/88SW (n=20)
Expression	Poor, difficult to document as a set. Local clusters of T1 are obvious in a few places and measurements seemingly confirm the existence of the set, but T1 is difficult to find over most of outcrop
Shape	Subplanar; most curve gently along strike and dip; some curve substantially
Roughness	Fairly smooth; very slightly irregular; smoother than T2 surfaces
Exposed Length	Commonly 0.5-1 m; as long as 1.5 m; true lengths unknown
Exposed Height	Commonly 0.2-0.6 m; as high as 0.8 m; true heights unknown
Structures	None seen
Spacing	0.15-0.7 m where set is best expressed in a small area toward the east end of outcrop; widely scattered and much more widely spaced elsewhere
Mineralization	No mineral coatings seen
Remarks	None

T2

Median Orientation	N30W/85SW (n=24)
Expression	Very well; dominant set at this locality
Shape	Planar to subplanar; most planar or nearly so; some curve gently along strike and dip
Roughness	Fairly smooth but irregular
Exposed Length	Commonly 0.5-2 m; true lengths unknown
Exposed Height	Commonly 0.3-0.5 m; true heights unknown

Station Number	CH6
Structures	Arrest lines
Spacing	Commonly 0.15-1 m, but variable; increasing westward where the set declines in prominence
Mineralization	No mineral coatings noted; surfaces discolored to pale gray; weathering not conducive to their preservation
Remarks	None
T3	
Median Orientation	N47E/89NW (n=16)
Expression	Poor, widely scattered across the outcrop
Shape	Subplanar, some nonplanar, broadly sinuous along strike
Roughness	Fairly smooth, similar to that of T1, but a few T3 are more irregular
Exposed Length	Commonly 0.2-1 m; true lengths unknown
Exposed Height	Commonly 0.1-0.3 m; largest 0.6 m; true heights unknown
Structures	Several probable arrest lines
Spacing	Variable and unobtainable; certainly wide, but too few to determine
Mineralization	No mineral coatings seen. Surfaces discolored pale gray
Remarks	All seen were measured.
T4	
Median Orientation	N82W/86SW (n=13)
Expression	Poor
Shape	Subplanar to nearly planar; most nearly planar over short, exposed distances
Roughness	Fairly smooth; identical to T3; some have slight irregularities and others more irregular
Exposed Length	Commonly 0.3-2 m; true lengths unknown
Exposed Height	Commonly 0.3-0.5 m; true heights unknown
Structures	Probable arrest lines; possible inclusion hackle
Spacing	0.2-0.4 m where several occur together; generally much wider and unobtainable.
Mineralization	No mineral coatings noted; surfaces discolored to pale gray
Remarks	All seen were measured.
Terminations	Few reliable relations seen at this locality; not a good location to establish relative age of sets. T1 and C1 intersect; T2 and C1 intersect; multiple T3 and T2 intersect; multiple T3 abut T2; T2 and T1 intersect; probable T3 abuts T1; probable T4 abuts T2; T2 and T4 intersect; T1 abuts questionable T2.
Miscellaneous Remarks	A N79E/84NW, possible cooling joint (planar, very smooth), is exposed for a length of 2.5 m at drill hole USW UZ-N48. This joint has a character unlike other sets here.
Summary	Five sets of joints are present at this outcrop, though only two are well expressed. One of these, a set of cooling joints, is characterized by near-horizontal to moderate dips and smooth surfaces, some bearing well-defined tubular structures. These fractures transect foliation at small to moderate angles and are analogous to the low-dipping cooling joints documented at several other localities, notably CCR2, CUL2, and CUL3. Only one undoubted cooling joint of steep dip was observed. Three (T1, T3, and T4) of the four tectonic joint sets are weakly expressed. The T2 set, in contrast, is abundant and is easily the dominant set. Joints of all four sets have more irregular traces and somewhat rougher surfaces than those of the low-dipping cooling set. Reliable abutting relations are few and sufficient only to show that T3 is the younger set relative to T2.

Station Number CH6

At this locality the separate existence of T1 and T2 joints as two distinct sets rather than one of exceptionally broad range in strike is not evident from the orientation data alone--a problem similar to that of the T1 and T3 sets at station CH2, and for the same reasons. Strike distributions of the two sets miss overlapping by a scant 6°, a result of the near equality between their strike dispersions (27° for both sets) and the median angular separation (26°) between them. Complicating the situation further is the curvature of portions of some T1 joints to attitudes approaching those of T2. Nonetheless, local areas where multiple fractures striking N. 25°-35° W. coexist with other fractures striking N. 0°-10° E. provide visual proof of two sets rather than one, and both sets are well known from other outcrops in the region. The T1 joints are slightly smoother than those of T2, are much more widely spaced, and show a greater tendency to curve along their length.

Station Number	CH7
Shape	Nonplanar to subplanar; many surfaces are highly irregular; some of the irregularities are caused by the joint surfaces cutting many lithophysae
Roughness	Fairly smooth between lithophysal cavities; rough elsewhere
Exposed Dimension	Commonly 0.5-1 m; some at least 2 m across; true dimensions unknown
Structures	None seen
Spacing	0.2-0.6 m where set is best expressed; greater than 0.6 m over most of outcrop; some as close as 5 cm
Mineralization	Pale orange-tan, sparkly, fine-grained noncalcareous mineral (quartz ?) apparent in lithophysal cavities cut by SH joint surfaces. Surfaces are discolored to light gray
Remarks	Lithophysal cavities probably acted as origin nuclei for some SH joints, which appear to have propagated through many such cavities. The tendency for SH surfaces to intersect cavities is in part responsible for their extremely irregular surfaces. Several SH joints, if they are assumed to be continuous where they exist both E & W of multiple T1, are > 2 m across; some 3 m or more. Surface are so irregular that continuity of the joint is not certain, but some of these probably are fairly large joints.
Terminations	Many SH and T1 intersect; probable SH abuts T1; two T4 abut T1; T4 and T1 intersect; T3 probably abuts T1; SH abuts T1; SH and T4 intersect; several probable SH definitely abut T4. Age relation of T4 to SH uncertain; T1 is oldest set.
Summary	The earliest joints at this exposure form a prominent set of median orientation N. 9° E./85° N. W. and probably correspond to the T1 tectonic set. Nearly at right angles to these, and confirmed by abutting relations to be of younger age, are short joints of the T4 set, present here in moderate abundance. Together the two sets form a nearly rectangular system of steeply dipping joints conspicuous to the eye. Subvertical joints probably corresponding to the T3 set (median strike: N. 46° E.) are present also but are too few in number to be certain of the validity of the set.

Subhorizontal joints about parallel to foliation form a fourth set. Abutting relations show that they are younger than the T1 and probably also the T4 set (no relations with the T3 set were seen). Flattened lithophysal cavities appear to have acted as origin points for some of these fractures, whose late age and highly irregular surfaces suggest an origin due to erosional unloading.

Station Number	CH7
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'22" N., long 116°26'55" W.
Location	SW slope of Whale Back Ridge, at base of slope, in the wash
Exposure Description	Area exposed is 45 m across a 22° slope and 15 m upslope; exposure is 50 percent. Caliche fills the fractures in the wash. Here, high in section, the lithology is transitional to lower lithophysal zone
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
T1	
Median Orientation	N09E/85NW (n=19)
Expression	Very well; most prominent set
Shape	Subplanar, many curved to sinuous along strike. Dips more regular
Roughness	Most surfaces are highly weathered, but original surfaces were fairly smooth and irregular.
Exposed Length	Commonly 1-2 m; some up to 4 m; probably close to true lengths
Exposed Height	Commonly 0.5-1 m; some up to 2 m; true heights unknown
Structures	None seen
Spacing	5-20 cm where set is best expressed, widening to 30-60 cm elsewhere
Mineralization	Few surfaces have patchy remnant coatings of a white, microcrystalline, noncalcareous mineral; presumably quartz. Many surfaces weathered to pale gray.
Remarks	None
T3	
Median Orientation	N46E/89NW (n=6)
Expression	Very poor, nearly absent here, while common at other outcrops. Few seen, and only one large one is present
Shape	Subplanar, sinuous along strike
Roughness	Fairly smooth, but fairly irregular
Exposed Length	Longest T3 seen is 2 m, true lengths unknown
Exposed Height	Highest T3 seen is 0.5 m; true heights unknown
Structures	None seen
Spacing	Indet.
Mineralization	Very fine-grained, white, platy to scaly, noncalcareous mineral coating resembling chalcedony; surfaces discolored to pale gray
Remarks	None
T4	
Median Orientation	N86W/88SW (n=24)
Expression	Moderate; visually apparent over parts of the outcrop
Shape	Subplanar, some gently curving, somewhat more irregular than T1
Roughness	Fairly smooth, but highly irregular
Exposed Length	Commonly 0.5-1 m; close to true lengths
Exposed Height	Commonly 0.2-0.6 m; true heights unknown
Structures	Arrest line
Spacing	0.5-1 m where set is well expressed; wider spacings elsewhere
Mineralization	No mineral coatings noted. Surfaces are highly weathered and discolored to pale gray.
Remarks	None
SH	
Median Orientation	N07E/08SE (n=12)
Expression	Poor, locally moderately well expressed

Station Number	CH8
Quadrangle	Topopah Spring SW, 7.5', lat 36°51'50" N., long 116°26'36" W.
Location	SW-facing slope of Pagany Wash, about 0.5 mi from mouth of wash, at 4030 ft elevation
Exposure Description	SW-facing hillslope, on slope of about 27°, with about 70 percent exposure. Area encompasses 20 m across slope and 30 m upslope. Here the hackly and lower lithophysal zones here are similar in appearance, gross lithology, and fracture pattern. At this locality they are not readily distinguishable and comprise a single mechanical unit.
Stratigraphic Unit	Tiva Canyon Tuff, primarily hackly zone of Scott and Bonk (1984), but measurements also taken in the gradational zone above the hackly zone and below the lower lithophysal unit

T1

Median Orientation	N03E/89SE (n=16)
Expression	Well, only obvious set at this locality
Shape	Subplanar, often slightly irregular or undulatory along strike
Roughness	Some are fairly smooth, but most are fairly rough
Exposed Length	Commonly 1-2 m; longest seen are about 3 m; numerous small T1 with lengths of 0.2 m or less are interspersed between larger joints
Exposed Height	About 1 m or less
Structures	None seen
Spacing	Extremely variable and seemingly without pattern. T1 is sparse over large expanses, but elsewhere, 3 or 4 are spaced 20-30 cm apart.
Mineralization	Irregular, thick fillings of caliche in which are embedded numerous fragments of wall rocks (fragments commonly angular, many rectangular, and 1-2 cm long) are common along T1, in zones commonly 0.5-2 cm wide. The zones appear not to represent cementation of surface rubble but instead are vertically and horizontally extensive zones of caliche-cemented rubble that seemingly represent reactivation and shear along pre-existing T1 joint surfaces. Other T1 joints are mineralized, but these white, fine-grained, coatings of chalcedony (?), are thin and inconspicuous.
Remarks	None

T2

Median Orientation	N43W/86SW (n=8)
Expression	Poor, all seen were measured.
Shape	Indet.
Roughness	Smooth, but irregular
Exposed Length	0.5-1 m is representative
Exposed Height	0.2-0.3 m is representative
Structures	None seen
Spacing	Indet.
Mineralization	One surface is coated with a sugary druse of tiny white crystals (quartz ?).
Remarks	A low confidence set of wide strike variation and rare presence. Individual T2 joints are widely scattered across the outcrop.

T4

Median Orientation	N87E/88SE (n=12)
Expression	Very poor overall; widely scattered and abundant only in one area where they are closely spaced
Shape	Subplanar and often curved, significantly more so than T1 joints

Station Number	CH8
Roughness	Fairly smooth to slightly rough
Exposed Length	Nearly all are small with lengths of 0.22-0.5 m; longest seen was just over 1 m
Exposed Height	Commonly 0.1-0.3 m
Structures	None seen
Spacing	Indet.
Mineralization	Thin films of seemingly structureless white mineral, possibly opal, but looks more like chalcedony because of its sugary texture. Also present is a pale yellow to pale orangish to milky white, sugary textured crystal druse with a duller luster than the other mineral.
Remarks	All seen were measured. Narrow or fairly tight joints with no evidence of slip or reactivation.

SH

Median Orientation	N10W/10NE (n=5)
Expression	Poor; inconspicuous on outcrop
Shape	Subplanar to locally nonplanar; irregular in gross shape
Roughness	Fairly smooth but bumpy
Exposed Dimension	Small; only 10-20 cm across
Structures	None seen
Spacing	Indet.
Mineralization	None seen
Remarks	All seen were measured. The surfaces are discolored to a pale orange-gray color, but these are only the walls of flattened lithophysae, some of which appear to have acted as origin flaws for these nearly horizontal joints. Their small size, and especially their rarity contrasts greatly with their abundance, larger size, and visual prominence at station CH2. The difference between the two stations relative to how strongly the SH set is expressed is extreme.
Terminations	Many T4 abut T1; many T4 and T1 intersect; no abutting relationships of T2 with other sets observed
Miscellaneous Remarks	Towards the top of this outcrop is a well-exposed contact between cll and crs, marked in one place by a prominent and open horizontal joint. A good place to look at the change in joint patterns across the contact and to compare the two zones.
Summary	The T1 joints of median N. 3° E. strike form the only obvious and well-expressed set at this locality. Secondary opening of some T1 joints locally resulted in large (0.5-2.0 cm) wall separations, the intervening space being filled with angular clasts of wall rock cemented by a dull, locally banded carbonate material resembling caliche or travertine. Reactivated T1 joints in one portion of the outcrop define a zone 1-2 m wide traceable for a distance of more than 25 m upslope, with neither end exposed. The T4 joints of approximate E-W strike constitute the only other set recognizable with fair certainty in this exposure. Their short lengths, irregularly shaped surfaces, and consistent terminations against T1 joints are common properties. Joints of northwest strike form a dubious set of wide strike variation (58°). Only eight of these joints could be found for measurement. Most or all of them likely correspond to the T2 tectonic set, but no abutting relations were seen to test the inference, and the measured strike range is nearly double the norm for this set. Equally rare are small, subhorizontal joints similar in character to those described at station CH7, and like them apparently the result of lateral propagation of sheetlike fractures from the edges of flattened lithophysal cavities. A notable feature of this locality is that the hackly and overlying lower lithophysal zones responded to applied stress as a single mechanical unit. The fracture network thus is not stratabound here, but rather is continuous from one unit into the other, reflecting the lack of sharp contact or abrupt gradation between the two.

Station Number	CH9
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'15" N., long 116°24'51" W.
Location	West side of Fran Ridge, north half, directly above wash on W-facing slope
Exposure Description	Station is at base of slope, directly above wash that parallels the west side of Fran Ridge. Area encompassed is 40 m across slope and 2 m upslope; dip of beds exposes stratigraphic thickness of 5 m. Area is 40 percent exposed on a 30° slope. Although mapped by Scott and Bonk (1984) as hackly, the lithology at CH9 approaches that of the clinkstone zone
Stratigraphic Unit	Tiva Canyon Tuff, hackly zone of Scott and Bonk (1984)
C1	
Median Orientation	N69W/83SW (n=24)
Expression	Poor to moderately well; locally variable
Shape	Curviplanar; some curve > 20° in strike in distances of 1.5 m
Roughness	Smooth; surfaces not much weathered
Exposed Length	0.5-3 m; true lengths probably significantly greater than those exposed. C1 joints strike perpendicular to hillslope.
Exposed Height	0.3-1.5 m; true heights indet.
Structures	Very weakly developed tubular structures on one joint. Tubes are present on only part of joint surface
Spacing	Commonly 0.7-2 m; observed to range from 0.2-2.5 m
Mineralization	White to pale gray, layered, botryoidal, , noncalcareous coating (probably chalcedony), 0.5-4 cm thick on three joint surfaces, apparently resulting from reopening of C1; botryoidal on SE-facing surface and flush against joint on SW surface. White, granular, noncalcareous coatings 0.5 m or less on many C1. The botryoidal mineral overlies granular mineral and is younger. Possible other mineral present is thin, white, platy, noncalcareous mineral, but this mineral may be same as mineral already noted. This mineral very probably vapor phase. Surfaces discolored light gray (probable alteration rind).
Remarks	Obvious and well-defined set, very probable cooling set
C2	
Median Orientation	N46E/87NW (n=15)
Expression	Moderate
Shape	Curviplanar, some curve as much as 48° over lengths of 1.5 m; trace lengths are sharp, curves are smooth; variable along strike and dip; dip changes more modest than strike changes
Roughness	Smooth; surfaces not much weathered
Exposed Length	0.4-2.5 m; true lengths probably significantly greater than exposed lengths
Exposed Height	0.1-0.9 m; true heights indet., but probably slightly greater than exposed heights
Structures	Well-defined arrest line on one joint
Spacing	Commonly 0.4-0.8 m; but locally wider; 0.4-1.5 m observed
Mineralization	Many completely mineralized with very thin (0.5 mm or less), white, granular, noncalcareous coating. No external morphology preserved on coating, so presumably joints were completely filled; surfaces discolored light gray, possible alteration rind
Remarks	Probable cooling joints. Small wall separation.
C3	
Median Orientation	N67W/20NE (n=5)
Expression	Moderate
Shape	Subplanar, surfaces irregular to very irregular
Roughness	Fairly rough
Exposed Length	0.3-0.5 m; true lengths probably not much greater than largest exposed lengths
Exposed Height	0.2-0.4 m; true heights probably not much greater than largest exposed heights

Station Number	CH9
Structures	None seen
Spacing	Indet.; observed range 0.3-1 m; best exposed at south end of outcrop
Mineralization	All surfaces are coated with thin (<0.5 mm-thick), well preserved, white to colorless, drusy, noncalcareous mineral. One joint surface has a thick, white to gray, botryoidal, noncalcareous mineral coating, outer surface of mineral facing down
Remarks	Like **SH** joints in appearance, but mineralized. Interpreted as cooling set.

T1

Median Orientation	N04W/82SW (n=13)
Expression	Fairly well overall; moderate locally
Shape	Probably planar to gently curviplanar, but only short distances exposed
Roughness	Fairly smooth to slightly rough; some nearly as smooth as C2 and C1; others distinctly rougher
Exposed Length	0.4-0.8 m; true lengths probably not great because lateral continuations of T1 joints are not present
Exposed Height	0.1-0.6 m; true heights indet.
Structures	Twist hackle on one joint; arrest line on one joint
Spacing	Highly variable; locally as close as 15-20 cm, but absent or nearly so over much of outcrop. Due to small joint size and sparsity, true spacings cannot be obtained over much of outcrop
Mineralization	All have thin (< 0.5 mm), white, granular, noncalcareous mineral coatings. Most joints lack gray, altered surfaces, but three joint surfaces are discolored to a light gray, as C2 and C1; and thus are suspected cooling joints.
Remarks	None

SH

Median Orientation	N66W/14NE (n=16)
Expression	Moderate
Shape	Subplanar, surfaces irregular to very irregular
Roughness	Fairly rough
Exposed Dimension	0.1-2 m; true lengths probably not much greater than largest observed length
Structures	None seen
Spacing	Indet.; observed range is 0.3- 1 m; best exposed at south end of outcrop
Mineralization	None seen; **SH** set probably was never mineralized
Remarks	Probably foliation-parallel and rocks, upon exposure, are spalling further along foliation, forming plates locally 0.5-2 cm thick, giving the zone its hackly appearance. Almost certainly unloading joints. There is no gradation between this set and C3 mineralized set; **SH** joints are completely devoid of minerals while C3 is completely mineralized.
Terminations	Small probable C2 abuts C1; C2 and C1 intersect; C1 hooks into C1; T1 probably abuts C1; T1 hook into and probably abuts C2; **SH** and C1 intersect; T1 abuts C1; T1 abuts C2; one T1 abuts C3; three **SH** abut C1; **SH** probably abuts T1
Summary	Two sets of steeply dipping cooling joints form a nearly rectangular network at this locality; median strikes are N. 69° W. and N. 46° E. for the dominant and subordinate components, respectively. Some joints of both sets curve markedly along strike, 20°-48° within a lateral distance of only 1.5 m, but changes in dip are considerably more modest. Tubular structures are all but absent on these joints, as seems common for the hackly unit, but the broad curvature and smooth surfaces of the C1 and C2 sets are properties much more consistent with cooling than tectonic joints. The single joint seen with weakly developed tubular structures strikes N. 36° W., at the extreme northern end of the probable strike range of the C2 set.

Station Number CH9

Shallow-dipping joints parallel to foliation form a single well-defined group based on orientation but appear in the field to represent two sets, one mineralized and the other not. Joints of the presumed earlier set are coated over large portions of their surfaces with a thin crystal druse, whereas associated joints of similar orientation are devoid of all sign of mineralization. The barren fractures almost certainly are unloading joints similar to those documented at other localities. The mineralized joints possibly are due to cooling (and are so indicated in our notes), but their irregular and somewhat rough surfaces are inconsistent with this interpretation. Equally well they too could be unloading joints, formed earlier than the others, before erosional downcutting drained rocks that formerly were saturated. The paucity of abutting relations precludes confident interpretation.

Vertical T1 joints of nearly N-S strike form the only other obvious set in this outcrop. Even the largest among them are smaller than many C1 and C2 cooling joints, and the T1 joints terminate against these earlier fractures with consistency. Some of their surfaces are nearly as smooth as those of the cooling joints, but most are perceptibly rougher. Nearly all lack the pale gray alteration rinds characteristic of the earlier cooling sets. The few exceptions--smooth joints with discolored surfaces--probably are cooling joints whose orientations overlap those of the T1 set. In one portion of the outcrop, for example, a C2 cooling joint striking N. 46° E. curves broadly to N. 02° W., and thus along part of its length has an orientation coincident with the T1 set. Where only small portions of such joints are exposed it is difficult to distinguish them with certainty from the associated tectonic joints.

Station Number	CLL1
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'32" N., long 116°26'21" W.
Location	Isolation Ridge, at base of wash on north side of unnamed wash that bisects Isolation Ridge
Exposure Description	Outcrop extends along base of wash for 20 m and 5 m up the SW-facing slope on the north side of the wash. Unit is about 60 percent exposed on a 25-40° slope.
Stratigraphic Unit	Tiva Canyon Tuff, lower lithophysal zone of Scott and Bonk (1984)

C1

Median Orientation	N70W/73NE (n=10)
Expression	Well over most of outcrop
Shape	Curviplanar; dip consistent for each joint but dip direction changes for separate joints
Roughness	Smooth, very probably very smooth on fresh surfaces, but surfaces are weathered
Exposed Length	0.2-3 m; true lengths greater, some are probably as great as 6 m
Exposed Height	0.2-3 m; true lengths greater, some are probably greater than 4 m
Structures	All joints in set have tubular structures; their size varies from 1 mm-3 cm in diameter
Spacing	Variable, as close as 0.1 m, as great as 3 m; some surfaces stained black and orange
Mineralization	Caliche on a few joint surfaces; gray alteration rinds bordering tubes are visible on some joint surfaces
Remarks	Definite cooling joints, based on presence of tubular structures, smoothness, and to a lesser extent shape.

CM

Remarks	Three joints belong to this group. (1) A N69W/37SW cooling joint with small tubular structures. Exposed dimensions of joint are 3.5 and 6 m. Joint surface does not cut lithophysae. (2) A N58E/90 joint with small tubular structures. Exposed length and true length is 0.3 m; exposed height is 0.2 m. (3) A N65W/35SW joint with a smooth surface and gray alteration rind that weathers orange. Exposed length of joint is 0.3 m; exposed height is 0.4 m.

T1

Median Orientation	N11W/86NE (n=17)
Expression	Variable; moderately well expressed in wash bottom but poorly expressed over much of the rest of the outcrop; widely scattered and commonly absent
Shape	Subplanar; very irregular along strike and dip on a cm scale, at least partly because the joints are developed in highly anisotropic, lithophysae-rich rock
Roughness	Rough to very rough
Exposed Length	0.1-0.6 m; exposed lengths equal true lengths for most
Exposed Height	True heights probably not much greater than exposed heights
Structures	None observed
Spacing	2-3 m where best expressed; numerous small joints close together in about a 1-m wide zone at bottom of wash. Trend of zone is parallel to joint strike but zone incompletely exposed
Mineralization	None observed except for caliche
Remarks	None

T3

Median Orientation	N28E/85SE (n=19)

Station Number	CLL1
Expression	Variable; well expressed locally but elsewhere widely scattered and poorly expressed to absent. Better expressed than T1
Shape	Subplanar but very irregular both along strike and dip on a cm to decimeter scale, much resembling T1
Roughness	Rough to very rough
Exposed Length	0.1-2.2 m; true lengths equal to or close to exposed lengths for most
Exposed Height	0.1-1.8 m; true heights probably not much greater than exposed heights measured
Structures	None observed
Spacing	2-10 cm where best expressed but much wider over other parts of outcrop
Mineralization	None observed except for caliche
Remarks	Interpreted as tectonic set. Larger T2 are compound surfaces that result from breakage along multiple, closely spaced, and overlapping T2; these are not single joint surfaces but appear so from a distance
Terminations	Relations were not discernible
Miscellaneous Remarks	The lower lithophysal zone here contains abundant lithophysal cavities, ranging from 3-10 cm across. The rock is gradational into the rounded step at this locality. About 5 or 6 crude, gently dipping joints (not measured) cut rock about parallel to the foliation. These joints have irregular surfaces extending for several meters.
Summary	Morphologic differences between cooling and tectonic joints reach an extreme at this locality due to the highly lithophysal nature of the rock. The cooling joints form a single well-defined set characterized by prominent tubular structures, smooth joint surfaces between the tubes, and minimum (exposed) lengths generally >1.5 m. The associated tectonic joints, in contrast, form two sets whose joints are small, rough, and irregular, with maximum (true) lengths generally <0.4 m and commonly less than half that value. Median strikes are N. 11° W. (T1) and N. 28° E (T3).

The small size of the tectonic joints probably is attributable to repeated interruption of fracture growth by the abundant lithophysal cavities in the rock. Local "warping" of stress trajectories near these same cavities is the likely cause of the irregular fracture traces as well: on the local (decimetric) scale of the T1 and T3 joints the rock is highly anisotropic. The cooling joints, however, formed before the lithophysal cavities developed and originally had smooth, nearly featureless surfaces, later stretched and torn as tubular structures developed during degassing of the tuff.

Station Number	CKS1
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'01" N., long 116°27'18" W.
Location	Shallow trench on crest of small ridge 10 m SE of drill hole USW UZ-N66, south of Highway Ridge road leading to Yucca Crest. Exposure is 50 percent.
Exposure Description	Shallow bulldozed trench approximately 7 m long, 5 m wide, and 1.5 m deep; trench axis NE-SW
Stratigraphic Unit	Tiva Canyon Tuff, clinkstone zone of Scott and Bonk (1984)

T1

Median Orientation	N02W/80SW (n=19)
Expression	Well, cuts diagonally across the trench
Shape	Planar
Roughness	Smooth to slightly bumpy on some; irregularities have surface relief of several mm at most
Exposed Length	0.5-2.5 m
Exposed Height	1 m or less
Structures	Probable arrest lines
Spacing	Most 1-1.5 m; locally a little less among minor T1
Mineralization	Same as T3
Remarks	Small, sparse lithophysal cavities cut by T1

T3

Median Orientation	N44E/85NW (n=15)
Expression	Moderately well overall; well expressed on the NW wall of the trench, weakly to moderately expressed on trench floor, absent on SE wall
Shape	Planar to subplanar, some gently sinuous along strike
Roughness	Variable; most fairly rough but a few more smooth
Exposed Length	0.5-1.2 m; true lengths unknown; T3 joints strike parallel to the trench walls
Exposed Height	0.6-1 m; true heights unknown
Structures	Probable arrest line
Spacing	Unobtainable but apparently variable; set well expressed on NW wall and decreases SE
Mineralization	Fine crystalline, medium orange-brown vitreous, noncalcareous mineral on many T3 (presumed to be quartz), overlain by a scaly noncalcareous tan material probably of surficial origin. Medium-tan alteration rind 1 mm or less.
Remarks	T3 cuts sparse lithophysal cavities present at this locality

T4

Median Orientation	N90E/81S (n=8)
Expression	Weak
Shape	Subplanar, gently curving along strike
Roughness	Apparently fairly smooth; but very few surfaces exposed
Exposed Length	0.5-1 m
Exposed Height	0.1 m or less on trench floor, one joint is 0.7 m high on trench wall; true heights unknown
Structures	Probable arrest line
Spacing	1.5-3 m observed, but too few to be meaningful
Mineralization	Thin (thinner than T3 or T1) medium tan alteration rind
Remarks	None

SH

Median Orientation	N07W/10NE (n=19)
Expression	Well, prominent on trench floor
Shape	Subplanar to nonplanar; billowing
Roughness	Fairly smooth
Exposed Dimensions	Commonly 0.5-2 m, true dimensions of some greater

Station Number	CKS1
Structures	One arrest line
Spacing	Variable, from 10 cm to at least 0.75 m. Few spacings can be determined because of shallowness of trench
Mineralization	Lacks orange-brown mineral (presumably quartz) as T3 and T1, but are coated with scaly material that is present on T3 and T1. Joint surfaces discolored to pale grayish tan (presumed alteration rind), but is thinner than rind on T3
Remarks	SH joints cut small, sparse lithophysal cavities present in the rock
Terminations	One T1 abuts T4 (questionable); T4 and T1 intersect; T3 and T1 intersect; T4 abuts a probable T1; SH abuts a probable T1; SH abuts T1; T1 abuts a possible T4; several SH and T1 intersect; T4 hooks into and abuts a possible T1. Abutting relationships ambiguous at this locality.
Summary	Several factors facilitate recognition of joint sets at this locality: narrow range in orientation within sets, large orientation differences between sets, and fresh exposure. Most abundant are T1 joints, which extend diagonally across the floor of the shallow bulldozer trench, and T3 joints, which form its northwestern wall. Both sets are visually apparent. Sparse T4 joints form a third set, weakly expressed here but well known from other localities. Coatings of a fine-grained, vitreous, noncalcareous mineral, presumably quartz, are common on T1 and T3 joints but lacking on surfaces of the later T4 set. A fourth set of joints, of gentle (4°-21°) northeast dip, is well exposed on the floor of the trench. Abutting relations and lack of quartz(?) coatings suggest a relatively young age and thus a probable origin due to unloading rather than cooling.

Station Number	CKS2
Quadrangle	Topopah Spring SW, 7.5', lat 36°49'39" N., long 116°24'47" W.
Location	North half of Fran Ridge, just east of NE-trending fault mapped by Scott and Bonk (1984), and directly south of station CUL1
Exposure Description	Station is located in bottom of ravine and along east side, just above ravine bottom. Measurements were taken over a distance of 18 m parallel to ravine and 3 m upslope on the east side of the ravine. The clinkstone forms ledges, but talus covers most of the 25° slope. Clinkstone is exposed on both sides of the ravine here, but all measurements were taken from the east slope and along the ravine bottom. Overall exposure is 35 percent.
Stratigraphic Unit	Tiva Canyon Tuff, clinkstone zone of Scott and Bonk (1984)

C1

Median Orientation	N76E/88SE (n=21)
Expression	Well, most prominent set
Shape	Planar to very curviplanar
Roughness	Fairly rough; very undulatory along strike and dip. Some C1 surfaces have small (3 cm) angular breaks along strike. Surfaces are bumpy
Exposed Length	0.09-3 m; true lengths greater
Exposed Height	0.16-1 m; true heights greater
Structures	Several probable arrest lines
Spacing	Commonly 1-2 m; as close as 0.09 m
Mineralization	Surfaces are weathered; one C1 surface is caliche coated. Surfaces stained black by manganese.
Remarks	C1 forms risers

C2

Median Orientation	N22W/84SW (n=5)
Expression	Poor
Shape	Subplanar over very short exposed lengths
Roughness	Indet., but very undulatory along strike and dip
Exposed Length	0.25-0.45 m; true lengths greater
Exposed Height	0.07-0.25 m; true heights greater
Structures	Possible arrest line
Spacing	Indet., too few joints to determine
Mineralization	Surfaces weathered and stained black

T3

Median Orientation	N26E/84SE (n=19)
Expression	Moderately well
Shape	Subplanar to curviplanar
Roughness	Indet., due to weathering. Possibly fairly rough, undulatory along strike
Exposed Length	0.13-1.2 m; true lengths greater
Exposed Height	0.16-0.4 m; true heights greater
Structures	None seen
Spacing	Variable; in closely spaced zones, but also as much as 1 m apart
Mineralization	Surfaces weathered, surfaces stained black
Remarks	T3 joints commonly pinch together; T3 joint strikes are about the same as N35E-trending fault mapped by Scott and Bonk (1984).

T4

Median Orientation	N72W/85SW (n=9)
Expression	Poor

Station Number	CKS2
Shape	Subplanar to curviplanar
Roughness	Indet.; small undulations along strike and dip
Exposed Length	0.3-0.7 m; true lengths greater
Exposed Height	0.12-0.33 m; true heights greater
Structures	One arrest line seen
Spacing	Indet.; too few joints to determine
Mineralization	Surfaces weathered and stained black
Remarks	None

SH

Median Orientation	N50W/16NE (n=6)
Expression	Fairly well; second most prominent set
Shape	Subplanar
Roughness	Indet.; most are irregular along strike and dip
Exposed Dimension	0.3-1.5 m; true dimensions greater
Structures	None seen
Spacing	Commonly 0.2-0.4 m; observed as close as 0.13 m
Mineralization	Surfaces are weathered; some protected joint surfaces are caliche coated
Remarks	SH joints are nearly parallel to the rock foliation and forms horizontal steps. Not included in this set are numerous, smaller partings, parallel or nearly parallel to SH joint surfaces. These small partings are caliche-filled, have white rims around them, and appear to be due to erosional unloading and splitting of the rock upon exposure.

M

Orientation	N09E/83SE, N04E/85SE, N38W/79SW, N21W/41SW, N45E/87NW
Terminations	Low confidence in abutting relationships at this locality. C2 and SH intersect; C2 and T4 intersect; C2 and C1 intersect; one T4 and N9E/SE (T1?) intersect; one T4 abuts N40W; N50E abuts T4; N40W and SH intersect; one C1 abuts T4; several C1 abut C2; C1 hooks into and abuts T3; C1 and T4 intersect; one C2 abuts C1; one T4 abuts T3
Miscellaneous Remarks	Low-confidence locality
Summary	The fracture network at this locality is nearly identical to that at nearby station CUL1, as shown by the following pairs of median orientations of sets:

Set	CKS2	CUL1
C1	N76E/88SE	N76E/87NW
C2	N22W/84SW	N21W/86SW
T3	N26E/84SE	N35E/87NW
T4	N72W/85SW	N72W/76SW

At both stations the oldest cooling set is that striking north-northwest, though the younger set at right angles to it is represented by more abundant joints. That these are cooling rather than tectonic joints is suggested by several lines of evidence: (1) The orientation of the C1 set has no known counterpart among tectonic sets of the area; (2) Tubular structures on C2 joints at station CUL1 demonstrate an origin by cooling despite the similarity in orientation to joints of the T2 tectonic set; and (3) Abutting relations at both localities suggest that the C2 joints are the oldest set present. The undulatory nature of the C1 and C2 joint surfaces, more pronounced than that of the other sets at this locality, is an additional property more characteristic of cooling than tectonic joints. Joint roughness, however, is nearly useless here as a discriminator between tectonic and cooling sets: the rock is too highly weathered for details of fracture-surface morphology to be preserved. For similar reasons no siliceous mineral coatings were observed on any joint.

Station Number	CKS2
	Joints other than those due to cooling form three sets. Most prominent are irregular fractures (SH set) of low northeast dip, parallel to rock foliation and probably due to erosional unloading. The T3 and T4 sets, both striking at high angles to the cooling sets, also are recognizable components of the total fracture network.

Station Number	CKS3
Quadrangle	Topopah Spring SW, 7.5', lat 36°49'36" N., long 116°25'23" W.
Location	Trench exposure south of drill hole UE-25p #1, on west side of small, unnamed ridge directly west of Fran Ridge and east of Bow Ridge
Exposure Description	Trench is located on east side of Paintbrush Fault, at east end of trench where clinkstone is exposed 1-2 m below the surface on the trench floor. Rock is about 5 percent exposed on a 10-20° dipping floor surface for about 9 m upslope and parallel to trench by 4 m across trench.
Stratigraphic Unit	Tiva Canyon Tuff, clinkstone zone of Scott and Bonk (1984)
C1	
Median Orientation	N35W/79SW (n=7)
Expression	Moderate, present at west end of outcrop
Shape	Planar to curviplanar; one joint curves from N29 to N49W over a 0.8 m length
Roughness	Indet., due to lack of good exposures and minerals obscuring many surfaces. Possibly fairly smooth with small irregularities.
Exposed Length	0.2-0.8 m, true lengths variable and probably greater, but not much greater
Exposed Height	0.06-0.75 m, true heights indet.
Structures	None observed
Spacing	Indet.; two joints are spaced 7 cm apart
Mineralization	Caliche and sparse patches of cream-colored, dull, noncalcareous mineral. A 1-2 mm thick, gray alteration rind is present on most C1 joint surfaces. C1 joints are completely filled.
Remarks	None
C2	
Median Orientation	N55E/87NW (n=7)
Expression	Moderate to poor; several long C2 joints are fairly obvious
Shape	Curviplanar; one joint curves 34° over a length of 2.6 m
Roughness	Very smooth; very gradual change in dip
Exposed Length	0.3-2.6 m; true lengths extremely variable, some greater than 2.6 m
Exposed Height	0.02-0.4 m; true heights indet., but greater than observed exposed range
Structures	None observed; surfaces are filled or coated
Spacing	Indet., due to lack of continuous exposures; observed as close as 1 m; two joints appear to be spaced 3 m apart
Mineralization	One joint has a white, noncalcareous mineral fill (resembling chalcedony or opaline silica) 13 cm thick; another joint has same fill, 2 cm thick. Small pieces of angular clinkstone breccia, contained within the fill, are present in two joints. Some joints are barely open, but completely filled. All have a 1 mm-thick, gray alteration rind.
Remarks	All seen were measured. Other joints with C2 orientations are present but are nonplanar and lack alteration rinds, and thus cannot be determined to belong to C2 set.
SH	
Median Orientation	N21W/11NE (n=7)
Expression	Well; most obvious set; forms ledges along trench floor
Shape	Subplanar
Roughness	Indet.; very irregular along strike and dip
Exposed Dimension	Exposed dimensions range from 0.2-1.3 m
Structures	None observed; surfaces mostly covered by talus, dirt, and caliche
Spacing	Variable; spacings commonly range from 0.1-0.3 m
Mineralization	Surfaces are heavily coated with caliche; surfaces are altered to a gray color which may be the result of weathering, rather than an alteration rind

Station Number	CKS3
Remarks	**SH** set dip parallel to pumice foliation. Numerous, shorter **SH** joints are present, but were not measured.
M	
Orientation	N82E/72SE, N81E/86SE, N85E/81SE, N80E/83NW, N85E/90SE, N85W/89NE
	N04N/79SW, N01E/88NW, N09W/88NE
	N20W/90SW, N18W/80SW, N22W/85SW, N20W/85NE, N24W/73SW, N23W/66NE
	N60W/77NE
	N44E/25SE
	N25E/88NE
Terminations	One C2 abuts C1; one **SH** abuts C2; some C1 end blind before reaching C2; one C2 and C1 intersect; one C1 crosses a filled C2 and barely continues for 1.5 cm; three C1 abut C2; three C1 abut C2.
Miscellaneous Remarks	Low-confidence locality due to lack of exposures. Clearing the exposure would reveal many more abutting relationships. Measurements were taken at waist level as one long C2 joint deflected the compass needle 20°. All sets appear to have once been filled, with some fill now weathered away.
Summary	Recognition and interpretation of fracture sets at this locality is complicated by the poor exposure, the evident complexity of the fracture network, the curving nature of some of the fractures, and the rarity of clear abutting relations. Doubtless more sets are present than those defined here.

Joints of steep to vertical dip are present over a wide range of strike in the trench, but among them appear to be two sets with median strikes of N. 35° W (C1) and N. 55° E. (C2). Joints of the C2 set show common curvature along strike, locally as much as 34° over a distance of only 2.6 m, and have very smooth surfaces suggestive of cooling joints. The C1 joints are of broadly similar character, though perhaps not as smooth, but such minor portions of their walls are exposed that surface roughness was difficult to judge for this set. They could equally well be regarded as later joints of the T2 tectonic set, and only the termination of a single C2 joint against a C1 joint favors their interpretation as members of a rectangular system of cooling joints.

Numerous steeply dipping joints at this locality have been reopened and filled with a dull, cream-colored siliceous material locally containing small, angular fragments of clinkstone. The largest such filling, within a long C2 joint, is 13 cm thick, and at least four others measure 2-5 cm across. Opening of these joints is a probable reflection of movement on the nearby Paintbrush Canyon fault, whose trace as inferred from aeromagnetic anomalies to the north and outcrops to the south (Scott and Bonk, 1984) lies within the trench. The fault strikes north-northeast and is downthrown on the west. Those joints opened the most strike within 50° of the fault, but joints more nearly perpendicular to it--including those of the C1 set--were little affected and lack thick mineral fillings. The observed distribution of extensional strain thus is broadly compatible with normal movement on the fault, as is the apparent left-lateral sense of movement along a fracture of about N. 85° E. strike, which resulted in offset of a C2 joint by 2-3 cm.

Foliation-parallel fractures that dip gently (9-15°) to the northeast and divide the rock into steplike ledges. Due to their orientation at high angles to nearly all other joints they are the most obvious set. Their irregular surfaces and lack of mineral coatings, except for surficial caliche, suggest they are unloading joints.

Station Number	CKS4
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'17" N., long 116°26'35" W.
Location	Unnamed wash east of Whale Back Ridge, down valley approximately 30 m from where road splits, and extends along N side and S side of Whale Back ridge; about 100 m S25E from drill hole UE-25 UZN #56.
Exposure Description	Tilted ledge about 30 m across slope by 5 m upslope at northern nose of small, north-trending ridge. Outcrop faces N to NNE and is 6-12 m above road level. About 30 percent exposed on 25° slope. Stratigraphic thickness covered is 3-4 m.
Stratigraphic Unit	Tiva Canyon Tuff, clinkstone zone of Scott and Bonk (1984)

C1

Median Orientation	N75E/85NW (n=7)
Expression	Weak to moderate; however exposure orientation is unfavorable to show them
Shape	Planar to locally subplanar; some gently sinuous along strike
Roughness	Very smooth, featureless surfaces
Exposed Length	0.5-4 m
Exposed Height	0.2-1.4 m
Structures	Plumose structure; some inclusion hackle originates at sanidine crystals. C1 joints cut lithophysae
Spacing	Indet., due to low numbers; observed spacings of 0.6, 2, and 3.5 m seen at south end of outcrop where most C1 were measured; few joints overlap
Mineralization	None observed; joint surfaces are slightly discolored to pale gray
Remarks	All seen were measured. Although numbers seen are low, they define a good set. Abutting relationships confirm this set to be old and strengthen their interpretation as cooling joints.

T1

Median Orientation	N06W/86SW (n=12)
Expression	Moderately expressed locally and obvious locally
Shape	Subplanar
Roughness	Fairly rough and irregular on a small scale, even where protected from weathering; large joints tend to be irregular along dip but relatively invariant along strike
Exposed Length	0.4-2.5 m; commonly range from 1-2 m; lengths minimized by exposure orientation and ledgy nature of outcrop, so true lengths could be considerably greater than those exposed
Exposed Height	0.5-2 m; common range also 0.5-2 m; true heights unknown as most parts of outcrop are only 2-3 m high
Structures	None observed
Spacing	Irregular; set is missing from much of the outcrop or is represented by the occasional "stray" joint; in one place the T1 joints are spaced 5-50 cm apart in a zone 2 m wide
Mineralization	None seen
Remarks	

T2

Median Orientation	N31W/77SW (n=13)
Expression	Well expressed and visually prominent over most of the outcrop
Shape	Subplanar; some curve gently along strike and a few more strongly, though strikes show a fairly narrow range; sinuosity along dip is common also
Roughness	Slightly to moderately rough; perhaps a bit smoother than T1 but not as smooth as C1
Exposed Length	0.3-2.6 m; commonly range from 0.5-2.5 m; minimized by exposure orientation; true lengths unknown
Exposed Height	0.3-1.2 m; generally < 1.5 m; true heights probably greater, but uncertain due to lack of exposure
Structures	Prominent hook of T2 into T2

Station Number	CKS4
Spacing	Irregular; 0.4-1.5 m where best expressed; few are spaced only 0.1 m apart, but increasing elsewhere to 2 m or less and locally absent
Mineralization	None seen
Remarks	Overall character of T2 set is much like T1 set.
SH	
Median Orientation	N25W/21NE (n=13)
Expression	Well expressed; visually prominent because of the large size and gently dipping attitude of its joints
Shape	Subplanar to locally nonplanar; irregular; these joints divide the outcrop into crude, gently dipping slabs
Roughness	Rough, but also badly weathered
Exposed Dimension	Ranges from 0.6-5 m
Structures	None seen
Spacing	Commonly ranges from 0.3-0.8 m (thickness of slabs)
Mineralization	None seen
Remarks	SH set gives outcrop its ledgy appearance. Joints belonging to this set have relatively constant orientations and appear to be parallel, or nearly so, to the plane of flattening of the fairly sparse lithophysae here. The terminating relationships are ambiguous and the age of this set relative to others is unknown. Not surprising, however, as joints belonging to SH set could readily have formed during erosional unloading (more than one episode of such?) and the rock continues to split along surfaces parallel to SH upon weathering.
Terminations	Multiple SH and T1 intersect; multiple SH and T2 intersect; two T2 abut SH; multiple SH abut T1; T1 abuts SH; one SH abuts T2; two T2 abut C1; one T1 and C1 intersect; one T2 hook into another T2; no terminating relationships between T1 and T2 were observed.
Miscellaneous Remarks	All readings were taken from the ledgy exposure. Above the ledge, the rock loses its ledgy appearance. Here, C1 set appears to be more abundant and of more diverse orientation.
Summary	Cooling joints at this locality are few in number--the exposure is oriented unfavorably for them to crop out--but stand apart from all other joints in the exceptional smoothness of their surfaces. Abutting relations, though sparse, confirm them as the oldest joints present. The median strike of the set--N. 75° E.--matches none of the known tectonic sets and provides additional indirect evidence that these are cooling joints. As is normal for the clinkstone unit, tubular structures on cooling-joint surfaces are absent. Most of the steeply dipping joints in this outcrop are members of either the T1 or T2 sets. The T1 joints in one area are spaced only 5-50 cm apart and there form an obvious set, but over most of the outcrop they are widely spaced and inconspicuous among the much greater numbers of T2 joints. Median strikes of the sets are N. 6°W. and N. 31°W., respectively. The most conspicuous joints in this outcrop are large fractures that divide the rock into crude, gently tilted slabs that weather to prominent ledges. These fractures are tightly grouped in orientation and are parallel, or nearly so, to the plane of flattening of the sparse lithophysae in the rock. Probably they are unloading joints.

Station Number	CRS4
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'35" N. long 116°26'24" W.
Location	Isolation Ridge, on SE-facing slope
Exposure Description	Thin, resistant ledges exposed 12 m above wash bottom that bisects Isolation Ridge. Station area is 15 m across slope and 6 m upslope. Lithophysal poor and well-fractured locality. Exposure is 70 percent.
Stratigraphic Unit	Tiva Canyon Tuff, rounded step zone of Scott and Bonk (1984)
T1	
Median Orientation	N07W/88SW (n=15)
Expression	Moderately well expressed
Shape	Planar to subplanar, some curving along strike, less so along dip; among the best formed at this locality
Roughness	Fairly rough to rough, surfaces weathered
Exposed Length	0.9-5.5 m; true lengths greater; some probably at least 6 m long; several true lengths not greater than 0.2 m.
Exposed Height	0.3-1.5 m; true heights indet.
Structures	Twist hackle observed on one joint surface; surfaces cut lithophysae
Spacing	Commonly 0.5-1.5 m; 0.2-0.6 m where set is best developed. Spacings are as great as 2 m; wider spacings were not observed, as set orientation parallels the slope
Mineralization	Caliche is present locally; surfaces are stained black and orange
Remarks	None
M	
Orientations	N87E/85NW, N75E/76NW
Terminations	Several T1 abut joints of diverse other orientations, suggesting the set has a tectonic origin.
Summary	Abundant fractures cut the rock at this locality, but the T1 set described below is the only one readily defined. Most of the other fractures have such diverse orientations and irregular, nonplanar surfaces that little pattern seems to exist among them. Terminations of T1 joints against other, diversely oriented fractures suggest that the T1 set is tectonic and that some (many?) of the other fractures are cooling joints. The fairly rough surfaces of the T1 joints would seem to be in accord with this view. The variable and locally strong weathering of joint surfaces at this locality, however, limits the use of smoothness as a discriminator between tectonic and cooling joints. Smooth surfaces are preserved on portions of several probable cooling joints of about N. 20° W. strike, but these fall outside the strike range of all but one member of the T1 set. See also station CRS-5, a similar locality in the same unit nearby.

Station Number	CRS5
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'33" N., long 116°26'24" W.
Location	NE-facing slope of southernmost arm of Isolation Ridge
Exposure Description	Joints measured along area 20 m across slope and 15 m upslope, about 12 m above the bottom of main wash cutting Isolation Ridge. Exposure is 60 percent.
Stratigraphic Unit	Tiva Canyon Tuff, rounded step zone of Scott and Bonk (1984)
C1	
Median Orientation	N70W/83NE (n=9)
Expression	Poor, but in one area five joints are readily visible and are located in a zone 2 m wide. Elsewhere the set is most unconvincing and not at all defendable as a set
Shape	Planar to subplanar; slight changes along strike; some joints show fairly abrupt curvature along strike
Roughness	Fairly smooth where not badly weathered; slightly "rippled" along dip.
Exposed Length	0.3-1.8 m; true lengths indeterminate but greater than those exposed
Exposed Height	0.2-1 m; true heights indeterminate but greater than exposed
Structures	None seen
Spacing	Indeterminate, but widely spaced over most of outcrop where set cannot even be defined. In area where set is definable, spacings are 0.1-1 m.
Mineralization	Caliche is present locally; joint surfaces are stained black
Remarks	Interpreted as a cooling set based on their fairly smooth surfaces--a low confidence set.
M	
Orientation	N02W/80NE, N20W/81NE
Terminations	None seen
Summary	The C1 joints here are interpreted as cooling joints on the basis of their fairly smooth surfaces. The presence of five of these fractures within a zone 2 m wide in one small portion of the outcrop is what prompted recognition and measurement of this set; elsewhere at this locality the C1 joints are widely scattered, few in number, and unconvincing as a fracture set. Here, as at station CRS4, abundant fractures that pervade the rock are of extremely diverse orientation, and many are irregular and curved, precluding confident recognition of sets. The impression gained from prolonged inspection of both outcrops is that little pattern exists to the local fracture network other than the sets described. Steeply dipping joints striking about N. 5°-20° W. were seen at both localities but were not remeasured here; see notes for CRS4 for description.

Station Number	CRS6
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'30" N., long 116°26'22" W.
Location	Isolation Ridge, at base of wash on SSW side
Exposure Description	Ledgy outcrop about 40 m long and 7 m high at base of wash. Measurements made over area about 10 m across slope by 6 m upslope, starting 1-2 m above bottom of wash, in lower part of unit. Directly below this zone, in wash, is more massive, lithophysal rich, non-ledgy uppermost part of lower lithophysal zone. Exposure is 70 percent.
Stratigraphic Unit	Tiva Canyon Tuff, rounded step zone of Scott and Bonk (1984)
C1	
Median Orientation	N39W/86NE (n=12)
Expression	Moderate
Shape	Planar to gently curving along strike
Roughness	Smooth; surfaces are weathered
Exposed Length	0.4-10 m; true lengths indet., but lengths are thought to be long
Exposed Height	0.2-1.5 m; true heights indet.
Structures	Surfaces cut few lithophysae, far fewer than other sets at this station
Spacing	Indet.; set is exposed stepwise down the outcrop; no two joints are exposed on the same ledge to reveal spacing
Mineralization	Caliche coats some surfaces. A druse of finely crystalline, translucent, noncalcareous white mineral coats some surfaces. On top of the druse is a 0.5 mm-thick coating of pale gray noncalcareous mineral with a botryoidal outer surface. Pale gray alteration rinds are present
Remarks	C1 forms risers of ledges.
C2	
Median Orientation	N53E/81NW (n=8)
Expression	Moderately poor
Shape	Planar to gently curviplanar
Roughness	Smooth; surfaces slightly rippled with ripple axes parallel to strike. Not quite as smooth as C1.
Exposed Length	0.3-2.7 m; true lengths indet. but greater than observed
Exposed Height	0.2-1.5 m; true heights probably not much greater than largest measured
Structures	Surfaces cut few lithophysae
Spacing	Indet.; appears to be fairly widely spaced.
Mineralization	Caliche coats some surfaces. Some surfaces have a thin coating of white, translucent, noncalcareous, fine crystalline druse. Thin, pale gray 1-1.5 mm alteration rinds present
Remarks	Interpreted as a cooling set. All seen were measured.
T1	
Median Orientation	N05W/90 (n=23)
Expression	Very well
Shape	Planar to subplanar
Roughness	Moderately rough; surfaces are slightly irregular along strike and dip
Exposed Length	0.2-3.5 m; true lengths indet.
Exposed Height	0.2-1.5 m; true heights greater, but possibly not by too much
Structures	Surfaces cut lithophysae. One T1 hooks into T1; probable twist hackle and step face
Spacing	Observed range of 0.2-4 m; common range of 0.5-1.2 m
Mineralization	Thin coating (0.2-0.4 mm) of a formless, translucent, white to pale gray, noncalcareous mineral resembling opal or chalcedony
Remarks	Only prominent joints measured.

Station Number	CRS6
T4	
Median Orientation	N78W/81NE (n=9)
Expression	Very poorly expressed
Shape	Subplanar to locally nonplanar
Roughness	Rough, with very irregular surfaces
Exposed Length	0.2-1.4 m; true lengths probably not much greater than observed
Exposed Height	0.1-1.2 m; true heights indet.
Structures	Surfaces cut few lithophysae
Spacing	Indet.
Mineralization	None seen
Remarks	A low confidence set.
SH	
Median Orientation	N24E/09SE (n=11)
Expression	Well; a visually prominent set
Shape	Nearly planar on a gross scale
Roughness	Rough, but surfaces are highly weathered; true roughness indet.
Exposed Dimension	Greatest observed dimension is 8.5 m; smallest observed dimension is 1 m
Structures	Surfaces probably cut lithophysae, but cannot determine for certain
Spacing	Observed range is 0.3-1.5 m; common range is 0.5-0.8 m
Mineralization	None observed, surfaces badly weathered
Remarks	Debris cover and shifting of blocks prevent confident interpretation of abutting relationships. Huge size argues for this set being early, but cannot confirm for certain. SH forms steps.
Terminations	Two T1 abut C2; three T4 abut T1; one T1 hooks into and abuts C2; C2 and SH intersect; many T4 abut T1; T1 and SH intersect; one SH abuts T1.

Summary

Recognition of fracture sets at this locality was aided considerably by the moderate to large orientational separation and distinct differences in fracture style between cooling and tectonic sets. Three of the five sets are represented by abundant joints, and abutting relations, though not numerous, nevertheless are consistent. For these reasons the fracture network here probably is better and more completely understood than at most other localities.

Two of the sets (C1, C2) form a nearly rectangular system of vertical cooling joints. No tubular structures were observed, as seems characteristic of the rounded step unit, but the following properties establish the suggested origin of the sets: (1) Several joints of the oldest known tectonic set (T1) abut or hook into members of the C2 cooling set, confirming the cooling joints as among the oldest fractures present. (2) Joints of both cooling sets have smooth surfaces, whereas those of the tectonic sets are more irregular and rough. (3) The cooling joints are of large size. Exposed lengths of 2-10 m are common, whereas few of the tectonic joints exceed 2 m in exposed length. (4) The cooling joints cut few lithophysae, almost certainly because they formed during the early stages of degassing of the rock. The later tectonic joints cut greater numbers of lithophysae and thus have conspicuously "pitted" surfaces--an effect similar to, but less pronounced than that already described for station CLL1 in the lower lithophysal unit.

Two additional sets of vertical joints correspond to well-known tectonic sets of the area. The oldest of these (T1), of median N. 5° W. strike, is by far the most prominent set at this locality and is represented by great numbers of closely spaced joints. The younger, T4 set is only weakly expressed, but 7 of its 9 joints terminate against members of the T1 set, confirming its late age relative to other sets. The two sets are nearly perpendicular to each other and form a second rectangular system superimposed on the earlier system of cooling joints.

The fifth set consists of large, foliation-parallel joints that divide the rock into ledges. Though their large size is consistent with an early age, uncertain abutting relations due to shifting of fracture-bounded blocks in outcrop preclude confident interpretation.

Station Number	CRS7
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'35" N., long 116°26'53" W.
Location	Unnamed wash along north side of Whale Back Ridge, near east end of ridge, approx 60 m N35W of drill hole USW H-4. Exposure is 90 percent.
Exposure Description	Narrow, washed-out area along base of SW-facing hillslope on NE side of wash. Area of fresh outcrop is 1-3 m wide and about 30 m long
Stratigraphic Unit	Tiva Canyon Tuff, rounded step zone of Scott and Bonk (1984)
C1	
Median Orientation	N55W/85SW (n=11)
Expression	Moderately poor
Shape	Commonly sinuous along strike and more regular along dip, though very little of their vertical dimension is visible
Roughness	Smooth, nearly featureless surfaces
Exposed Length	0.4-3 m
Exposed Height	0.1-0.6 m; true heights indet., but undoubtedly much greater than those observed
Structures	No tubular structures observed
Spacing	Few spacings were observed because long dimension of exposure is nearly parallel to C1 set. Observed spacings are 1.3 m and possibly 1.7 m
Mineralization	Thin (0.5-1.5 mm), pale gray alteration rinds; fresh color of rock is medium violet-brown. Some C1 retain a thin film of a white, noncalcareous mineral deposited upon the discolored surface. Caliche commonly fills joints of this set, though fill is not as thick as along the wider T2 joints; maximum thickness of fill observed is about 1.2 cm.
Remarks	Interpreted as a cooling set
T2	
Median Orientation	N24W/87SW (n=14)
Expression	Well expressed, prominent set and the only one easily defined at this locality
Shape	Subplanar; notably more irregular along strike than C1 joints which show only smooth, gradual curvature
Roughness	Moderately smooth, discernibly rougher than C1
Exposed Length	0.4-2.2 m; lengths variable from true lengths of 0.5 m or less to 2.2 m
Exposed Height	0.1-0.5 m
Structures	One T2 hooks into C1; one small hook of T2 into another T2; small twist hackle is superimposed on the abrupt hook
Spacing	Locally 2-4 cm; in most places 0.5-1 m
Mineralization	Many joints are filled with 0.5-2 cm of a chalky white calcareous mineral resembling caliche, and in some of these the material is prominently banded and interlayered with a pale gray to white noncalcareous mineral (probably opal or chalcedony), to form composite calcite-silica veins resembling those of Trench 14.
Remarks	None
Terminations	Three T2 abut C1; one T2 hooks into and abuts C1. Abutting relations are consistent with C1 being the older set.
Summary	Cooling joints in this exposure form a single set of relatively narrow strike range. Characteristics shared with known and inferred cooling joints at other localities include smooth surfaces, sinuosity along strike, and relatively large size. Multiple abutting relations confirm them to be the earliest fractures present. Though not abundant, the cooling joints differ in overall appearance from the associated tectonic joints and in most cases can be recognized on sight.

Station Number CRS7

The most prominent set at this locality is the T2 tectonic set. Its joints have more irregular traces and discernibly rougher surfaces than those of the associated cooling joints, and they are present in far greater numbers. Many of the T2 joints have been opened and are filled with 0.5-2.0 cm of a chalky white calcareous material resembling caliche. This material in places is interlayered with a pale gray to white noncalcareous mineral, presumably opal or chalcedony, to form composite calcite-silica veins resembling those in Trench 14. Similar but generally thinner fillings were seen within some of the cooling joints also.

Station Number	CUL1
Quadrangle	Topopah Spring SW, 7.5', lat 36°49'41" N., long 116°24'45" W.
Location	Fran Ridge, north half, at bottom of ravine near NE-trending fault mapped by Scott and Bonk (1984)
Exposure Description	Measurements taken from two near-vertical outcrops located 15 m apart and directly above ravine bottom. Northernmost outcrop is on west side of ravine, just above the ravine bottom, near a 2 m^2 boulder that has fallen to the ravine bottom. Southernmost exposure is on east side of ravine, near another rounded boulder located 15 m south of boulder to the north, and extends southward for about 10 m. Northernmost area encompasses 10 m across slope and 3 m upslope; southernmost area encompasses 10 m across slope and 2 m vertically. Exposure is 90 percent.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)
C1	
Median Orientation	N76E/87NW (n=5)
Expression	Poor
Shape	Planar
Roughness	Indet. due to weathering; one joint is smooth
Exposed Length	0.16-3 m; true lengths greater
Exposed Height	0.4-2 m; true heights greater
Structures	None seen
Spacing	Indet.
Mineralization	Orange and black stains are present. A very thin, cream-colored, noncalcareous mineral is present on one joint
Remarks	Surfaces cut lithophysae.
C2	
Median Orientation	N21W/86SW (n=2)
Expression	Fairly well; fairly obvious at outcrop although only two joints were seen
Shape	Planar to curviplanar
Roughness	Surfaces weathered but smooth
Exposed Length	Range, based on two joints is 0.5-1.5 m; true lengths greater
Exposed Height	Range, based on two joints is 0.3-0.5 m; true heights greater
Structures	Tubular structures present on one joint which cuts a few 2.5 cm-long lithophysal cavities
Spacing	Indet.; too few joints to determine
Mineralization	Sparse caliche; one joint is filled with white, noncalcareous mineral.
Remarks	None
T2	
Median Orientation	N32W/84SW (n=7)
Remarks	Characteristics of this set were not recorded in the field as this set was too ill-defined to designate as a set. Subsequent evaluation by the investigators has led to a reinterpretation of this set as an identifiable set, based on its lack of tubes (distinguishing the set from C2) and its different orientation from other sets identified at this locality.
T3	
Median Orientation	N35E/87NW (n=11)
Expression	Fairly well
Shape	Subplanar to curviplanar; some curve as much as 15° in 1.5 m. Joints of this set tend to curve and pinch into each other
Roughness	Indet. due to weathering, but appear to be very irregular along strike and dip
Exposed Length	0.02-2.5 m; true lengths greater

Station Number	CUL1
Exposed Height	0.35-1.5 m; true heights greater
Structures	None seen
Spacing	Indet., but spacings as close as 0.4 m and as wide as 0.8 m observed
Mineralization	Orange and black stains are present
Remarks	Surfaces cut lithophysae

T4

Median Orientation	N72W/76SW (n=5)
Expression	Poor
Shape	Subplanar
Roughness	Indet. due to weathering, but surfaces are very rough
Exposed Length	0.4-2 m
Exposed Height	0.5-1.4 m
Structures	None seen
Spacing	Indet.; three joints are spaced 0.2-0.3 m
Mineralization	None seen
Remarks	Joint surfaces cut lithophysae.

M

Orientation	N11E/55SE, N11E/59SE

SH

Median Orientation	N17E/12NW (n=4)
Expression	Poor
Shape	Subplanar; surfaces very irregular around lithophysal cavities
Roughness	Indet. due to weathering; but surfaces are very irregular along strike and dip
Exposed Dimension	Greatest dimension exposed is 3 m; smallest dimension exposed is 0.4 m
Structures	None seen
Spacing	Indet.; two joints are spaced 3 m apart and two joints are spaced 0.35 m apart
Mineralization	Orange and black stain is present on all joint surfaces. Caliche is present on some joint surfaces.
Remarks	Joint surfaces cut lithophysae. SH set roughly parallels rock foliation.

M

Orientation	N11E/55SE, N11E/59SE
Terminations	None seen
Miscellaneous Remarks	Tubular structures were seen on two joints in the upper lithophysal zone, above and west of this station, near the ridgecrest of the ridge and below the road which runs along the ridgecrest. Orientations of these joints are N68E and N38W, very different from C2 joints identified at this station.
Summary	Cooling joints in this exposure are few in number (5) but conform closely to a rectangular system with median strikes of N. 76° E. and N. 21° W. All of them have smooth surfaces except where modified by weathering, and some show tubular structures. Joints of similar orientation, also with tubular structures, on the nose of the ridge to the west provide additional evidence of the presence and areal extent of the two cooling sets. Remnants of a thin, white to cream-colored noncalcareous mineral coating are preserved on some of the cooling joints but are lacking from the later tectonic joints. Tectonic joints dominate at this locality, and among them at least three sets--T2, T3, and T4--can be recognized. The irregularity of their traces, both along strike and dip, is a consistent feature that sets them apart from the cooling joints. The sequence of formation of the tectonic sets could not be established from the sparse abutting relations observed; the identity of the sets thus is inferred by analogy to other outcrops in the region. Also present in this exposure are several fractures of modest dip and with highly irregular surfaces. Probably these are unloading joints, but too few are present to have merited detailed study.

Station Number CUL1

See also the notes for nearby station CKS2, where the fracture network in an underlying unit is nearly identical to that described here.

Station Number	CUL2
Quadrangle	Topopah Spring SW, 7.5', lat 36°49'23" N., long 116°24'49" W.
Location	Fran Ridge, north half, directly SE of fault mapped by Scott and Bonk (1984)
Exposure Description	Resistant nose exposed across slope. Station begins just south of ravine located where cul is faulted. Station continues east for 60 m, ending at ridge nose. Outcrop is a natural pavement where flat, NE-facing slabs slope 29°. CUL2 is located in lowermost cul where it is in sharp contact with clinkstone. Lowermost 5 m of cul comprises CUL2. Cooling joints are present at and near (within 0.5 m) of the upper lithophysal/clinkstone contact (which is itself a cooling joint). Exposure is 80 percent.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)
C1	
Median Orientation	N10W/83SW (n=17)
Expression	Well expressed, most obvious set
Shape	Curviplanar, some gently sinuous along strike and dip
Roughness	Indet. due to weathering; some are extremely irregular along strike and dip; a few are smooth and gently undulatory along strike and dip
Exposed Length	0.7-9 m; true lengths greater
Exposed Height	0.2-2 m; true heights greater
Structures	Surfaces cut lithophysae; arrest lines on several C1 joints south and just beyond this station
Spacing	Variable; commonly spaced 1-3 m apart; some are spaced as close as 7-20 cm
Mineralization	Some surfaces have patches of caliche. Most surfaces are badly weathered to an orangish-tan color and are stained black in places
Remarks	Very probable cooling joint set, based on prominence, spacing, and shape. C1 does not extend into clinkstone below, rather C1 abuts the cooling joint upper lithophysal/clinkstone contact. Most C1 measured; all prominent C1 measured.
C2	
Median Orientation	N76E/89NW (n=18)
Expression	Well expressed; about as well as C1 set
Shape	Curviplanar
Roughness	Same as C1; weathering has removed much of the surfaces
Exposed Length	1-5 m; true lengths greater
Exposed Height	0.5-2.5 m; true heights greater
Structures	(2) C2 joints have tubular structures and their surfaces cut lithophysae
Spacing	Commonly spaced at 1-4 m; a few C2 are spaced 0.2-0.5 m apart
Mineralization	Same as C1 set
Remarks	Only a few of the tubular structures are anastomosing. Most C2 observed were measured; prominent ones measured. C2 abuts the cooling joint upper lithophysal/clinkstone contact.
C3	
Median Orientation	N79W/21NE (n=4)
Expression	Very poor; observed only on N end of outcrop, and only in one area.
Shape	Curviplanar; (1) joint is conchoidal
Roughness	Very smooth, but very slightly irregular along strike and dip
Greatest Dimension	0.8 m observed

Station Number	CUL2
Structures	Small (< 1-3 mm diameter) tubular structures, non or weakly anastomosing. Tubes run parallel to each other and to strike, penetrating the rock 1-2 mm. C3 surfaces are nonlithophysal. Alteration rinds were not observed, but weathering may have removed rind
Spacing	Very close; about 7-10 cm apart
Mineralization	Surfaces weathered to orangish-tan color with spotty black stain and black stain coats tubes.
Remarks	All C3 observed were measured. C3 set was observed in the lowermost cul, about 2 m stratigraphically above the upper lithophysal/clinkstone contact. Stretching directions (perpendicular to tubular structures) measured are N12W, N02E, N04W, N24W, N26W.
CM	
Orientation	N12E/46SE, N60W/84SW, N48W/35SW
Remarks	Three sub-horizontal or shallow dipping cooling joints, are exposed at north end of station. Surfaces are very smooth with tubular structures having the same character as those on C3. Surfaces weathered orangish-tan with black stain coating parts of the surfaces and tubes. Small patch of cream-colored, noncalcareous mineral on one joint. This joint set, like C3 is about 2 m stratigraphically above the upper lithophysal/clinkstone contact. One joint (possible C3), roughly parallels pavement surfaces.
Terminations	All C1 abut upper lithophysal/clinkstone contact; all C2 abut upper lithophysal/clinkstone contact; one C1 abuts (both ends) C2; many C1 and C2 intersections
Summary	Cooling joints dominate the fracture network of this extensive outcrop and form prominent, though rather ill-defined sets of moderate to large orientational variability. Two sets are at nearly right angles are apparent from the data. The joints of one set (C1) strike N. 26° W. through north to N. 11° E., a 37° range, and have a median strike of N. 10° W. Those of the second set (C2) exhibit a 49° strike range, from N. 50° E. through east to N. 81° W., with a median value of N. 75° E. In outcrop both are well expressed and represented by abundant, generally curviplanar joints. Tubular structures preserved on two C2 joint walls leave little doubt as to the origin of the set, whose median orientation in any case matches none of the known tectonic sets of the area. The C1 set, however, is problematical: no tubular structures were observed, and the set spans the common orientation range of both the T1 and T2 tectonic sets. Abutting relations show only that a single C1 joint postdates two nearby C2 joints, consistent with either a cooling or tectonic interpretation for the set. Most other C1 and C2 joints intersect. The commonly sinuous, curviplanar shape of the C1 joints is the strongest indication that some or many of them are cooling joints, but we cannot exclude the possibility that a significant portion of this set is instead tectonic. Weathering of many of the joint faces has been sufficiently extensive that joint roughness at this locality is not a reliable discriminator between cooling and tectonic joints. Smooth, sinuous cooling joints of gentle (16°-28°) northward dip, slightly inclined to the rock foliation, form a third but weakly expressed set (C3) within one small area toward the north end of the outcrop. Tubular structures are of similar orientation on all four surfaces and indicate a stretching direction of about N. 12° W., nearly parallel to the median dip line of the fractures. See also the notes for nearby station CUL3, where the fracture network is closely similar to that described here but the individual sets are much better defined.

Station Number	CUL3
Quadrangle	Topopah Spring SW, 7.5', lat 36°49'27" N., long 116°24'43" W.
Location	East side of Fran Ridge
Exposure Description	Measurements taken from resistant ledge formed by the upper lithophysal zone on east side of ridge and pavement located directly above ledge. Most measurements were from the pavements, so height measurements not discernible. The upper lithophysal/clinkstone contact is fairly obvious at the base of the ledge (also lowermost horizon of station), and is located at a large subhorizontal parting that marks an abrupt lithologic change between the two zones. Measurements were taken from the pavements and ledge, covering a stratigraphic thickness of about 5 m. Lateral distance covered was about 15 m. Exposure is 70 percent.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)

C1

Median Orientation	N11W/78SW (n=17)
Expression	Well; most obvious set; visually prominent on pavement surfaces
Shape	Planar to curviplanar, most show some strike variation
Roughness	Fairly smooth where best preserved
Exposed Length	1-6 m; some joints appear to be much longer than exposed lengths, but could not be confirmed as continuous
Exposed Height	0.2-1.2 m; true heights indet., but greater than exposed heights
Structures	None seen; joint surfaces cut lithophysae
Spacing	Commonly between 1-2 m over much of outcrop; locally increasing to as much as 6 m. A few are spaced at 0.5 m
Mineralization	None seen
Remarks	Abutting relationships make C1 probable cooling set

C2

Median Orientation	N80E/88SE (n=15)
Expression	Moderate to weak
Shape	Subplanar, most curve along strike
Roughness	Indet.; most surfaces not exposed; the C2 joint with tubular structures appears to be fairly smooth
Exposed Length	1-7 m; true lengths indet., but shorter than C1 joints and abut C1 joints
Exposed Height	0.1-1 m; true heights indet.
Structures	One C2 joint has weakly developed tubular structures
Spacing	Commonly 2-4 m
Mineralization	None seen
Remarks	This station is not a good place to characterize this set.

C3

Median Orientation	N48W/10NE (n=2)
Expression	Very poor
Shape	Planar
Roughness	Smooth, slightly irregular along surface. Surface irregularity on one C3 joint surface is the result of small scoop-shaped depressions on the surface
Exposed Dimension	0.7-.5-5 m; true dimensions indet.
Structures	One joint has tubular structures with diameters ranging from 1-3 mm, spaced 4-7 cm apart. Very well-developed inclusion hackle with hackle faces commonly 1 cm long and commonly 0.2-0.5 mm high. Inclusion hackle is at a high angle (80°) to tubular structures.
Spacing	1.2 m between two joints seen
Mineralization	Where exposed, surfaces are stained black. Thin coatings of opaque white noncalcareous mineral are present

Station Number CUL3

Remarks

C3 is very tight (barely open). Both joints are located within the bottom 2 m of the upper lithophysal zone, near the contact with the clinkstone zone. C3 set parallels foliation.

Terminations

Many C2 abut C1; probable C1 abuts C3; many C1 and C2 intersect; possible C2 abuts C3; C3 intersects several C1

Summary

Two sets of steeply inclined cooling joints form a well defined and visually evident rectangular network at this locality, where a broad expanse of rock is exposed as a gently inclined pavement surface along the crest of a ridge. Median orientations of the sets are similar to those at nearby station CUL2, but the sets are considerably less variable in orientation. The joints of both sets are fairly large--exposed lengths of 3-5 m are common--and most are sinuous along strike. Tubular structures were observed, weakly developed, on a single C2 joint. The rarity of tubular structures on supposed cooling joints again, as at station CUL2, leaves open the question of how to interpret the C1 set, whose joints partially overlap in orientation both the T1 and T2 tectonic sets. Here, however, abundant terminations of C2 against C1 joints establish C1 as the older set and thereby demonstrate that it too must be due to cooling. We interpret the network at station CUL2 similarly and for both stations have interpreted the sets as cooling joints.

A further parallel between the two stations is the local presence of gently inclined cooling joints (C3) bearing weakly developed tubular structures on their surfaces. Only two such joints were observed at station CUL3. One of these is intersected by a vertical C1 cooling joint, but the individual tubes are continuous across the break, thereby establishing the gently dipping C3 fractures as the oldest cooling joints present. The chronology of cooling joints at this outcrop is thus well established as C3 > C1 > C2.

The steeply dipping C1 and C2 cooling joints cut through lithophysal cavities in the rock and thus clearly formed after at least some of the cavities had developed; similar joints are present at numerous other localities. The smooth, continuous surfaces of the gently dipping C3 cooling joints, in contrast, are interrupted only by weakly developed tubular structures; none of these joints transect lithophysae. We interpret this to mean that the gently dipping joints grew in nonlithophysal rock and thus that they predate other joints that grew during the later stages of cooling.

Station Number	CUL4
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'27" N., long 116°24'21" W.
Location	Fran Ridge, south-facing slope of the E-W trending ridge at northernmost tip of Fran Ridge
Exposure Description	Area is 30 m across slope by 5 m upslope. Outcrop is a resistant, nearly vertical cliff exposure and pavement sloping 9° and forming top of resistant cliff. Stratigraphic thickness covered is approximately 3 m. Station is located just above the upper lithophysal/clinkstone contact at base of upper lithophysal zone here. Exposure is 70 percent.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)

C1

Median Orientation	N01W/84SW (n=23)
Expression	Well
Shape	Planar; some very sinuous along strike and dip; few curviplanar
Roughness	Most are fairly rough; some are fairly smooth where surface is protected from weathering; all are irregular along strike and dip
Exposed Length	0.8-5.5 m; true lengths greater for most
Exposed Height	0.3-3 m; true heights greater, but maybe not by much
Structures	Large (1 m) arrest line noted on joint outside of the station area. Joint surfaces cut lithophysal cavities
Spacing	As close as 0.3 m and as wide as 3 m
Mineralization	Surfaces are stained black
Remarks	Surfaces extensively weathered. Only most prominent joints measured. Tentatively interpreted as cooling joints based on expression, prominence (long lengths), and shape, and terminating relationships with C2. Range of C1 may be much greater as joints may be turning.

C2

Median Orientation	N90E/90 (n=11)
Expression	Well, but less so than C1 (appear to be fewer C2)
Shape	Planar to curviplanar
Roughness	same as C1
Exposed Length	1-3 m; true lengths greater for most
Exposed Height	0.2-1.2 m; true heights greater, but maybe not by much
Structures	Several large arrest lines. Some C2 cut 3-8 cm lithophysal cavities; some C2 appear to not cut lithophysal cavities, but uncertain due to extensive weathering of surface
Spacing	Commonly spaced 1.5 m apart; observed as wide as 3 m
Mineralization	Surfaces stained black
Remarks	Surfaces extensively weathered. Only most prominent joints measured. Tentatively interpreted as cooling joints based on expression, shape, terminating relationships with C1. Range of C2 may be much greater, as joints may be turning. Set is prominent on the north side of the ridge, directly south of main road to Yucca Mountain.
Terminations	C1 and C2 intersect;, some C1 cross upper lithophysal/clinkstone contact (horizontal parting); some C1 abut upper lithophysal/clinkstone contact (horizontal parting); possible C2 hooks into and abuts C1
Miscellaneous Remarks	Very low-confidence locality. Lack of tubular structures on near-vertical joint surfaces at this locality is interpreted to be due to their absence in general at this stratigraphic horizon. An abrupt change in the size of lithophysal cavities occurs at the upper lithophysal/clinkstone contact at this locality, from small (avg 1 cm diameter) in cul above the contact to zone of large (avg 3-8 cm diameter) below, where the cavities are less abundant.

Station Number CUL4

Summary

Joints at this locality form two major orientational groups, but interpretation of their significance is uncertain at best because style differences between cooling and tectonic joints are too slight to distinguish confidently between them. The simplest interpretation, based partly on analogy to stations CUL2 and CUL3 farther south, is that the groups represent two major sets of steeply dipping cooling joints with median strikes of N. 1° W. and N. 90° E. The relatively broad strike distributions (56° and 39°, respectively), large size, and sinuous, curved shapes of many of the joints are consistent with this view; so too is the fact that the network defined by the two sets is very nearly a rectangular one. The sequence of readings obtained for the C1 set as it was traced from one end of the outcrop to the other suggests gradual turning of the set from N. 10°-15° E. strikes through north to N. 25°-30° W., another property not uncommon among cooling joints and responsible in part for the large strike variation of the set. The joints of both sets, however, have irregular traces along both strike and dip, a property all but unknown among undoubted cooling joints. Surface roughness is an unreliable discriminator between cooling and tectonic sets at this locality due to variable weathering of the joints, whose walls range from fairly smooth to moderately rough.

The sets conceivably could also be interpreted as tectonic and composed dominantly of T1 and T4 joints. The broad strike distribution of the most prominent group, from N. 19° E. to N. 36° W., suggests that some T2 joints might also be present to account for the higher north-northwest strikes. The strike distribution, however, is continuous, and neither the orientation data nor the outcrop offer any obvious evidence that two sets rather than one are represented by this group. The pronounced sinuosity of some of the joints is additional evidence against a tectonic interpretation. The abundance and abnormally large size of the "T4" joints likewise are problematical, as elsewhere these joints are almost uniformly small and generally only weakly expressed as a set. For these reasons we favor an interpretation as two well-expressed cooling sets but feel that some tectonic joints of like orientation might also are present. The latter might well account for some of the rougher and more irregular joints of both orientational groups.

Also present at this locality are scattered joints of northeast strike, probable members of the T3 set, but too few were observed to verify the existence of the set or to justify their full documentation.

Station Number	CUL5
Quadrangle	Topopah Spring SW, 7.5', lat 36°51'23" N., long 116°26'38" W.
Location	SE end of Azrael Ridge, north of Drill Hole Wash on SW-facing slope of Azrael Ridge, east of drill hole UE-25a no.5
Exposure Description	Station is located in the upper lithophysal zone about 20 m upslope from the wash bottom. Here, several small areas with about 20 percent exposure are located in an almost completely covered area extending 40 m across slope and 6 m upslope. Approximately 2 m of stratigraphic thickness is intermittently exposed on a 20° slope.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)
C1	
Median Orientation	N45W/83NE (n=15)
Expression	Moderately well
Shape	Most are planar
Roughness	Very smooth
Exposed Length	0.03-2 m; true lengths greater
Exposed Height	0.01-1.6 m; true heights greater
Structures	Tubular structures present on all but one joint, whose surface is not visible. Joint surfaces do not cut lithophysae.
Spacing	Variable; observed range of 0.05-1.4 m; observed spacings close to true spacings.
Mineralization	Most joints are coated with caliche; some are filled with caliche. Tan alteration rinds with thicknesses averaging 1 mm are present on most joints with alteration rinds also bordering the tubular structures.
Remarks	C1 set is parallel to slope and is very tight (most have < 1 mm of wall separation). One joint has a wall separation of 7 mm. Interpreted as a cooling set.
C2	
Median Orientation	N38E/85NW (n=6)
Expression	Poor to moderate overall; set is not immediately obvious on outcrop
Shape	Planar; some may be curviplanar but short exposed lengths prevent determination
Roughness	Very smooth
Exposed Length	0.2-1.4 m; true lengths greater
Exposed Height	0.04-0.4 m; true heights greater
Structures	Tubular structures are present on all joints. Average diameter of tubes is 4 mm, but as great as 1 cm observed. Joint surfaces do not cut lithophysae
Spacing	Indet.; orientation of set with regard to slope prevents determination. Range of 1-2 m observed
Mineralization	None seen. Thin (< 1 mm), light gray alteration rinds present on most surfaces. Small alteration rinds also border tubes.
Remarks	All seen measured. Cooling set.
T1	
Median Orientation	N07W/88NE (n=9)
Expression	Poor
Shape	Nonplanar, very irregular along trace
Roughness	Rough, surfaces are irregular
Exposed Length	0.2-0.4 m; true lengths not much greater
Exposed Height	0.01-0.2 m; true heights close to exposed heights
Structures	Surfaces do not cut lithophysae.
Spacing	Variable, but fairly closely spaced. Observed spacings of 0.07-0.3 m. Some joints barely overlap along their lengths.
Mineralization	None seen

Station Number	CUL5
Remarks	This set has same character (size, shape) as T3 set. T1 set is interpreted as tectonic in origin based on shape, roughness, and size.
T3	
Median Orientation	N18E/86SE (n=7)
Expression	Poor
Shape	Nonplanar over very short exposed lengths
Roughness	Rough
Exposed Length	0.1-0.5 m; true lengths indet.; too poorly exposed to determine
Exposed Height	0.1-0.3 m; true heights indet.; too poorly exposed to determine
Structures	Joint surfaces cut lithophysae
Spacing	Indet.
Mineralization	None seen.
Remarks	T3 set is interpreted as tectonic in origin, based on roughness and shape. T3 set is not well-defined here, but nevertheless is definable as a set.
Terminations	Four C1 and T1 intersect; probable T1 abuts C1; one T1 abuts C2

Summary	As at station CLL1 in a similar rock type, morphologic differences between cooling and tectonic joints at this locality are extreme. The cooling joints, all but one of which bear prominent tubular structures as proof of origin, form two well-defined sets nearly at right angles (83°). Median strikes of the major and subordinate sets are N. 45° W. (C1) and N. 38° E. (C2), respectively. Joint walls between individual tubes are uniformly smooth and nearly featureless, and the joints do not cut lithophysae. The later tectonic joints, in contrast, have rough, irregular surfaces and cut through numerous lithophysal cavities, giving them a crude, "pockmarked" appearance quite unlike that of the cooling joints. Two sets of tectonic joints were documented, one (T1) moderately well expressed and the other (T3) considerably less so. Numerous additional fractures, not measured but of approximate N. 30° W. strike and uniformly short (<20 cm) length, probably correspond to the T2 set.

Station Number	CUL6
Quadrangle	Topopah Spring SW, 7.5', lat 36°52'26" N., long 116°26'03" W.
Location	Isolation Ridge, NE-facing slope of southernmost arm
Exposure Description	Station is located near top of zone, approximately 30 m above wash bottom. Intermittently exposed on 18-26° slope for 30 m across slope and 6 m upslope. Stratigraphic thickness of 4-5 m. Exposure is 10-20 percent. Above the station, the zone is nonlithophysal.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)

CM

Orientation	Median not calculated; not definable as a set N27W/72NE, N25W/85NE, N55W/74NE, N23E/73NW, N18E/87SE, N10E/72SE
Expression	Very poor
Shape	Planar to slightly curviplanar
Roughness	Smooth; fairly uniform where short lengths and heights are visible
Exposed Length	0.6-3.5 m; true lengths indet.; true length of two joints is 1.3 m
Exposed Height	0.2-1.6 m; true heights indet., but greater than those observed
Structures	All CM have tubular structures with diameters avg. 1 cm. Three joints cut lithophysae
Spacing	Indet.
Mineralization	One joint has patches of a very thin (<1 mm) cream-colored, platy, noncalcareous mineral. Probable light orangish-tan alteration rind on all joints
Remarks	Surfaces badly weathered. The orientation range of CM is probably broader than observed, but absence of tubular structures and short lengths make other possible CM joints too tenuous to include in set. Wall separation is less than 2 mm.

T1

Median Orientation	N09W/83NE (n=9)
Expression	Moderately poor
Shape	Nonplanar; few are subplanar
Roughness	Moderately rough; surfaces are irregular along strike and dip
Exposed Length	0.2-2 m; true lengths indet., but greater
Exposed Height	0.1-0.5 m; true heights indet., but greater
Structures	None seen
Spacing	Observed spacings of four joints range from 6-10 cm; two joints are spaced 1 m apart
Mineralization	Small patches of caliche on one joint
Remarks	Surfaces are badly weathered. Numerous, very short joints possibly belonging to this set are present, but not included in set due to their uncertainty as T1 joints.

T3

Median Orientation	N50E/81NW (n=3)
Expression	Poor
Shape	Nonplanar
Roughness	Moderately rough
Exposed Length	0.3-1.3 m observed, true lengths unknown
Exposed Height	0.02-0.4 m observed, true heights unknown
Structures	Cuts lithophysae, en echelon, left-stepping trace at a 4 cm-scale
Spacing	Indet.
Mineralization	Indet.
Terminations	One T1 abuts a subhorizontal joint

Station Number	CUL6
Miscellaneous Remarks	This station was selected because of dissatisfaction with CUL9; however, this locality isn't much better. The single sub-horizontal joint (N82W/16NE) observed appears to be an unloading joint, as it parallels foliation, has an irregular surface, and its surface cuts lithophysae.
Summary	Tubular structures and smooth joint walls facilitated recognition of cooling joints at this locality. All dip steeply, but too few were observed to permit definition of sets and description of the pattern formed by them. The six observed show a wide range in strike, from N. 23° E. to N. 55° W. The only tectonic joint set recognizable with certainty is the T1 set, of median N. 9° W. strike and steep east dip. The T1 joints and cooling joints overlap strongly in orientation, but their differing character in outcrop permits distinction between them: whereas the cooling joints are uniformly smooth, the walls of T1 joints are both moderately rough to the touch and irregular on a decimetric scale. The T1 set as so defined forms a tight orientational group with a strike range of only 21°. The cooling joints, as already noted, are much more variable in orientation. The conformance between style and orientation--smooth joints of variable strike versus rougher joints of consistent strike--emphasizes that two different sets are present. Several joints of northeast strike suggest the possible presence of the T3 tectonic set, but these were too few in number to recognize as valid sets.

Station Number	CUL7
Quadrangle	Topopah Spring SW, 7.5', lat 36°51'00" N., long 116°26'47" W.
Location	On ridge top of Live Yucca Ridge, at western boundary of NTS where No Trespassing sign is posted on the south side of the ridge
Exposure Description	Station is located on the ridge crest and on north and south sides of ridge crest, 20 m across slope by 10 m upslope. Small, well-exposed areas of outcrop between larger areas covered with talus. Exposure is 10-15 percent on a horizontal to 16° slope. Stratigraphic thickness covered is about 4 m. CUL7 is located to the east of the Ghost Dance fault, about midway between pavement 100 to the west and pavement 500 to the east.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)

C1

Median Orientation	N55E/80NW (n=13)
Expression	Moderately well to poor overall; best exposed on the north side of ridgecrest
Shape	Planar to curviplanar, mostly planar over observed fairly short lengths
Roughness	Very smooth
Exposed Length	0.3-3 m; true lengths greater
Exposed Height	0.02-0.5 m; true heights greater
Structures	All C1 have tubular structures. Tube diameters vary from 1 mm-2.5 cm. Joint surfaces do not cut lithophysae.
Spacing	Indet.; observed as close as 0.15 m and as wide as 1.5 m
Mineralization	1 mm-thick alteration rinds observed on many joints
Remarks	All seen were measured. Most C1 joints were measured on the north side of the ridge. Definite cooling set based on presence of tubular structures.

C2

Median Orientation	N45W/83NE (n=13)
Expression	Moderately well to poor overall; best exposed on south side of ridge crest
Shape	Planar to curviplanar, mostly planar over short lengths observed
Roughness	Very smooth
Exposed Length	0.15-2.5 m; (1) joint has a true length of 0.4 m; true lengths greater
Exposed Height	0.05-0.4 m; true heights greater
Structures	All C2 joints have tubular structures and their surfaces do not cut lithophysae
Spacing	Common range = 0.6-1 m; observed spacings are 0.7, 0.6, 1, and 1.2 m
Mineralization	None seen
Remarks	All seen were measured. Most C2 were measured on the south side of the ridge; only one measurement was taken on the north side. Definite cooling set based on the presence of tubular structures.

T

Median Orientation	N14W/80SW (n=5)
Expression	Indet.
Shape	Indet.
Roughness	Moderately smooth (possibly due to weathering); surfaces are very irregular along strike and dip on a 5-10 cm scale.
Exposed Length	0.3-0.5 m; true lengths greater
Exposed Height	0.15-0.2 m; true heights greater
Structures	Joint surfaces cut lithophysae
Spacing	Indet.; two joints are spaced 0.5 m apart
Mineralization	Surfaces are weathered to a light gray color

Station Number	CUL7
Remarks	Many joints are present with orientations ranging from N40W to N20E. These cannot be separated into distinct sets at this locality. Therefore, the strike range may be broader than indicated. Set is interpreted to be tectonic based on roughness, short lengths, and to a lesser degree, the absence of tubular structures (in proximity to joints with tubular structures).
M	
Orientation	N38E/88NW, N20E/83NW
Terminations	C1 and C2 intersect; one T abuts C1
Miscellaneous Remarks	Locality is not good for discerning terminating relationships. The outcrop is highly fractured and other sets probably are present.
Summary	Abundant cooling joints, all steeply dipping and with tubular structures on their surfaces, form two well-defined sets nearly at right angles in this exposure. In most places, however, the cooling-joint network is more nearly unidirectional than rectangular, for the northeast-striking joints of the C1 set dominate the north end of the exposure and the northwest-striking C2 joints the south end, in both places to the near exclusion of the complementary set. Strong lateral changes in relative prominence of cooling sets have been noted elsewhere as well. On pavement 600, for example, only one set of northeast-striking cooling joints is evident, but abundant surfaces of a second set are present in outcrop only a few meters farther west (see station CUL8). Gently dipping cooling joints analogous to those documented in the upper lithophysal zone at stations CUL2 and CUL3 are represented here by a single fracture (N20E/10SE). Small tubular structures on its surface leave little doubt as to its origin. Tectonic joints are abundant, but abutting relations are poorly exposed and confident separation of sets cannot be made. The abundance of joints striking north-northwest to north-northeast makes it probable that the T1, T2, and T3 sets are present in some combination, as reflected by the few selected readings "T." The irregular surfaces of these joints on a decimetric scale contrast sharply with those of the associated cooling joints.

Station Number	CUL8
Quadrangle	Topopah Spring SW, 7.5', lat 36°52'05" N., long 116°27'24" W.
Location	Unnamed ridge directly north of Drill Hole Wash and north of drill hole USW G-1, near the ridge crest
Exposure Description	Station CUL8 is located directly north and 3 m directly west of Pavement 600, and is located within the same stratigraphic horizon as Pavement 600. Measurements were taken from an area encompassing 30 m along slope and 6 m upslope. The rock is intermittently exposed on a 15° south-facing slope; exposure is 40 percent.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)

C1

Median Orientation	N34W/89NE (n=21)
Expression	Well expressed and more abundant than C2
Shape	Mostly planar, few are curviplanar. Few C1 are slightly sinuous along strike on a 20-cm scale
Roughness	Very smooth
Exposed Length	0.2-7 m. True lengths greater for some C1; observed true lengths of 0.4 and 4 m
Exposed Height	0.01-1 m. True heights probably not much greater than 1 m
Structures	All joints have tubular structures with diameters commonly ranging from 0.2-1 cm. One C1 has tubes with diameters of 3 cm. Joint surfaces do not cut lithophysae
Spacing	Variable; occur commonly in closely spaced zones 0.2-0.5 m apart; also as widely spaced as 2.8 m; as widely spaced as C2 set
Mineralization	Same as C2. One joint has a 2 cm-wide tube which is filled with a cream-colored, noncalcareous mineral.
Remarks	All C1 seen were measured. Some C1 traces are discontinuous along strike (like some on Pavement 600). Wall separation of C1 is < 1 mm. Several C1 joints appear to be reactivated with fairly rough, subplanar joints extending from the end of a very smooth and planar C1 joint. These later joints cut lithophysae, while C1 joints do not. C1 joints roughly parallel the slope.

C2

Median Orientation	N42E/78NW (n=13)
Expression	Variable across outcrop; well expressed where closely spaced; very poorly expressed elsewhere
Shape	Mostly planar; few longer C2 joints are curviplanar
Roughness	Very smooth
Exposed Length	0.28-5.5 m; true lengths variable, some as short as 1.5 m; many lengths are >3 m
Exposed Height	0.02-0.3 m; true heights indet., but probably greater
Structures	All joints have tubular structures with diameters commonly ranging from 2 mm to 1 cm. One joint has tubes with diameters of 2.5 cm. Joint surfaces do not cut lithophysae
Spacing	Sporadic and variable; in closely spaced zones 0.2-0.5 m apart, but as widely spaced as 2.5 m.
Mineralization	Up to 1 mm-thick, light orange alteration rinds on some joints. All joints surfaces are stained light orange.
Remarks	All seen were measured. Many C2 traces are discontinuous along strike (like some on Pavement 600). C2 joints are not present near west end of station; most were observed at east end. Wall separation of C2 is < 1 mm.

CM

Orientation	N36E/54SE
Terminations	One C1 abuts C2; many C2 and C1 intersect; one C2 barely crosses a C1; some C2 terminate before reaching C1.

Station Number	CUL8
Miscellaneous Remarks	C1 and C2 formed at approximately the same time. Other sets are undoubtedly present, but not identifiable at this station.
Summary	Two sets of cooling joints form an obvious rectangular network on the gently dipping surface of this outcrop, located on a ridge crest immediately west of pavement 600. Tubular structures are present on all members of each set. As at station CUL7, the abundance and spacing of joints of both cooling sets varies dramatically over short lateral distances. Here in outcrop the C1 set is dominant and the C2 set is of variable prominence, well expressed in some areas but only weakly expressed in others. A short distance to the east, however, on pavement 600, the C1 set is missing completely and only the C2 set is evident. Such strong lateral shifts in joint abundance within individual sets emphasize that small exposures may reveal only part of the local fracture network, and that absence of a given set on the outcrop scale does not imply its absence from the general area. Other, tectonic sets of joints exist here but are too weakly expressed to be distinguished with confidence. In general the tectonic joints are much shorter than the cooling joints, have fairly smooth (as opposed to very smooth) surfaces, and cut through lithophysal cavities, whereas the cooling joints do not.

Station Number	CUL9
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'38" N., long 116°26'26" W.
Location	Southwest-facing slope of Isolation Ridge
Exposure Description	Intermittent exposure extending laterally across slope for 10 m and 12 m upslope. Area is located below and just west of large talus boulder on slope. Stratigraphic thickness covered is about 4 m, on a 30°, SW-facing slope. Station is located in the lower middle section of the upper lithophysal zone, where the unit is only about 10 percent exposed.
Stratigraphic Unit	Tiva Canyon Tuff, upper lithophysal zone of Scott and Bonk (1984)
C1	
Median Orientation	N50E/75NW (n=5)
Expression	Poor
Shape	Planar; lengths exposed over very short distances
Roughness	Very smooth, uniform along strike and dip
Exposed Length	0.3-0.9 m; true lengths greater
Exposed Height	0.1-0.4 m; true heights greater
Structures	Tubular structures present on some joints; diameter of tubes varies from 1-10 mm. Joint surfaces do not cut lithophysae
Spacing	Indet.; as great as 2 m
Mineralization	Caliche coats one joint surface. Tubular structures are filled with caliche. An alteration rind was not observed, but weathering may have removed rinds
Remarks	Cooling set based on presence of tubular structures and very smooth surfaces.
C2	
Median Orientation	N51W/79NE (n=4)
Expression	Poor
Shape	Planar
Roughness	Very smooth
Exposed Length	0.2-0.6 m; true lengths greater
Exposed Height	0.05-3 m; true heights greater
Structures	Tubular structures are present on all but one poorly exposed joint
Spacing	Indet.; too few joints to determine
Mineralization	None seen. Surfaces are weathered
Remarks	Cooling set due to presence of tubular structures
CM	
Orientation	N77E/57NW
T1	
Median Orientation	N10E/86NW (n=14)
Expression	Variably expressed along outcrop; moderately expressed in some areas, poorly expressed elsewhere
Shape	Subplanar to curviplanar; longer joints are curviplanar
Roughness	Mostly rough, some are very rough; all are irregular along strike and dip
Exposed Length	0.1-2 m; true lengths greater
Exposed Height	0.02-0.9 m; true heights indet.
Structures	Joint surfaces cut lithophysae
Spacing	Variable, but commonly 0.2-0.5 m; swarms of short T1 joints are spaced 0.04-1 m apart
Mineralization	None seen. Surfaces are weathered
Remarks	Interpreted as probable tectonic due to rough, irregular surfaces. T1 is definable as a set based primarily on orientation, and is distinguished from C1 and C2 on lack of tubular structures, orientation, and roughness

Station Number	CUL9
T2	
Median Orientation	N31W/82SW (n=4)
Expression	Poor
Shape	Sinuous, very irregular along strike and dip
Roughness	Very rough
Exposed Length	0.2-1.0 m; true lengths greater
Exposed Height	0.05-1.0 m; true heights greater
Structures	None seen
Spacing	Indet.
Mineralization	None seen
T4	
Median Orientation	N75W/81SW (n=7)
Expression	Poor over most of outcrop; very poor in some areas
Shape	Nonplanar, very sinuous along strike and dip
Roughness	Very rough and very irregular along strike and dip
Exposed Length	0.2-1.2 m; true lengths greater, but probably not much greater
Exposed Height	0.05-0.3 m; true heights greater, but probably not much greater
Structures	None seen. Joint surfaces cut lithophysae
Spacing	Indet.; two joints are spaced 0.15 m apart
Mineralization	None seen. Surfaces are weathered
Remarks	Probable tectonic set. All joints dip SW and many T4 traces pinch NW, forming a wedge. Small swarms of N40E/85NW-85NE joints abut the T4 set.
Terminations	Not clear at this locality.
Miscellaneous Remarks	There are probably other sets at CUL9, but are not discernible here. Well-defined sets (N32-N55E, N18W) are present in rounded step zone below. Horizontal sets may be present at CUL9 but if so, they are obscured by talus. Lower lithophysal unit in ravine bottom below is workable as is upper cliff unit here. (Probable cooling joints in upper cliff unit are N70E and N18W).
Summary	Two sets of steeply dipping cooling joints at high angles to each other are present at this locality, but neither set is well expressed and few measurements were obtained. The exceptionally smooth surfaces and abundant tubular structures readily distinguish the cooling joints from the several sets of tectonic joints in the same rocks. Among the tectonic joints, those of the T1 set (median strike: N. 10° E.) are the most common. The set is variably expressed across the outcrop, obvious in some places and subtle in others, but its joints are consistently oriented. At right angles to these are joints of the late T4 set, poorly expressed overall and of typically crude shape, but nonetheless recognizable as a set because its joints lie at high angles to all others. Several joints probably correlative with the T2 set were measured also. The rough, irregular surfaces of all these joints are unlike those of the associated cooling joints.

Station Number	CUC1
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'38" N., long 116°27'15" W.
Location	On small SE-trending spur off Azrael Ridge, on the NE-facing slope, near the ridge crest
Exposure Description	Resistant cliff exposure, where the upper cliff zone forms a near vertical cliff directly above the gradational contact with the upper lithophysal zone. Measurements taken laterally across the E-facing slope for about 45 m; and for about 10 m upslope where about 10 m thick section of upper cliff unit is 90 percent exposed on the cliff face. The contact between the upper cliff and upper lithophysal zone is about 10 m below the ridgetop.
Stratigraphic Unit	Tiva Canyon Tuff, upper cliff zone of Scott and Bonk (1984)

CM

Median Orientation	No median calculated; orientations are too diverse. Orientations range from N86W-N87E. N42E/70NW, N42E/82NW, N40E/88NW, N52E/70NW, N46E/65NW, N40E/85NW, N44E/51NW, N70W/77NE, N06E/76NW, N51E/83NW, N86W/65NE, N87E/71SE, N62E/66NW, N70E/89NW, N85W/88NE, N70W/66NE, N68W/83NE, N86W/78NE, N35W/90NE, N28W/88SW, N33W/86SW, N34W/84NE, N56W/82SW, N46W/90SW, N61W/78NE
Expression	Moderately well overall, poor at north end of station
Shape	Planar and curviplanar
Roughness	Surfaces weathered, but appear smooth
Exposed Length	1-8 m; true lengths much greater
Exposed Height	0.8-9 m; true heights much greater
Structures	Tubular structures present on 4 joint surfaces. On one joint, tubes are absent in the top 6 m of exposed joint surface, but present below.
Spacing	Fairly widely spaced; 5-6 m over much of the outcrop; 2-6 m range observed
Mineralization	One joint surface is coated with caliche and a thin film of a white, noncalcareous mineral, and is altered to a pale pink color
Remarks	CM set may include two or more cooling joint sets, but diversity of orientations and absence of abutting relations prevent separation into component sets. Only a few of the joints extend about 1 m stratigraphically into the gradational upper lithophysal zone directly below

T2

Median Orientation	N21W/85SW (n=12)
Expression	Well
Shape	Planar and curviplanar
Roughness	Rough
Exposed Length	1-7 m; true lengths much greater
Exposed Height	1.5-5.5 m; true heights much greater
Structures	None seen
Spacing	Locally as close as 0.5 m; as great as 2 m observed
Mineralization	None seen
Remarks	None

M

Orientation	N03E/74NW, N05W/84SW, N28E/80NW
Terminations	Not clear at this locality

Station Number	CUC1
Summary	Cooling joints, some with tubular structures on their surfaces, are abundant and dominate the local fracture network over a lateral distance of 45 m. Nearly all the cooling joints dip steeply--70° or more--but their strikes cover a broad range. Cooling sets at this scale are ill-defined. Within much smaller portions of the outcrop, however, strike variability typically is less and the readings appear to conform to one and locally both sets of a crude rectangular system. Near the southern end of the station, for example, eight joints ranging in strike from N. 40° E. to N. 52° E. suggest the presence there of a cooling set of median N. 43° E. strike. Several additional joints at high angles to these are probable members of the complementary set. Sufficient readings to prove the existence of these sets, however, are unobtainable due to the coarseness of the fracture network and its changing orientation over short lateral distances. Nevertheless, the pattern of readings obtained in tracing this exposure along its length seems more indicative of a partially systematic rather than a nearly random network. Additional fractures in this outcrop have consistently rough surfaces distinct from those of the associated, more smooth-walled cooling joints. Orientations of these rough joints fall within a narrow range that conforms to the T2 tectonic set, here apparently well-defined but nonetheless inconspicuous in outcrop among the greater numbers of cooling joints, some of which have identical orientations.

Station Number	CUC2
Quadrangle	Topopah Spring NW, 7.5', lat 36°52'36" N., long 116°27'14" W.
Location	Northernmost arm of Azrael Ridge, on nose of small spur
Exposure Description	Resistant, near-vertical cliff exposed on the nose of the small spur and along the SW-facing slope near the ridgetop. Area traversed from nose of ridge along slope for about 20 m. About 8-10 m stratigraphic thickness is exposed.
Stratigraphic Unit	Tiva Canyon Tuff, upper cliff zone of Scott and Bonk (1984)

C1

Median Orientation	N38W/86NE (n=21)
Expression	Well, most obvious set at this locality
Shape	Planar to curviplanar, most tending toward curviplanar, but fairly uniform in dip
Roughness	Smooth where not weathered, but many highly weathered
Exposed Length	1-10 m; some true lengths are probably greater for some
Exposed Height	0.3-9 m; true heights greater; some are probably greater than 10 m
Structures	Most joints have tubular structures. One joint has a very well developed arrest line (joint propagated SE). C1 joint surfaces cut lithophysae. Delicate slickenside striations pitch 9°NW on C1 surface N54W/67NE; sense of slip unknown.
Spacing	Commonly 2-4 m; locally 0.5-1 m
Mineralization	White, noncalcareous mineral coating preserved on one joint
Remarks	Zone of C1 joints extends downward 2-3 m into gradational upper cliff/upper lithophysal lithology, though tracing individual surfaces far into this gradational area was not accomplished because cover rendered continuity of joint traces uncertain. This set exists in both the upper cliff and upper lithophysal units.

C2

Median Orientation	N36E/77NW (n=7)
Expression	Poor
Shape	Curviplanar, gently curving
Roughness	Smooth where least weathered
Exposed Length	2-6 m; true lengths greater, possibly much greater
Exposed Height	1.5-5 m; true heights greater, but possibly not much
Structures	Large tubular structures on 4 joint surfaces. Surfaces cut large lithophysae
Spacing	Indet.; too few for meaningful data; in places greater than 8 m; two joints are spaced 4 m apart
Mineralization	None seen
Remarks	C2 set does not appear to extend downward into gradational upper lithophysal zone.

C3

Median Orientation	N02E/83NW (n=4)
Expression	Poor; all were observed in a 3-m length of outcrop on the west end
Shape	Planar
Roughness	Very smooth where least weathered
Exposed Length	2-6 m; true lengths probably greater
Exposed Height	2.3-6 m; true heights probably greater, but not by much
Structures	Three joints have tubular structures
Spacing	Indet.; too few to determine; two joints are spaced 1 m apart at west end of outcrop
Mineralization	Small patch of white, non-calcareous mineral on one joint
Remarks	A low confidence set.

Station Number	CUC2
CM	
Number	No median calculated (n=2) Orientations are N85W/85SW, N80E/87NW
Expression	Poor; only two seen
Shape	Curviplanar
Roughness	Smooth where least weathered
Exposed Length	5 m (both joints)
Exposed Height	6-10 m
Structures	None seen; surfaces are weathered
Spacing	Very wide, but too few seen for meaningful measurement
Mineralization	None seen
Remarks	One joint extends downward into gradational upper cliff/upper lithophysal lithology
Terminations	One C2 fails to cross large C1 and is probably younger, though abutting relationship is not exposed. C1 is probably the oldest set
Miscellaneous Remarks	Some subhorizontal joints occur near the top of outcrop but were not measured. These are very crude, with irregular surfaces.
Summary	Abundant, large, steeply dipping cooling joints at this locality define a single well-expressed set of median N. 38° W. strike. Strike dispersion within this set (C1) is low relative to cooling sets elsewhere, and fully 19 of the 21 readings taken lie within 15° of the median value. These joints are present throughout the exposure and clearly dominate the local fracture network. At high angles to them are additional joints striking N. 31°-55° E., probably members of the complementary (C2) set, here of much subordinate expression. Lesser numbers of other cooling joints of diverse orientation are present also, but it should be noted that their numbers as measured are overrepresented relative to the dominant set. Four joints of nearly N-S strike within one small area at the western end of the exposure hint at the presence of a weak additional set, here labeled C3, but the existence of this set is uncertain at best. Nearly all of the cooling joints in this exposure contain tubular structures as proof of origin. Tectonic joints, if any, are few at this locality and do not form recognizable sets.

Station Number	CCR1
Quadrangle	Topopah Spring NW, 7.5', lat 36°53'02" N., long 116°27'37" W.
Location	NE-facing slope of Azrael Ridge, on the ridge crest
Exposure Description	Station encompasses an area 42 m across slope and 5 m upslope on near-vertical cliff exposure. Exposure is about 50 percent.
Stratigraphic Unit	Tiva Canyon Tuff, caprock zone of Scott and Bonk (1984)
C1	
Median Orientation	N71E/89NW (n=12)
Expression	Moderately poor
Shape	Curviplanar to planar
Roughness	Indet. due to weathering, but smooth; dip changes laterally
Exposed Length	0.5-5 m; true lengths much greater
Exposed Height	0.5-3 m; true heights greater
Structures	None seen. Joint surfaces cut lithophysae
Spacing	Indet.; three joints are spaced 1-2 m apart; common range possibly 0.5-2 m
Mineralization	None seen
Remarks	None
C2	
Median Orientation	N20W/87SW (n=4)
Expression	Poor
Shape	Curviplanar to planar
Roughness	Surfaces weathered, but smooth
Exposed Length	2-3 m (based on four joints); true lengths greater
Exposed Height	0.3-1.3 m (based on four joints); true heights greater
Structures	None seen
Spacing	Indet.; two joints are spaced 1.5 apart
Mineralization	None seen
Remarks	Surfaces cut lithophysae.
CM	
Orientation	N19E/90SE, N30E/89SE
T2	
Median Orientation	N27W/86SW (n=12)
Expression	Well; most prominent set at this locality
Shape	Subplanar, gently curving along strike and dip
Roughness	Surfaces weathered, but appear rough and bumpy
Exposed Length	0.4-2.2 m; true lengths much greater
Exposed Height	0.4-1.4 m; true heights much greater
Structures	None seen
Spacing	Erratic; seven joints present in a 2 m zone are spaced 0.1-1 m apart
Mineralization	None seen
Remarks	None
SH	
Median Orientation	N20W/04NE (n=10)
Expression	Well
Shape	Subplanar to planar
Roughness	Indet. due to weathering; roughness appears variable; some joints in the top 2 m of outcrop are fairly smooth and planar
Exposed Dimension	0.2-6 m; true dimensions greater
Structures	None seen

Station Number	CCR1
Spacing	Commonly as close as 0.1-0.3 m in top 2 m of outcrop; commonly 0.5-1 m in bottom 2 m of outcrop. Spacings get progressively closer up-section
Mineralization	None seen
Remarks	SH set is parallel to the foliation.
Terminations	Several SH abut T2; one SH abuts C2
Summary	Vertical joints with smooth surfaces, interpreted as cooling joints, form two sets at right angles at this locality. Median strikes of the major and minor cooling sets are N. 71° E. and N. 20° W., respectively. Additional vertical joints, but with rough, irregular surfaces quite different in character from those of the associated cooling joints, form a third set nearly coincident in strike (median: N. 27° W.) with the weaker of the two cooling sets. These rough joints correspond in orientation and general style to a tectonic set (T2) common at other localities; here they form by far the most strongly expressed set of the outcrop. No abutting relations among the joints of the three sets were observed. Additional joints (SH) with near-horizontal dips, parallel to the foliation in the tuff, form a fourth set in this exposure. Abutting relations show that this set postdates both the C2 cooling set and the T2 tectonic set. Increasing abundance of the subhorizontal joints toward the top of the exposure suggests that they are a late set formed in response to erosional unloading.

Station Number	CCR2
Quadrangle	Topopah Spring SW, 7.5', lat 36°50'01" N., long 116°28'08" W.
Location	Ridge crest of Yucca Crest, west of road that parallels Yucca Crest, at USGS benchmark No. 1 (1959)
Exposure Description	Steep cliff along west side of ridge, at the ridge crest; station is 20 m long (parallel to road) and 5-7 m high. Unit is 50 percent exposed; many out-of-place talus blocks litter the outcrop. Slope is variable, from 40-60°.
Stratigraphic Unit	Tiva Canyon Tuff, caprock zone of Scott and Bonk (1984)
C1	
Median Orientation	N52E/87SE (n=7)
Expression	Moderate
Shape	Planar to curviplanar, none curving greatly
Roughness	Variable; those with tubular structures are smooth; those without tubes are rough and irregular
Exposed Length	1-6 m; true lengths much greater for some
Exposed Height	0.5-6 m; true heights greater, but possibly not by much
Structures	Some C1 have tubular structures; all C1 cut lithophysae
Spacing	Extremely variable; 1.5-5 m where best expressed; increasing north and south where set disappears
Mineralization	None observed; all surfaces weathered; portions of all C1 surfaces stained black
Remarks	Set is readily defined in the center of station along 15 m of cliff edge where nearly all readings were taken. Set weakens to the north and south where is not recognizable. All C1 seen were measured. Set seems present only in the upper 4-6 m of zone which contains small lithophysae; below in rock with large lithophysae the set is absent.
C2	
Median Orientation	N43W/84SW (n=8)
Expression	Poor to moderate
Shape	Subplanar
Roughness	Variable; fairly smooth to rough
Exposed Length	0.7-4 m; true lengths greater
Exposed Height	0.7-1.8 m; true heights greater, but seemingly not as great as C1
Structures	Tubular structures present on one C2, where tube diameters are substantially smaller than those of C1. All C2 surfaces cut lithophysae
Spacing	Indet.; two C2 are spaced 0.6 m apart; two C2 are spaced 1.5 m apart
Mineralization	None seen;; all surfaces weathered and portions stained black
Remarks	All seen were measured. Set is present only in upper 4-6 m of outcrop, where rock contains small lithophysae; set disappears below as very large lithophysae appear.
C3	
Median Orientation	N24E/11SE (n=13)
Expression	Moderate to moderately well expressed
Shape	Most are nonplanar; some are curviplanar with broad, gently undulating curves
Roughness	Moderately smooth to smooth
Exposed Dimension	Up to 6 m seen; true dimension probably not much greater
Structures	Thin tubular structures; no lithophysal cavities are cut although the rock contains abundant lithophysal cavities
Spacing	Extremely variable; some C3 joints merge with other C3 joints. Observed spacings ranges from almost 0 to 5 m. In one area, several joints are present within a 0.5 m interval
Mineralization	Surfaces are altered to a light orange color

Station Number	CCR2
Remarks	All seen were measured. C3 set is observed also in the upper cliff zone, where it is best expressed. Most C3 joints were measured in the lower part of the caprock unit, where it is gradational with the upper cliff unit. C3 joints are not present in the top 4-6 m of the caprock unit here. C3 is a very tight set (< 1 mm).
CM	
Orientation	N09W/59SW, N13E/70SE, N80E/55NW, N86W/76SW, N76W/78SW, N78E/77SE, N81E/62NW, N80W/72SW
Terminations	C1 and C2 intersect; one C2 abuts C3
Summary	Two sets of steeply dipping cooling joints, with median strikes of N. 52° E. (C1) and N. 43° W. (C2), are present at this locality. Most of the joints in this area are sufficiently weathered that smoothness of fracture surface cannot readily be used to discriminate between tectonic and cooling joints, but the presence of tubular structures on some members of both sets provides ample evidence of their origin. The somewhat variable dips--20° to either side of vertical--appear common among cooling joints in this unit; see also data for stations CCR1 and CCR3.

The C1 and C2 cooling sets are restricted to the upper 4-6 m of the outcrop, where the rock contains abundant lithophysal cavities of small (5-10 cm) dimension. Below this interval, where large (20-40 cm) lithophysal cavities become increasingly abundant and the lithology is transitional to the upper cliff unit, cooling joints with tubular structures are of quite different orientation. No detailed study was made of this transitional lithology, but the few cooling joints (CM) measured in it appear to cluster around E-W and N-S strikes, the latter weakly expressed.

A third set of cooling joints, better expressed than the other two and conspicuous by virtue of its low dip, is present within the lower part of the caprock unit and in the rock below, but is missing from the topmost 4 m of the exposure. These differ from the similarly oriented but younger set of unloading joints discussed for the preceding station in at least four ways: (1) they are broadly curved surfaces that transect foliation at various low angles, in contrast to the nearly planar and foliation-parallel unloading joints; (2) tubular structures on some of their surfaces prove they are cooling joints; (3) they decrease rather than increase in abundance toward the top of the exposure; and (4) none of their surfaces transect lithophysae even though the rock is highly lithophysal, showing that the lithophysae postdate the joints. Probably these are the earliest cooling joints to have cut the rock. Tectonic joints likely are present as well in this exposure but do not form recognizable sets within the area measured. The fracture network of station CCR3 farther north is broadly similar.

Station Number	CCR3
Quadrangle	Topopah Spring SW, 7.5', lat 36°51'25" N., long 116°27'56" W.
Location	Yucca Crest, west side at cliff edge
Exposure Description	Low cliff exposure 6-10 m high and 45 m across slope. Measurements taken across entire cliff face. Cliff faces west and extends to grassy slope beneath. The bottom 2 m of the cliff is gradational to upper cliff unit. Exposure is 70 percent.
Stratigraphic Unit	Tiva Canyon Tuff, caprock zone of Scott and Bonk (1984)

C1

Median Orientation	N40E/84NW (n=16)
Expression	Well; about as well as C2; fairly uniform along length of exposure
Shape	Gently curved along both strike and dip; all curvature is gentle
Roughness	Smooth; rougher where weathered
Exposed Length	0.5-8 m; true lengths unknown
Exposed Height	0.6-9.5 m; true lengths probably 8 m or greater, but many partly covered or eroded; some extend to or near base of outcrop and cut nearly entire outcrop height
Structures	Surfaces cut lithophysae
Spacing	Variable; 1.5-2 m common; up to at least 7 m
Mineralization	No mineral coatings observed; surfaces are stained tan, orange, and black
Remarks	To the north this set rotates clockwise and N65-70E strikes become common (C2 set shows similar rotation in same sense). C1 is interpreted as cooling set on basis of large size, smooth surfaces, and analogy to joints of similar orientation with tubular structures at CCR2, located farther south on Yucca Crest

C2

Median Orientation	N69W/87SW (n=12)
Expression	Well; uniformly expressed along measured length of station
Shape	Curviplanar; most gently curved along lengths of 4 m or greater
Roughness	Smooth, as C1; rougher where weathered; many surfaces are weathered
Exposed Length	1-5.5 m; true lengths greater, possibly twice as great as the longest joints measured
Exposed Height	0.5-7 m; true heights probably close to the largest exposed heights. Some joints are 7 m high and probably most are at least 6 m high, extending from the cliff top to nearly the base of outcrop, but probably do not extend much below into upper cliff zone. Set has a wide range of heights.
Structures	None observed; joint surfaces cut lithophysae
Spacing	Variable; 0.4 m is smallest measured; up to 2 m is common; others up to 4 m
Mineralization	No mineral coatings observed; surfaces weathered; surfaces are stained tan, orange and black
Remarks	To the north the set gradually changes in orientation to more NNW strike; start picking up numerous N45-34W strikes as set gradually turns in the same sense as C1. C2 is interpreted as cooling set based on smoothness, great size, plus the fact that set C2 at CCR2, of same orientation and character, has tubular structures.

CM

Median Orientation	N17W/84SW, N10W/75NE, N26W/88SW, N07W/88SW
Expression	Weak; absent from parts of exposure and only 4 observed, but joints are nearly parallel to cliff edge, so minimal opportunity to observe
Shape	Planar to curviplanar
Roughness	Smooth; same as C1 and C2, but many surface weathered

Station Number	CCR3
Exposed Length	3-13 m; true lengths indeterminate but greater, probably much greater than those observed
Exposed Height	0.9-6 m; true heights possibly much greater than those observed
Structures	Same as C1 and C2
Spacing	Indet.; too few seen, but two are spaced 2.5 m apart
Mineralization	Same as C1 and C2
Remarks	Origin of set uncertain; resembles cooling joints but makes no sense relative to C1 and C2. Other, smaller and crudely formed joints about parallel to this set are present but were not measured because uncertain it is a set and could be either tectonic joints or release joints parallel to cliff edge. Large, smooth CM joints are present along much of cliff from CCR2 to CCR3.

M

Orientation	N80W/50SW, N35W/72SW
Terminations	Three C1 abut CM; one C1 abuts a horizontal joint; C1 abuts C2
Miscellaneous Remarks	C1 and C2 sets here are identical in character and are distinguished on basis of orientation. All major joints of all three sets were measured. The cliff at CCR3 does not extend into the large lithophysal part of the upper cliff zone.
Summary	Abundant, large, steeply dipping joints in this exposure form two well-expressed sets of nearly identical character; median strikes are N. 40° E. (C1) and N. 69° W (C2). Though tubular structures are lacking at this locality--they are of only local development in the caprock unit--both sets are interpreted as cooling joints on the basis of their large size, smooth surfaces (where best protected from weathering), and analogy to known cooling joints of broadly similar orientation at station CCR2 farther south. To the north both sets curve in a clockwise sense and within a distance of less than 50 m from the measured area have common strikes of N. 65-70° E. and N. 35-45° W. Such curvature, here amounting to 25°-30°, appears common among cooling joints but to date is unknown over similarly short distances among the tectonic joints of the region.

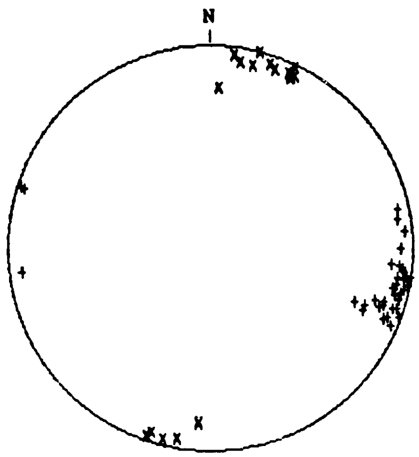
The abundance and moderately wide strike distribution of the cooling joints at this locality obscure recognition of additional sets. Four joints striking N. 7°-26° W. were measured because of their large size, but whether these correspond to T1 or T2 joints, to some mixture of both, or to additional cooling joints cannot be stated with certainty from the meager data available. The large size (exposed lengths of 3-13 m) and smooth surfaces of these joints argue for the latter interpretation, and they are labeled CM accordingly.

Abundant, subhorizontal fractures parallel to foliation cut the tuff at this locality, but were not measured. Many of these resemble the unloading fractures at station CCR1 and are interpreted likewise. Abutting relations, however, show at least one of the low-dipping fractures to predate a vertical cooling joint and suggest that a few subhorizontal cooling joints similar to those at station CCR2 might also be present.

APPENDIX B

STATION TV1, COOLING JOINTS

n = 54

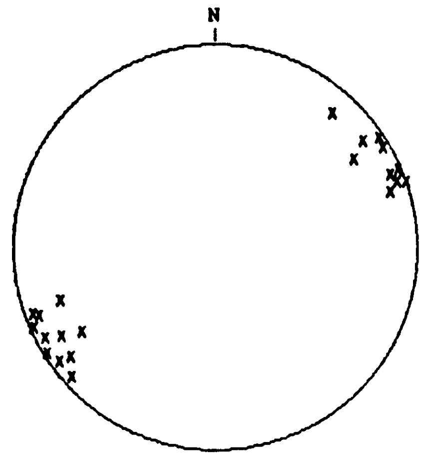


\+ TV1C1 n = 36
x TV1C2 n = 18

Schmidt net, lower hemisphere projection

STATION TV1, TECTONIC JOINTS

n = 21



x TV1T2 n = 21

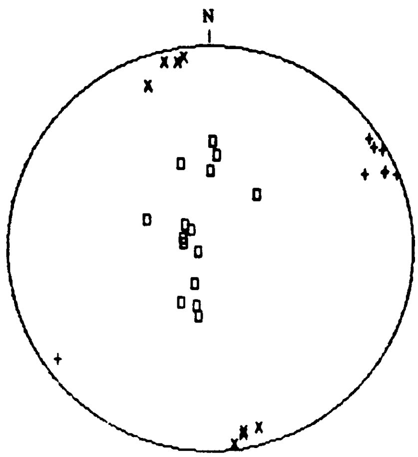
Schmidt net, lower hemisphere projection

TV1C1	C1-cont.	TV1C2
N22E70NW	N20E65NW	N86W75NE
N18E86NW	N22E81NW	N70W83SW
N17E79NW	N15E86NW	N72W85SW
N11E83NW	N18E84NW	N71W88NE
N08E87NW	N11E89NW	N83W85SW
N13E86NW	N20E70NW	N86W76NE
N17E74NW	N00E83NW	N76W87NE
N06E85NW	N20E89NW	N65W88SW
N05E79NW	N23E86NW	N64W84SW
N07E86NW	N21E83NW	N87W68SW
N05E83NW	N18E79NW	N72W85NE
N17E79NW	N09E86NW	N65W82SW
N08E90NW	N12E87NW	N81W82SW
N12E81NW	N18E86SE	N76W90SW
N05W86SW	N18E88SE	N77W82SW
N12W84SW	N09W83SW	N66W84SW
N19E77NW		N65W83SW
N14E83NW		N80W85NE
N07W83NE		
N09E83NW		

TV1T2
N31W86SW
N33W70SW
N18W80SW
N21W83NE
N20W86NE
N23W88SW
N24W88SE
N23W83SW
N20W85SW
N34W87SW
N32W88NE
N36W85NE
N49W77SW
N36W79SW
N37W79NE
N28W85NE
N19W70NE
N32W67NE
N42W85NE
N30W77NE
N19W90SW

STATION TOB1, COOLING JOINTS

n = 31

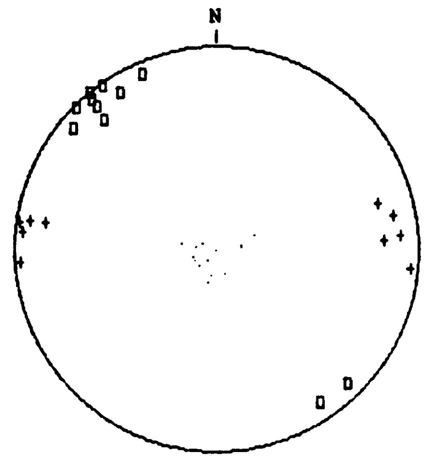


+	TOB1C1	n =	8
x	TOB1C2	n =	8
▫	TOB1C3	n =	15

Schmidt net, lower hemisphere projection

STATION TOB1, TECTONIC JOINTS

n = 35



+	TOB1T1	n =	10
▫	TOB1T3	n =	11
·	TOB1SH	n =	14

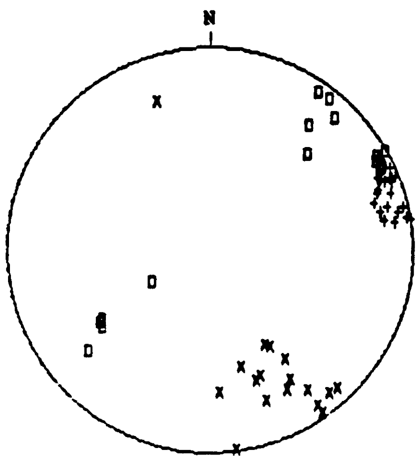
Schmidt net, lower hemisphere projection

TOB1C1	TOB1C2	TOB1C3
N35W85SW	N80E82NW	N80W28NE
N30W88SW	N75E81NW	N61W25NE
N32W85SW	N69E75SE	N76W24NE
N26W74SW	N80E82SE	N71E37SE
N36W82NE	N82E85SE	N90E32SE
N22W89SW	N76E84SE	N89W44SW
N24W83SW	N83E87NW	N86W38SW
N24W84SW	N80E81NW	N24E28SE
		N50W29SW
		N12E11SE
		N12W05NE
		N65W16NE
		N44E11SE
		N21E12SE
		N43E14SE

TOB1T1	TOB1T3	TOB1SH
N05E86SE	N50E86SE	N52W06NE
N08E88SE	N58E80SE	N03W10SW
N09E83SE	N46E82NW	N03E08SE
N03W72SW	N67E84SE	N09E14SE
N04W87NE	N55E88SE	N08W10SW
N16W72SW	N56E80NW	N45W10NE
N04W80SW	N49E74SE	N73E11NW
N06E86NW	N40E82SE	N80W11NE
N09E75SE	N51E90SE	N19W10NE
N11W78SW	N50E82SE	N75W14NE
	N45E88SE	N30W10NE
		N20W16SW
		N17E06SE
		N61W01NE

STATION TOB2, COOLING JOINTS

n = 54

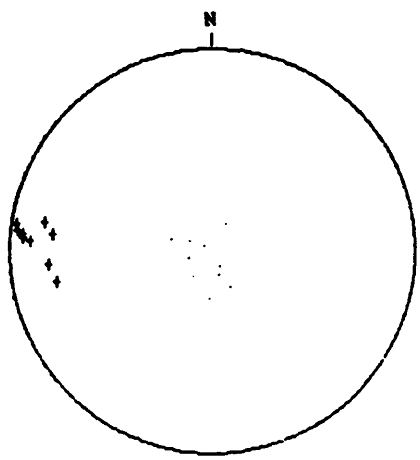


+	TOB2C1	n = 21
x	TOB2C2	n = 17
¤	TOB2C3	n = 16

Schmidt net. lower hemisphere projection

STATION TOB2, TECTONIC JOINTS

n = 19



+	TOB2T1	n = 9
·	TOB2SH	n = 10

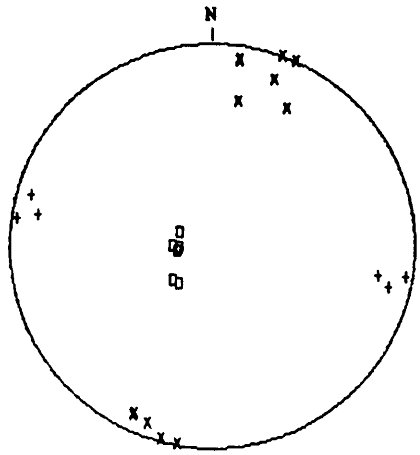
Schmidt net, lower hemisphere projection

TOB2C1	TOB2C2	TOB2C3
N21W85SW	N58E64NW	N36W55NE
N22W85SW	N75E50NW	N34W55NE
N25W87SW	N68E57NW	N33W53NE
N29W84SW	N86E60NW	N29W27NE
N23W80SW	N70E58NW	N40W67NE
N22W86SW	N58E47NW	N52W68SW
N16W73SW	N55E55NW	N52W85SW
N18W83SW	N60E45NW	N56W84SW
N13W75SW	N69E68NW	N47W79SW
N14W79SW	N61E68NW	N45W57SW
N10W76SW	N55E73NW	N26W82SW
N19W76SW	N47E82NW	N27W84SW
N22W88SW	N55E83NW	N26W84SW
N20W77SW	N55E87NW	N30W89SW
N12W84SW	N50E81NW	N29W82SW
N24W79SW	N70E67SE	N30W84SW
N22W82SW	N82E89NW	
N10W88SW		
N09W81SW		
N13W87SW		
N09W90SW		

TOB2T1	TOB2SH
N06E86SE	N30E04SE
N10E73SE	N53W13NE
N04E83SE	N17E17SE
N03E79SE	N63W12SW
N08E87SE	N17W10NE
N05W70NE	N86W19NE
N11W67NE	N66E07NW
N05E83SE	N75E10NW
N06E68SE	N64E16NW
	N23E10SE

STATION TR1, COOLING JOINTS

n = 24

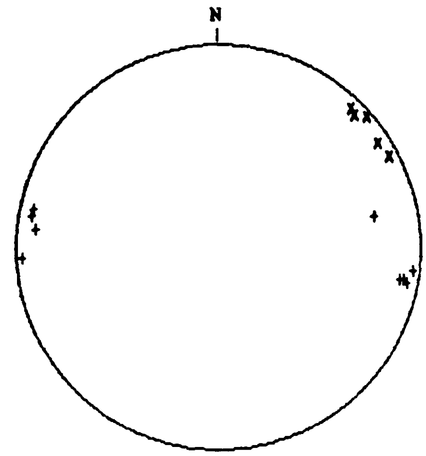


+ TR1C1	n =	6
x TR1C2	n =	12
▪ TR1C3	n =	6

Schmidt net, lower hemisphere projection

STATION TR1, TECTONIC JOINTS

n = 14



+ TR1T1	n =	9
x TR1T2	n =	5

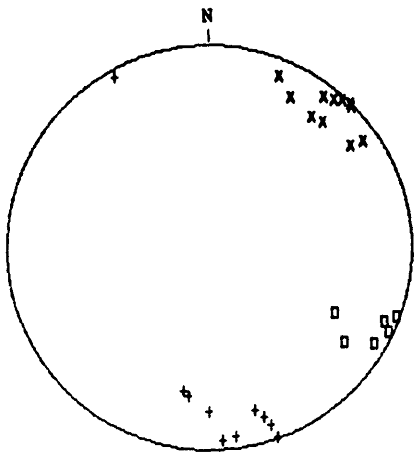
Schmidt net, lower hemisphere projection

TR1C1	TR1C2	TR1C3
N13E78NW	N80W62SW	N22E14SE
N10E76SE	N70W77SW	N01E16SE
N16E82SE	N82W66SW	N06W14NE
N09E86NW	N65W80NE	N48W20NE
N10E72NW	N65W81NE	N04W13NE
N08E87SE	N66W90SW	N41W21NE
	N70W82NE	
	N80W89NE	
	N70W90SW	
	N75W88NE	
	N82W83SW	
	N82W82SW	

TR1T1	TR1T2
N10E83SE	N33W83SW
N07E86NW	N44W83SW
N11E84NW	N46W84SW
N10E82NW	N41W87SW
N12E83SE	N28W85SW
N06E80SE	
N03W87NE	
N10E80NW	
N11W67SW	

STATION TC1, COOLING JOINTS

n = 28

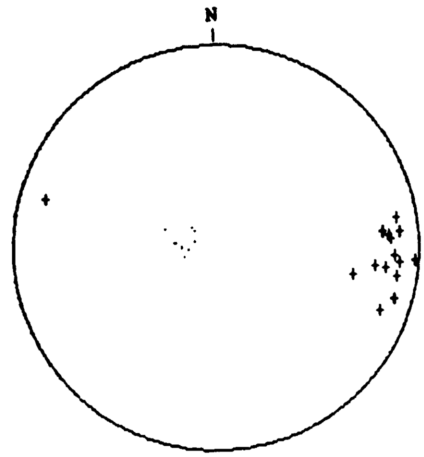


+ TC1C1 n = 10
x TC1C2 n = 12
◻ TC1C3 n = 6

Schmidt net, lower hemisphere projection

STATION TC1, TECTONIC JOINTS

n = 25



+ TC1T1 n = 15
· TC1SH n = 10

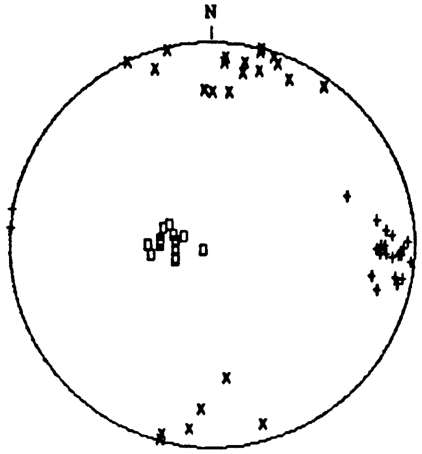
Schmidt net, lower hemisphere projection

TC1C1	TC1C2	TC1C3
N71E82NW	N35W82SW	N30E83NW
N86E85NW	N50W85SW	N25E87NW
N72E77NW	N48W73SW	N20E88NW
N61E86SE	N52W71SW	N27E59NW
N74E72NW	N68W81SW	N23E83NW
N82E84NW	N36W75SW	N35E70NW
N70E89NW	N46W90SW	
N82W63NE	N53W83SW	
N80W61NE	N62W74SW	
N90E70NW	N45W89SW	
	N48W88SW	
	N50W85SW	

TC1T1	TC1SH
N21E75NW	N08E17SE
N05W71SW	N08E16SE
N05W80SW	N39E11SE
N16E80NW	N41E13SE
N07E73NW	N15W13NE
N04E88NW	N01W14NE
N09E79NW	N02W11NE
N05E80NW	N18E09SE
N03W75SW	N21E22SE
N03E77NW	N03E14SE
N09W79SW	
N07E68NW	
N11E58NW	
N04W74SW	
N16E76SE	

STATION TC2, COOLING JOINTS

n = 61

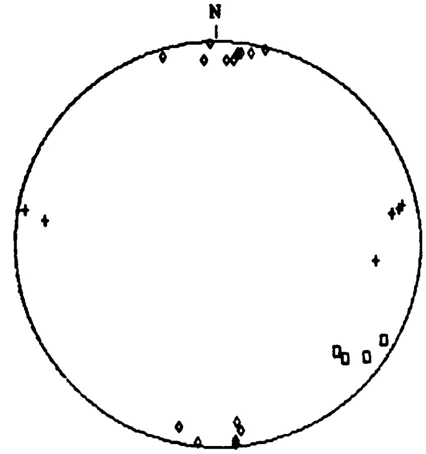


+	TC2C1	n = 24
x	TC2C2	n = 23
▫	TC2C3	n = 14

Schmidt net, lower hemisphere projection

STATION TC2, TECTONIC JOINTS

n = 25



+	TC2T1	n = 6
▫	TC2T3	n = 4
◇	TC2T4	n = 15

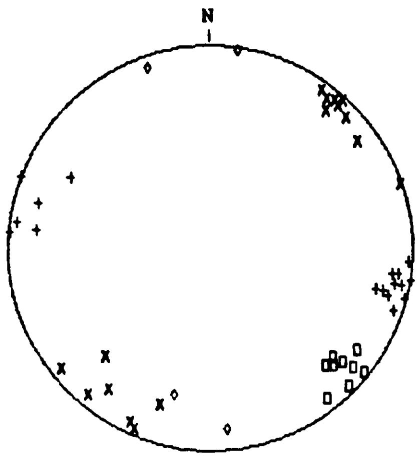
Schmidt net, lower hemisphere projection

TC2C1	TC2C2	TC2C3
N00E74NW	N90E65SE	N00E21SE
N15E73NW	N76W88SW	N21W16NE
N20W60SW	N80W81SW	N04E21SE
N05E88NW	N84W65SW	N05E21SE
N12E83NW	N75W78SW	N15E16SE
N03E83NW	N76W90SW	N22W16NE
N03E72NW	N65W79SW	N09W15NE
N10E81NW	N86W70NE	N26W04NE
N04E78NW	N83W81NE	N06E15SE
N01W86SW	N72W87SW	N26E19SE
N01E84NW	N77E88SE	N09W25NE
N11E69NW	N87E66SE	N15E12SE
N03W78SW	N74E81NW	N20E21SE
N10E85NW	N75W89NE	N00E26SE
N09W71SW	N72E80SE	
N10E90SE	N80W75SW	
N03E81NW	N70W84SW	
N01E70NW	N86W82SW	
N02E82NW	N86W79SW	
N03E75NW	N75W86NE	
N01E74NW	N65E89SW	
N05E90SE	N55W85SW	
N05W75SW	N84E56NW	
N00E72NW		

TC2T1	TC2T3	TC2T4
N12W82SW	N37E81NW	N87W80SW
N10W76SW	N30E84NW	N88E89SE
N06E67NW	N42E68NW	N84E77NW
N08E75SE	N42E73NW	N85E89NW
N11W80SW		N85W80SW
N10E86SE		N83E82NW
		N86E80SE
		N80W85SW
		N83W84SW
		N78W81NE
		N76W89SW
		N74E86SE
		N84W88NE
		N84W84SW
		N85E87NW

STATION TC3, COOLING JOINTS

n = 46

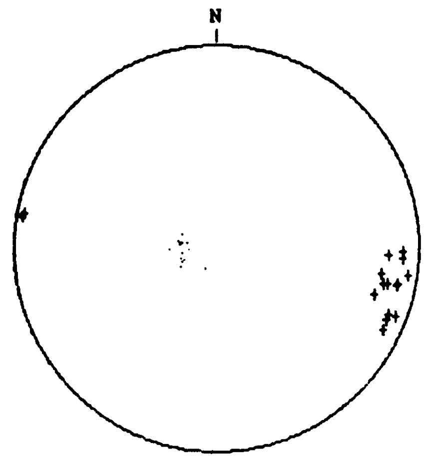


TC3C1	n =	17
TC3C2	n =	16
TC3C3	n =	9
TC3C4	n =	4

Schmidt net, lower hemisphere projection

STATION TC3, TECTONIC JOINTS

n = 31



TC3T1	n =	16
TC3SH	n =	15

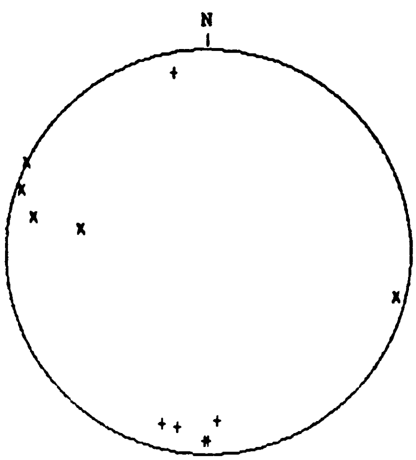
Schmidt net, lower hemisphere projection

TC3C1	TC3C2	TC3C3	TC3C4
N08E80NW	N50W84NE	N44E73NW	N76W64NE
N14E73NW	N39W84NE	N35E77NW	N82W88SW
N08E83NW	N54W75NE	N41E75NW	N85E79NW
N05E89SE	N46W64NE	N39E87NW	N71E84SE
N09E90NW	N36W79SW	N45E86NW	
N15E89NW	N55W85SW	N46E70NW	
N19E85NW	N48W88SW	N42E97NW	
N04E88NW	N52W83SW	N40E81NW	
N21E90SE	N50W85SW	N52E83NW	
N15E80NW	N50W78SW		
N11E82NW	N44W83SW		
N14E77NW	N19W89SW		
N15E77SE	N65W84NE		
N11E86NW	N72W70NE		
N08E86SE	N48W84SW		
N06E75SE	N67W87NE		
N27E66SE			

TC3T1	TC3SH
N12E75NW	N27W16NE
N03E81NW	N20W15NE
N23E80NW	N20W14NE
N26E81NW	N08E14SE
N12E73NW	N09E16SE
N16E70NW	N09W14NE
N21E84NW	N04E15SE
N09E71NW	N05E08SE
N08E85NW	N17W15NE
N10E86SE	N03W19NE
N09E87SE	N09E12SE
N12E80NW	N05W11NE
N02E74NW	N61W09NE
N21E80NW	N21E15SE
N01E81NW	N08E15SE
N11E80NW	

STATION TC4, COOLING JOINTS

n = 11

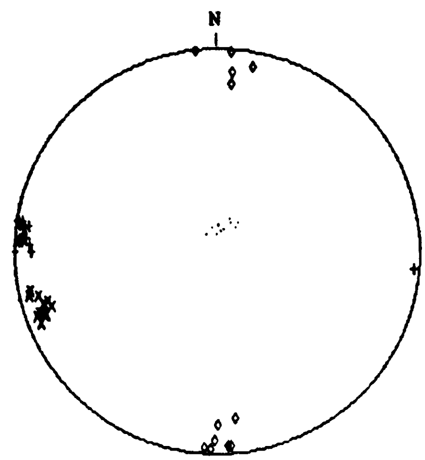


+ TC4C1 n = 6
x TC4C2 n = 5

Schmidt net, lower hemisphere projection

STATION TC4, TECTONIC JOINTS

n = 53



+ TC4T1 n = 15
x TC4T2 n = 14
◊ TC4T4 n = 12
TC4SH n = 12

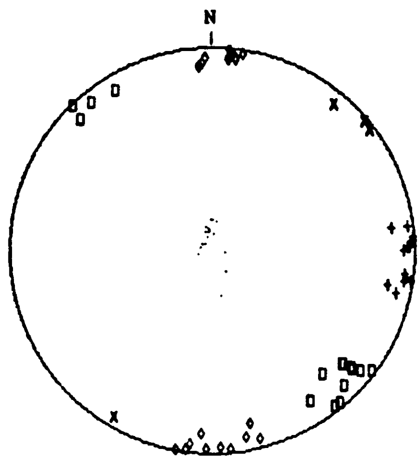
Schmidt net, lower hemisphere projection

TC4C1	TC4C2
N87E72NW	N10E54SE
N80W77NE	N26E90SE
N75W77NE	N18E87SE
N89W83NE	N11E77SE
N79E79SE	N13E85NW
N90E83NW	

TC4T1	TC4T2	TC4T4	TC4SH
N00E90SE	N17W79NE	N88W87NE	N85E07SE
N07E85SE	N17W78NE	N89W83NE	N57E08SE
N04E84SE	N18W75NE	N86E86NW	N78E10SE
N05E86SE	N16W76NE	N87E86NW	N88W10SW
N02E82SE	N20W84NE	N84E72NW	N87W11SW
N08E88SE	N12W84NE	N84E90SE	N74W09SW
N05E87NW	N19W81NE	N85W72SW	N55W14SW
N03E88SE	N19W82NE	N79W82SW	N53W12SW
N02E82SE	N20W79NE	N85W78SW	N88W11SW
N08E83SE	N12W84NE	N86W89SW	N66W13SW
N04E85SE	N20W80NE	N86W87NE	N70W14SW
N09E87SE	N14W80NE	N90E75NW	N80W08SW
N03E86SE	N22W83NE		
N09E89SE	N13W85NE		
N00E81SE			

STATION CC1, TECTONIC JOINTS

n = 70



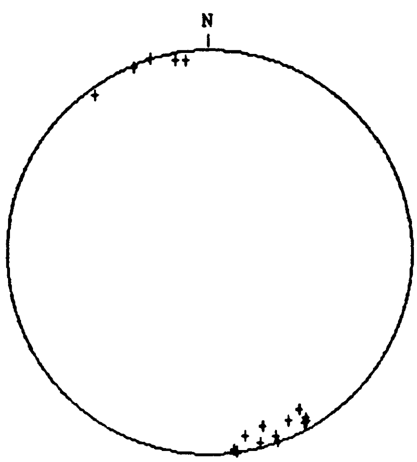
+	CC1T1	n =	14
x	CC1T2	n =	4
▫	CC1T3	n =	15
◇	CC1T4	n =	20
·	CC1SH	n =	17

Schmidt net, lower hemisphere projection

CC1T1	CC1T2	CC1T3	CC1T4	CC1SH
N09E85NW	N50W83SW	N50E87NW	N81W88SW	N86W07SW
N11E77NW	N37W87SW	N45E81SE	N86W79NE	N82W13SW
N01W87SW	N40W88SW	N37E88NW	N87E82SE	N58E10NW
N13E82NW	N59W85NE	N57E77NW	N76E85NW	N36E05SE
N09E85NW		N46E82NW	N85W90SW	N69E06SE
N07W78SW		N41E73NW	N85W86SW	N47E04SE
N01W86SW		N52E87NW	N78E76NW	N76E10SE
N07W87SW		N39E83NW	N88E85SE	N82E08SE
N09E89NW		N40E78NW	N88W87NE	N80E09SE
N00E84NW		N48E70NW	N82W88NE	N70E08SE
N08E86NW		N41E74NW	N83W85NE	N19E05SE
N04W89SW		N51E84SE	N79W89NE	N88W12SW
N07E85NW		N46E89SE	N84W87SW	N78E08SE
N03W89SW		N59E82SE	N85W84SW	N11E05NW
		N40E79NW	N83W85SW	N12W06NE
			N80E82NW	N88E12SE
			N86E80SE	N80E18NW
			N83W84SW	
			N88E86NW	
			N85E88NW	

STATION CH1, COOLING JOINTS

n = 17

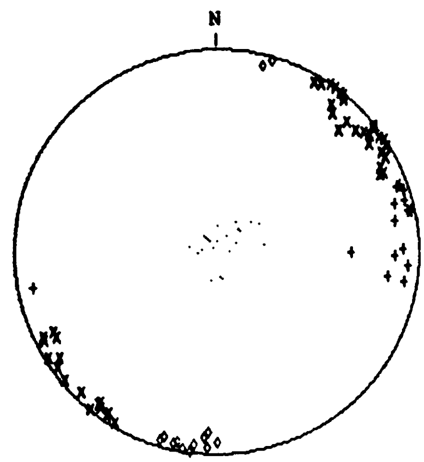


• CH1C1 n = 17

Schmidt net, lower hemisphere projection

STATION CH1, TECTONIC JOINTS

n = 93



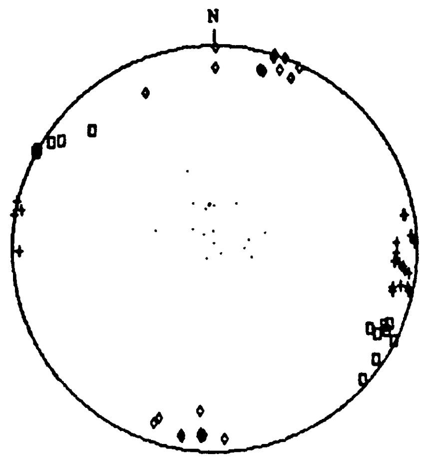
•	CH1T1	n = 16
x	CH1T2B	n = 42
◊	CH1T4	n = 13
·	CH1SH	n = 22

Schmidt net, lower hemisphere projection

CH1C1	CH1T1	CH1T2A	CH1T2B	CH1T4	CH1SH
N70E89NW	N20W86SW	N45W80SW	N25W80SW	N82W89NE	N08W19NW
N65E81NW	N12W86SW	N45W74SW	N26W85NE	N76W84SW	N06E06SE
N68E89SE	N15W80SW	N53W85NE	N38W88SW	N83W85NE	N33E02SE
N75E87NW	N11W82NE	N52W81SW	N39W83SW	N74W84NE	N06W08NE
N82E89NW	N12W88SW	N41W80SW	N25W78SW	N90E84NW	N33W20SW
N70E86NW	N01E77NW	N52W89SW	N28W79NE	N80W88NE	N88W04SW
N61E86NW	N15W86SW	N52W85NE	N39W89SW	N87W78NE	N09E11SE
N80E86SE	N18W87SW	N54W90SW	N32W88NE	N86W81NE	N41W12SW
N79E82NW	N00E56NW	N56W85NE	N27W80SW	N78W85NE	N57W07SW
N73E79NW	N20W84SW	N52W83NE	N26W79NE	N77W86NE	N79E11NW
N83E85SE	N01W81SW	N59W88NE	N39W89SW	N87W87NE	N56E05SE
N60E84NW	N08E74NW	N56W87NE	N36W87NE	N73W86NE	N83E10NW
N73E90SE	N12W88SW	N58W87SW	N32W89SW	N74W88SW	N24W08SW
N60E86NW	N04E84NW	N60W86SW	N31W84SW		N48E08SE
N54E86SE	N10W78SW	N51W89NE	N34W90SW		N58W14SW
N83E88NW	N09E83NW	N46W86NE	N40W88NE		N51E06SE
N60E78NW		N56W90SW	N27W85NE		N03E05NW
		N50W78SW	N29W85SW		N90E10SE
		N51W89SW	N37W84SW		N49E07SE
		N50W87SW	N35W88SW		N41W18SW
			N35W81SW		N78W12NE
			N34W83NE		N46W12SW

STATION CH2, TECTONIC JOINTS

n = 73



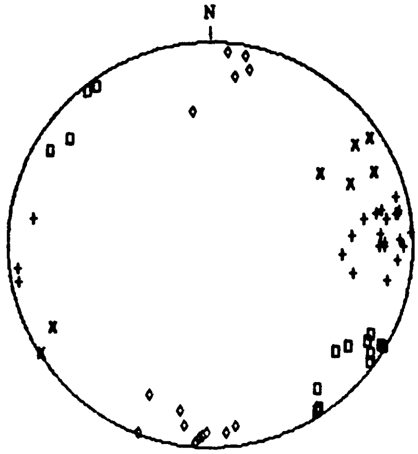
+	CH2T1	n =	20
▫	CH2T3	n =	14
◊	CH2T4	n =	21
·	CH2SH	n =	18

Schmidt net, lower hemisphere projection

CH2T1	CH2T3	CH2T4	CH2SH
N04E81NW	N27E89NW	N76W80SW	N82E07SE
N10W84SW	N41E87NW	N65W88SW	N64E20SE
N06E84NW	N24E81NW	N87E83NW	N75E02SE
N01E79NW	N33E86SE	N85W69NE	N16E25SE
N12E88NW	N27E79NW	N90E89SE	N89E17SE
N02W79SW	N44E73SE	N75W80SW	N48E07SE
N02W89SW	N23E86NW	N80W82NE	N51W05NE
N04W87SW	N23E83NW	N87W81NE	N17W21SW
N01W86NE	N29E90SE	N70W83SW	N40E12SE
N11E83NW	N27E75NW	N73W90SE	N76E16SE
N13E90SE	N34E86NW	N63W88SW	N84E18SE
N10W85SW	N28E90SE	N86W80NE	N12E15NW
N11E87NW	N35E82SE	N90E78SE	N40E03NW
N05E83NW	N25E83NW	N86W82NE	N65W20SW
N09E90SE		N70W90SW	N00E12NW
N12E79NW		N66E73SE	N81E17SE
N04E78NW		N73W88SW	N70E33SE
N11E87SE		N71W80NE	N15W14SW
N13E79NW		N80W83NE	
N07E86NW		N66W81SW	
		N72W77NE	

STATION CH3, TECTONIC JOINTS

n = 61



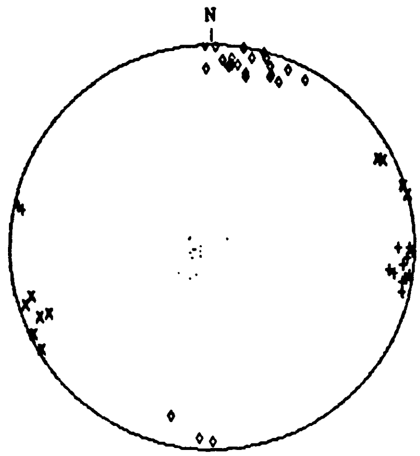
+	CH3T1	n =	23
x	CH3T2	n =	7
▫	CH3T3	n =	15
◊	CH3T4	n =	17

Schmidt net, lower hemisphere projection

CH3T1	CH3T2	CH3T3	CH3T4
N11E61NW	N33W89NE	N56E86NW	N85W85SW
N08E77SE	N33W54SW	N51E87SE	N82E56SE
N04W89SW	N28W77NE	N29E80NW	N68W69NE
N10W82SW	N24W77SW	N40E70NW	N82E79NW
N11E78NW	N34W84SW	N31E80NW	N87W85NE
N12W75SW	N24W64SW	N30E81SE	N82W79NE
N04E82NW	N35W76SW	N53E77NW	N85E82NW
N11W84SW		N54E86SE	N69W89NE
N10W83SW		N34E85NW	N82W73SW
N09W77SW		N57E87NW	N86W88NE
N00E72NW		N36E87NW	N85W85SW
N07W85NE		N37E76SE	N80W72NE
N04W73SW		N36E73NW	N89W82NE
N11W72SW		N30E87NW	N80W84SW
N00E75NW		N30E89NW	N88W84NE
N11W86NE			N78W78SW
N02W83SW			N65W89NE
N15W84SW			
N01W75SW			
N04E55NW			
N00E85NW			
N10W66SW			
N04W59SW			

STATION CH4, TECTONIC JOINTS

n = 62



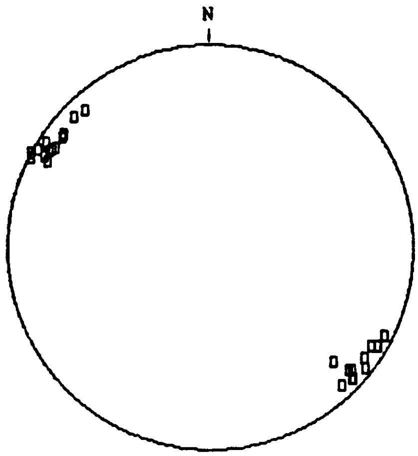
+	CH4T1	n =	15
x	CH4T2	n =	11
◊	CH4T4	n =	23
·	CH4SH	n =	13

Schmidt net, lower hemisphere projection

CH4T1	CH4T2	CH4T4	CH4SH
N00E81NW	N26W88NE	N88E77SE	N35W06NE
N09E87NW	N22W76NE	N78W85SW	N12W05NE
N00E87NW	N18W89SW	N90E85NW	N11W09NE
N05E84NW	N27W84SW	N82W80SW	N06W08NE
N11E85SE	N15W82NE	N87W82SW	N04W07NE
N01E89NW	N28W82SW	N84W83SW	N06E05SE
N10E85NW	N17W86NE	N76W75NE	N32W07SW
N12E88SE	N31W88NE	N81W90SW	N59W13NE
N13E86NW	N27W84SW	N79W76SW	N53W15NE
N09E86NW	N15W90SW	N74W87SW	N36W17NE
N07E77NW	N22W81NE	N85W79SW	N21E10SE
N11E85SE		N86W84NE	N25W09NE
N08E80NW		N75W89SW	N26E10SE
N08E88NW		N71W79SW	
N03E86NW		N84W80SW	
		N61W84SW	
		N72W83SW	
		N89W89SW	
		N67W85SW	
		N79W75SW	
		N68W77SW	
		N88E90SE	
		N71W78SW	

STATION CH5, TECTONIC JOINTS

n = 24



▫ CH5T3 n = 24

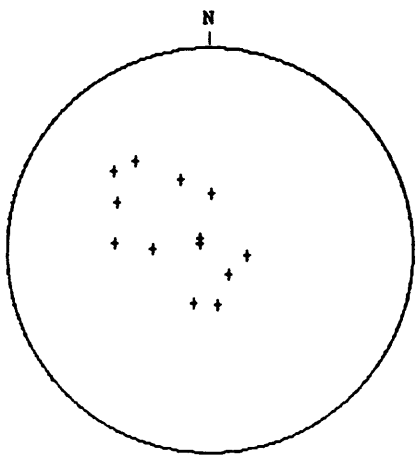
Schmidt net, lower hemisphere projection

CH5T3

N28E80SE
N32E82NW
N38E86NW
N28E90SE
N32E81SE
N31E85NW
N41E81NW
N37E80SE
N31E82SE
N38E81SE
N36E82NW
N47E83NW
N27E89SE
N33E80SE
N43E84NW
N42E80NW
N33E86SE
N30E88SE
N27E85NW
N48E81SE
N29E83SE
N43E71NW
N43E85NW
N44E83SE

STATION CH6, COOLING JOINTS

n = 13

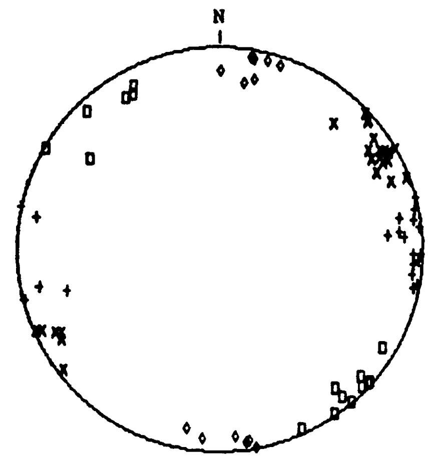


+ CH6C1 n = 13

Schmidt net, lower hemisphere projection

STATION CH6, TECTONIC JOINTS

n = 73



+	CH6T1	n =	20
x	CH6T2	n =	24
□	CH6T3	n =	16
◊	CH6T4	n =	13

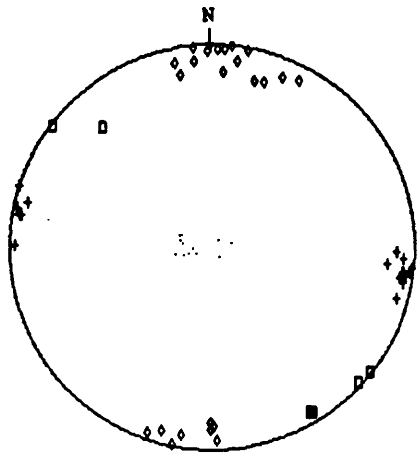
Schmidt net, lower hemisphere projection

CH6C1
N49E06SE
N67E31SE
N33E05SE
N27E43SE
N39E51SE
N50E48SE
N73W22NE
N08E15NW
N04E39SE
N89W23SW
N01E23SE
N83E22NW
N52E12NW

CH6T1	CH6T2	CH6T3	CH6T4
N15W90SW	N26W75SW	N35E67SE	N90E77SE
N12W80NE	N30W86SW	N62E61SE	N61W86SW
N04W80SW	N21W88SW	N30E89SE	N76W86SW
N12W88SW	N25W86NE	N42E83NW	N82W72SW
N10E89NW	N31W76SW	N46E84SE	N82E86NW
N15W67NE	N34W77SW	N49E89NW	N72W85SW
N03E88NW	N24W89NE	N50E78NW	N81E85NW
N01E85NW	N30W79NE	N50E84NW	N85W83NE
N10E81SE	N38W87NE	N58E77SE	N79E89NW
N09W86SW	N43W88SW	N42E88NW	N79W75SW
N04E85NW	N28W77NE	N44E87NW	N85E82NW
N10W79SW	N28W80SW	N65E87NW	N80W85SW
N06W78SW	N36W83SW	N61E77SE	N80W79NE
N07E85NW	N28W83SW	N41E88NW	
N15W89NE	N41W86SW	N31E83NW	
N07W89SW	N32W82SW	N55E89NW	
N11E87NW	N41W87SW		
N05W72SW	N30W90SW		
N01E89NW	N48W73SW		
N12E90SE	N30W80SW		
	N22W80SW		
	N31W83SW		
	N27W80NE		
	N31W84SW		

STATION CH7, TECTONIC JOINTS

n = 62



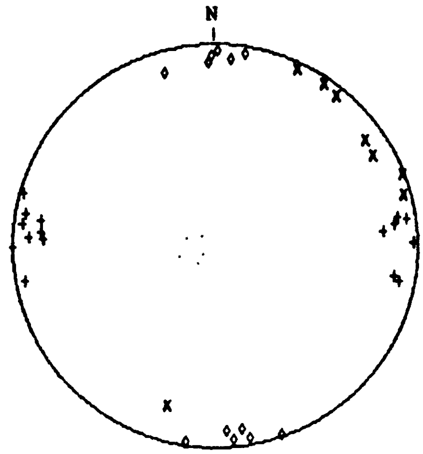
+	CH7T1	n =	19
▫	CH7T3	n =	6
◊	CH7T4	n =	24
·	CH7SH	n =	12

Schmidt net, lower hemisphere projection

CH7T1	CH7T3	CH7T4	CH7SH
N08E85NW	N46E69SE		N08E12SE
N02E80NW	N36E89SE	N89W79NE	N17W12NE
N06E76NW	N43E88NW	N86W76SW	N11W15NE
N01E87SE	N39E89NW	N72W74SW	N20E14SE
N08E88NW	N59E85NW	N89E86SE	N17W10NE
N08E84NW	N60E84NW	N79W88SW	N50W04SW
N18E90SE		N90E77NW	N21E13SE
N10E83NW		N82W82SW	N07W08NE
N04E84NW		N74W83NE	N22W07NE
N12E88SE		N89E85NW	N11W08SW
N11E85NW		N85E89SE	N12E13SE
N10E85SE		N89W76NE	N56E05NW
N10E83NW		N67W80SW	
N14E83SE		N80E75SE	
N09E86NW		N70W86NE	
N09E84NW		N78W89NE	
N10E86SE		N62W82SW	
N16E84NW		N85E81SE	
N07E89NW		N79E82SE	
		N90E90SE	
		N80W83NE	
		N88W87SW	
		N84W90SW	
		N86W88SW	
		N75W73SW	

STATION CH8, TECTONIC JOINTS

n = 41



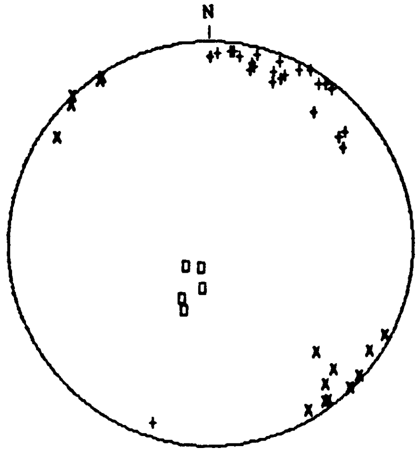
+	CH8T1	n =	16
x	CH8T2	n =	8
◇	CH8T4	n =	12
·	CH8SH	n =	5

Schmidt net, lower hemisphere projection

CH8T1	CH8T2	CH8T4	CH8SH
N16E88SE	N35W80SW	N74E78SE	N17E12SE
N03E81SE	N21W89SW	N89W86SW	N45W10NE
N10E78NW	N30W79SW	N87E81NW	N17W15NE
N10W85NE	N73W72NE	N85W82SW	N38W06NE
N10E84SE	N51W85SW	N82E81NW	N38E07SE
N01W88SW	N56W86SW	N81W86SW	
N03E74SE	N65W86SW	N88E80SE	
N00E90SE	N15W86SW	N85E86NW	
N09W80SW		N81W88NE	
N08W85SW		N71E89NW	
N07E85SE		N89E84SE	
N05W72SW		N80E86NW	
N07W78SW			
N09E76SE			
N11E81NW			
N05E75SE			

STATION CH9, COOLING JOINTS

n = 44

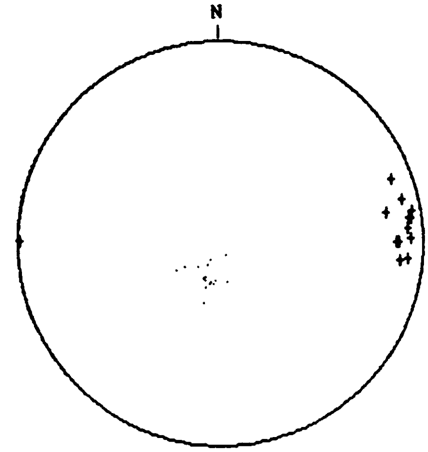


+ CH9C1 n = 24
x CH9C2 n = 15
□ CH9C3 n = 5

Schmidt net, lower hemisphere projection

STATION CH9, TECTONIC JOINTS

n = 29



+ CH9T1 n = 13
· CH9SH n = 16

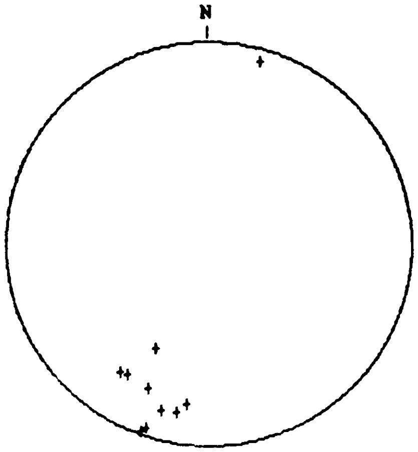
Schmidt net, lower hemisphere projection

CH9C1	CH9C2	CH9C3
N36W70SW	N53E86NW	N63W25NE
N63W86SW	N45E87SE	N42W13NE
N90E82SE	N54E86NW	N69W10NE
N52W72SW	N46E76NW	N68W29NE
N56W85SW	N47E90SE	N79W18NE
N40W72SW	N56E87SE	
N67W78SW	N46E64NW	
N88W84SW	N42E88NW	
N72W82NE	N28E87NW	
N40W76SW	N51E79NW	
N52W87SW	N46E89NW	
N84W85SW	N57E88SE	
N70W80SW	N60E85NW	
N76W79SW	N35E82SE	
N83W85SW	N34E84NW	
N54W87SW		
N77W77SW		
N69W75SW		
N76W86SW		
N77W81SW		
N81W83SW		
N69W86SW		
N60W89SW		
N66W80SW		

CH9T1	CH9SH
N00E77NW	N64W16NE
N05E82NW	N58W08NE
N20W79SW	N80W17NE
N01W83SW	N67E05NW
N07W84SW	N47W13NE
N04W82SW	N33W17NE
N07W83SW	N82W15NE
N13W81SW	N74W25NE
N01E89SE	N81E16NW
N10W72SW	N68W16NE
N06E78NW	N65W15NE
N09W85SW	N74W17NE
N00E76NW	N75W16NE
	N32W21NE
	N71W19NE
	N59W10NE

STATION CLL1, COOLING JOINTS

n = 10

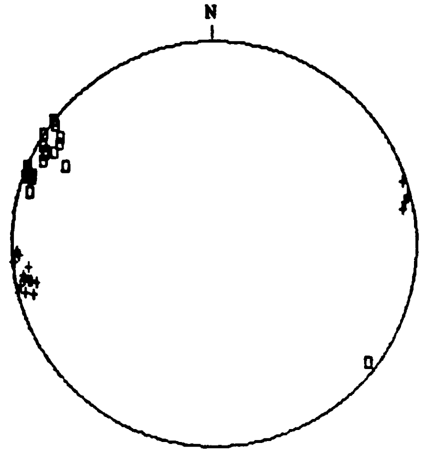


+ CLL1C1 n = 10

Schmidt net, lower hemisphere projection

STATION CLL1, TECTONIC JOINTS

n = 36



+ CLL1T1 n = 17
▫ CLL1T3 n = 19

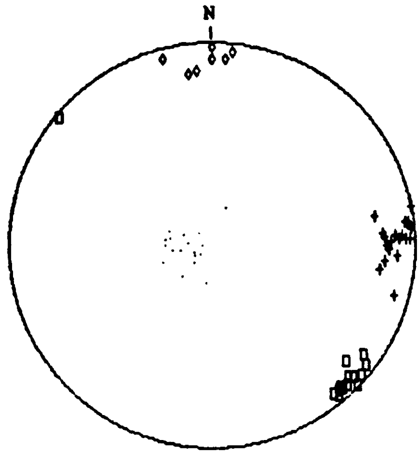
Schmidt net, lower hemisphere projection

CLL1C1
N71W86NE
N82W69NE
N79W74NE
N67W67NE
N58W65NE
N74W83SW
N63W48NE
N74W75NE
N55W66NE
N70W88NE

CLL1T1	CLL1T3
N10W85NE	N20E89SE
N12W88NE	N23E90SE
N14W89SW	N30E87SE
N09W85NE	N38E85NW
N11W82NE	N37E88SE
N15W82NE	N35E82SE
N12W86SW	N29E84SE
N18W88SW	N28E84SE
N11W83NE	N16E84SE
N12W79NE	N21E85SE
N07W82NE	N21E87SE
N14W86NE	N30E80SE
N02W87NE	N33E80SE
N03W86NE	N26E83SE
N10W84SW	N38E90SE
N05W89NE	N21E85SE
N11W81NE	N33E90SE
	N28E72SE
	N20E85SE

STATION CKS1, TECTONIC JOINTS

n = 60



+ CKS1T1	n =	19
▫ CKS1T3	n =	15
◊ CKS1T4	n =	7
· CKS1SH	n =	19

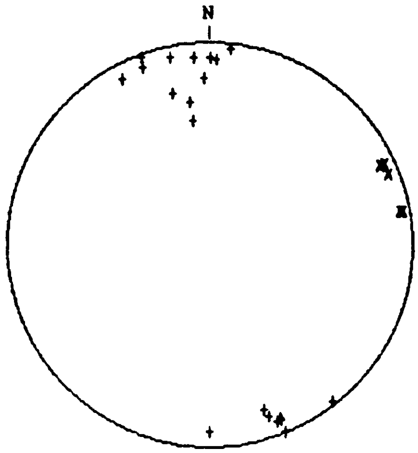
Schmidt net, lower hemisphere projection

CKS1T1	CKS1T3	CKS1T4	CKS1SH
N02W85SW	N43E85NW	N85E75SE	N32W06NE
N03W74SW	N48E85NW	N84W85SW	N32W08NE
N01E76NW	N41E76NW	N82E74SE	N01W19NE
N11W90SW	N41E87NW	N86W81SW	N70W16SW
N05W88SW	N51E84NW	N90E87SE	N10E17SE
N15E82NW	N44E82NW	N75E84SE	N01W04NE
N03E80NW	N50E86NW	N90E81SE	N20W21NE
N03W83SW	N48E83NW	*N86W	N80W15NE
N01W77SW	N43E84NW		N41W10NE
N07W85SW	N44E89NW		N03E10SE
N02W81SW	N49E84NW		N07W16NE
N03W79SW	N36E81NW		N43W10NE
N02W87SW	N46E85NW		N20E12SE
N08E72NW	N40E88SE		N41E07SE
N04W73SW	N38E85NW		N45W17NE
N10W70SW			N08W13NE
N05E74NW			N06E19SE
N00E75NW			N17E18SE
N07W87SW			N21W08NE

*dip not obtainable, orientation not plotted

STATION CKS2, COOLING JOINTS

n = 26

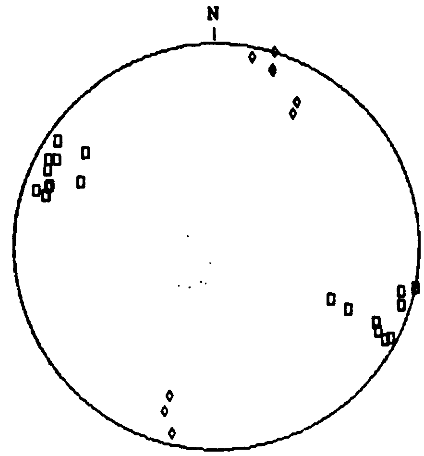


+ CKS2C1 n = 21
x CKS2C2 n = 5

Schmidt net, lower hemisphere projection

STATION CKS2, TECTONIC JOINTS

n = 34



□ CKS2T3 n = 19
◇ CKS2T4 n = 9
· CKS2SH n = 6

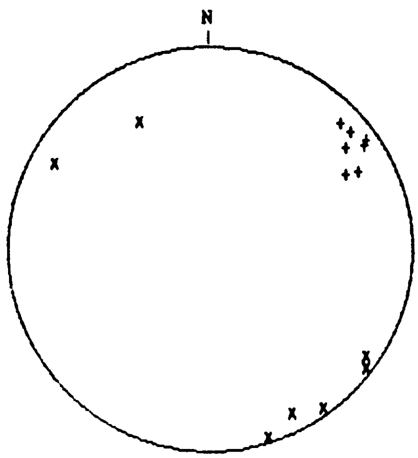
Schmidt net, lower hemisphere projection

CKS2C1	CKS2C2
N82E52SE	N25W84SW
N78E84SE	N22W84SW
N62E82SE	N25W82SW
N68E83NW	N10W85SW
N68E82NW	N10W86SW
N52E88NW	
N72E75NW	
N71E79NW	
N82E61SE	
N90E82SE	
N70E88SE	
N69E83SE	
N85E82SE	
N90E82NW	
N82E61SE	
N88W81SW	
N84W87SW	
N88E71SE	
N68E90NW	
N76E66SE	
N69E83NW	

CKS2T3	CKS2T4	CKS2SH
N14E83NW	N60W65SW	N70W07NE
N18E83SE	N76W84NE	N73W16NE
N29E84NW	N61W71SW	N56W20NE
N20E77SE	N72W74NE	N20E12SE
N36E69SE	N72W66NE	N46W22NE
N29E79SE	N72W80SW	N66W16NE
N25E81SE	N79W85SW	
N28E86NW	N72W81SW	
N21E77SE	N73W90SW	
N26E64SE		
N34E84SE		
N28E83SE		
N26E76NW		
N18E85NW		
N17E77SE		
N28E79NW		
N25E52NW		
N12E90NW		
N26E61NW		

STATION CKS3, COOLING JOINTS

n = 14

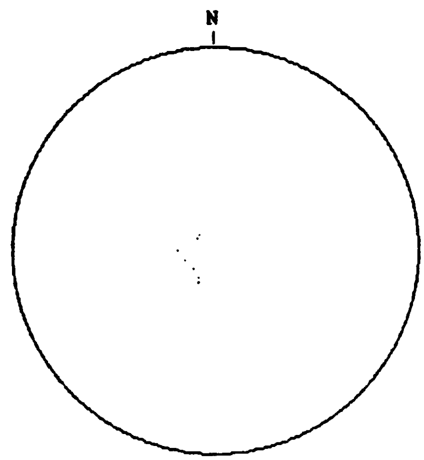


+ CKS3C1 n = 7
x CKS3C2 n = 7

Schmidt net, lower hemisphere projection

STATION CKS3, TECTONIC JOINTS

n = 7



· CKS3SH n = 7

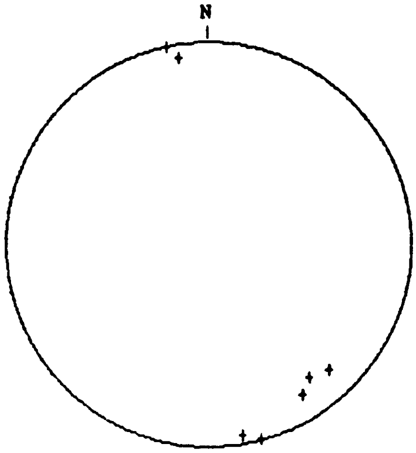
Schmidt net, lower hemisphere projection

CKS3C1	CKS3C2
N44W79SW	N38E87NW
N35W84SW	N73E87NW
N37W73SW	N55E86NW
N29W66SW	N35E83NW
N28W72SW	N29E77SE
N34W81SW	N64E80NW
N40W80SW	N61E61SE

CKS3SH
N62W15NE
N18W13NE
N00E15SE
N40W12NE
N34E09SE
N42E09SE
N57W13NE

STATION CKS4, COOLING JOINTS

n = 7

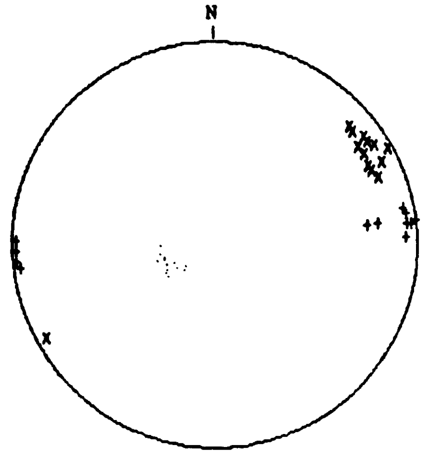


+ CKS4C1 n = 7

Schmidt net, lower hemisphere projection

STATION CKS4, TECTONIC JOINTS

n = 38



+ CKS4T1 n = 12
x CKS4T2 n = 13
· CKS4SH n = 13

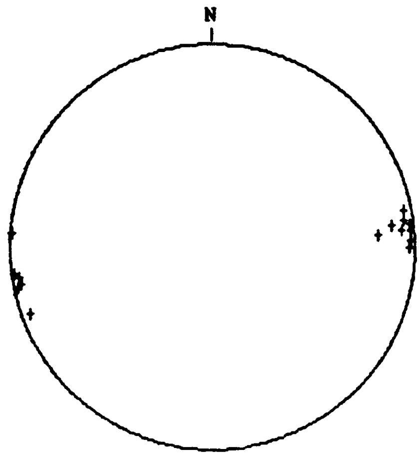
Schmidt net, lower hemisphere projection

CKS4C1
N78E90SE
N58E76NW
N53E71NW
N46E75NW
N81E83SE
N80E85NW
N75E89NW

CKS4T1	CKS4T2	CKS4SH
N07W70SW	N36W80SW	N35W23NE
N11W84SW	N34W80SW	N16W21NE
N07W65SW	N26W81SW	N17W24NE
N09W85SW	N31W75SW	N40W16NE
N02W88NE	N34W74SW	N24W18NE
N02W84SW	N32W82SW	N18W21NE
N07W90SW	N29W87SW	N23W21NE
N06W85SW	N39W77SW	N02W22NE
N01E88SE	N29W85NE	N28W22NE
N07W86NE	N27W74SW	N30W23NE
N06W87SW	N41W77SW	N10W22NE
N05W88NE	N25W74SW	N37W15NE
	N22W76SW	N33W18NE

STATION CRS4, TECTONIC JOINTS

n = 15



+ CRS4T1 n = 15

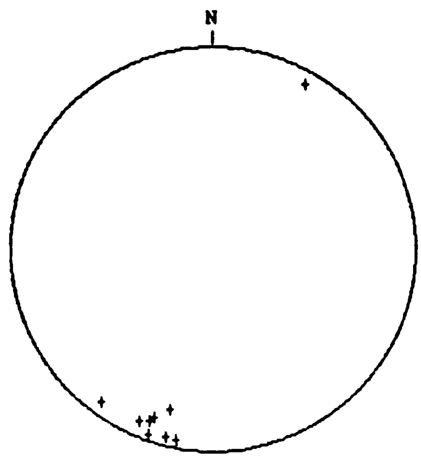
Schmidt net, lower hemisphere projection

CRS4T1

N05W88SW
N04W71SW
N05W83SW
N02W88SW
N08W89NE
N07W88SW
N11W86SW
N20W85NE
N12W88NE
N08W85SW
N11W86NE
N00E87NW
N04E89SE
N07W78SW
N09W86NE

STATION CRS5, COOLING JOINTS

n = 9



+ CRS5C1 n = 9

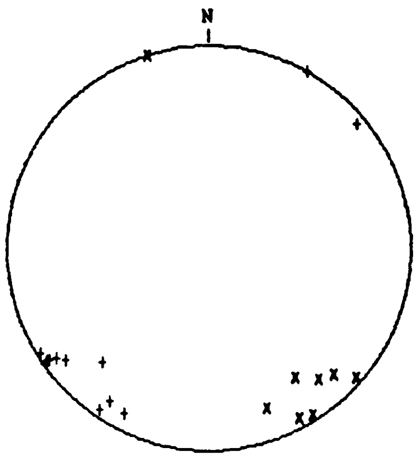
Schmidt net, lower hemisphere projection

CRS5C1

N70W80NE
N71W77NE
N54W83NE
N79W86NE
N75W71NE
N71W87NE
N76W85NE
N61W83SW
N67W82NE

STATION CRS6, COOLING JOINTS

n = 20

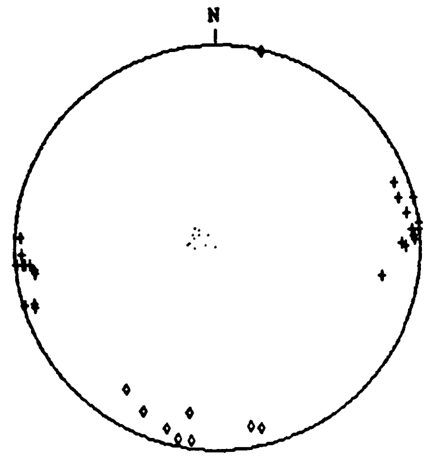


+ CRS6C1 n = 12
x CRS6C2 n = 8

Schmidt net, lower hemisphere projection

STATION CRS6, TECTONIC JOINTS

n = 43



+ CRS6T1 n = 23
◇ CRS6T4 n = 9
· CRS6SH n = 11

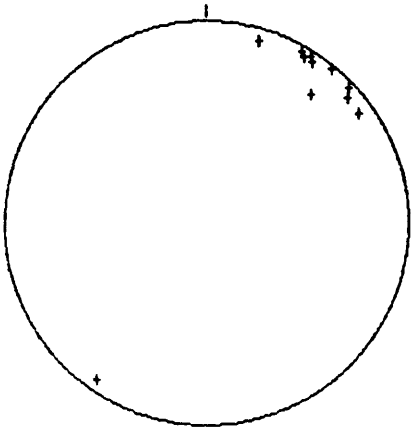
Schmidt net, lower hemisphere projection

CRS6C1	CRS6C2
N35W87NE	N70E73NW
N63W81NE	N56E66NW
N56W86NE	N50E74NW
N35W86NE	N45E77NW
N47W66NE	N62E65NW
N36W82NE	N58E87NW
N61W90SW	N41E87NW
N57W79NE	N72E90SE
N38W79NE	
N35W88NE	
N32W88NE	
N40W65SW	

CRS6T1	CRS6T4	CRS6SH
N05W86SW	N77E81NW	N06W09NE
N14W82SW	N80W72NE	N02E01SE
N10W84SW	N62W66NE	N33E09SE
N02W87SW	N80E79NW	N50E06SE
N05W90SW	N77W69SW	N40E12SE
N03W87SW	N57W72NE	N21E10SE
N08W80NE	N65W78NE	N27E11SE
N01W80SW	N74W82NE	N10E05SE
N05W85NE	N76W86NE	N06E11SE
N18W64NE		N41E10SE
N20W82SW		N02E12SE
N07W80NE		
N10E71NW		
N00E82NW		
N07W90SW		
N05W86NE		
N02W86NE		
N05W82NE		
N14W90SW		
N17W89NE		
N17W84NE		
N05W89NE		
N03E87SE		

STATION CRS7, COOLING JOINTS

n = 11

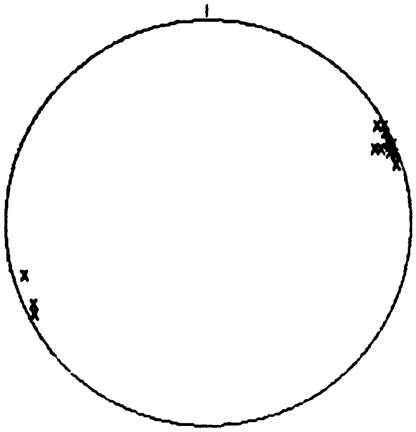


+ CRS7C1 n = 11

Schmidt net, lower hemisphere projection

STATION CRS7, TECTONIC JOINTS

n = 14



x CRS7T2 n = 14

Schmidt net, lower hemisphere projection

CRS7C1

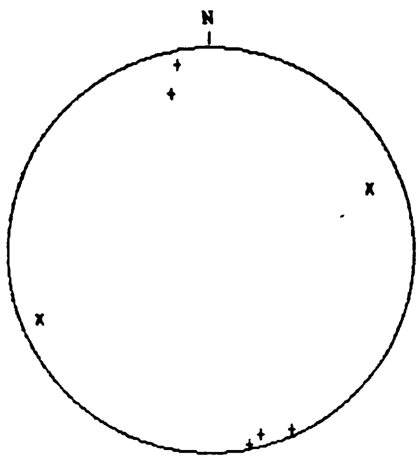
N51W71SW
N36W82SW
N51W88SW
N74W83SW
N55W84NE
N57W85SW
N44W87SW
N42W83SW
N58W87SW
N60W85SW
N61W87SW

CRS7T2

N23W82SW
N16W84NE
N23W89SW
N24W87SW
N25W85NE
N17W87SW
N21W86SW
N23W87SW
N30W86SW
N28W87NE
N29W89SW
N24W79SW
N20W88SW
N27W88SW

STATION CUL1, COOLING JOINTS

n = 7

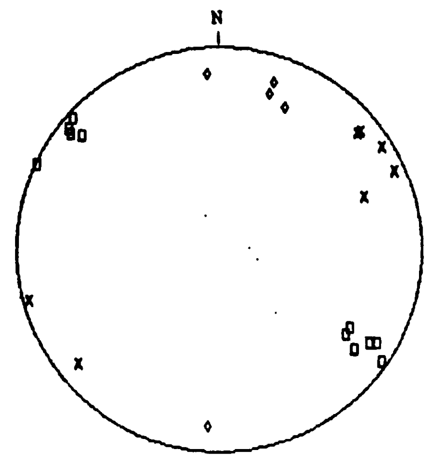


+	CUL1C1	n =	5
x	CUL1C2	n =	2

Schmidt net, lower hemisphere projection

STATION CUL1, TECTONIC JOINTS

n = 27



x	CUL1T2	n =	7
□	CUL1T3	n =	11
◊	CUL1T4	n =	5
·	CUL1SH	n =	4

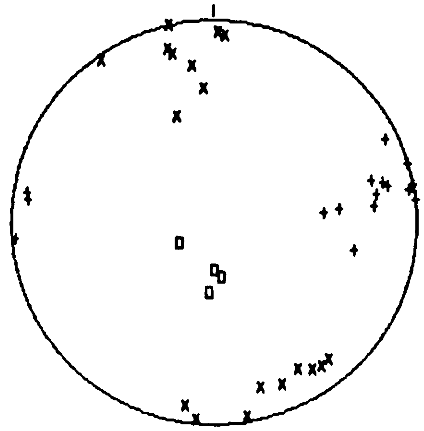
Schmidt net, lower hemisphere projection

CUL1C1	CUL1C2
N76E69SE	N22W80NE
N75E83NW	N21W73SW
N79E87NW	
N66E86NW	
N80E82SE	

CUL1T2	CUL1T3	CUL1T4	CUL1SH
N40W78SW	N25E89SE	N86W77NE	N68E15SE
N39W79NE	N31E79NW	N72W69SW	N04W12SW
N40W80SW	N38E82SE	N65W66SW	N16E16NW
N32W84SW	N40E77SE	N72W76SW	N48E34NW
N24W84SW	N42E87SE	N86E76SE	
N15W87NE	N39E85SE		
N20W65SW	N34E64NW		
	N31E64NW		
	N32E76NW		
	N37E72NW		
	N35E87NW		

STATION CUL2, COOLING JOINTS

n = 39



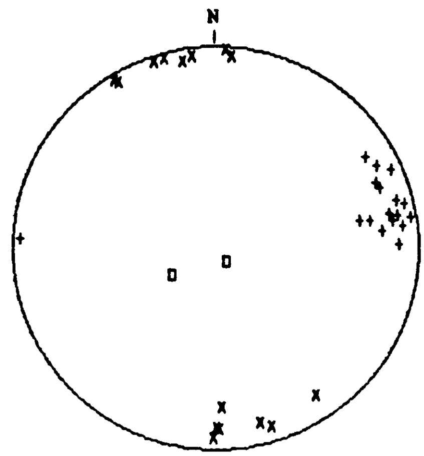
+	CUL2C1	n =	17
x	CUL2C2	n =	18
□	CUL2C3	n =	4

Schmidt net, lower hemisphere projection

CUL2C1	CUL2C2	CUL2C3
N10W87SW	N67E76NW	N82E22NW
N06W52SW	N80E87NW	N86W28NE
N05W45SW	N82E67SE	N30W16NE
N06W68SW	N76E75SE	N90E19NW
N15W69SW	N75E78SE	
N26W83SW	N53E77NW	
N11W89SW	N56E76NW	
N11W90SW	N85W88NE	
N09E83SE	N81W81NE	
N07E82SE	N89W84SW	
N12W76SW	N74E74NW	
N14W74SW	N70E46SE	
N17W90SW	N87W82SW	
N05W88NE	N77E90SE	
N10W70SW	N60E72NW	
N07W90SW	N50E77NW	
N11E60NW	N55E87SE	
	N85E56SE	

STATION CUL3, COOLING JOINTS

n = 34



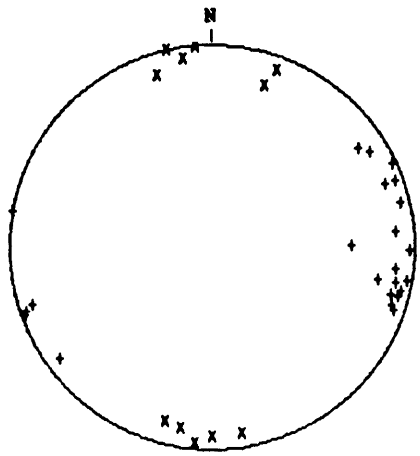
\+ CUL3C1 n = 17
x CUL3C2 n = 15
o CUL3C3 n = 2

Schmidt net, lower hemisphere projection

CUL3C1	CUL3C2	CUL3C3
N31W75SW	N72E87SE	N32W21NE
N20W75SW	N88E68NW	N55E07NW
N24W84SW	N80E83SE	
N15W81SW	N76E78NW	
N06W71SW	N89E79NW	
N09W87SW	N73E82NW	
N11W76SW	N56E77NW	
N13W85SW	N83E85SE	
N03E86SE	N75E87SE	
N10W66SW	N59E87SE	
N07W82SW	N87W88SW	
N01W79SW	N89W84NE	
N22W74SW	N85W85SW	
N09W77SW	N60E85SE	
N11W61SW	N90E78NW	
N27W78SW		
N10W80SW		

STATION CUL4, COOLING JOINTS

n = 34



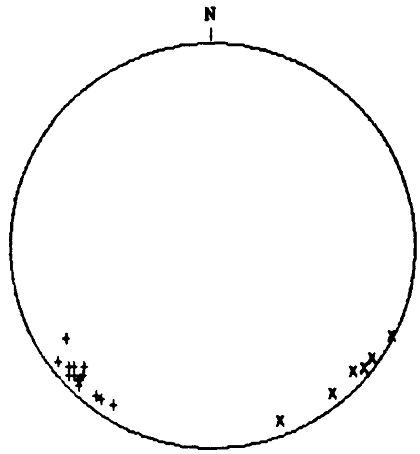
\+ CUL4C1 n = 23
x CUL4C2 n = 11

Schmidt net, lower hemisphere projection

CUL4C1	CUL4C2
N36W82NE	N90E83NW
N34W76SW	N81E82NW
N31W80SW	N80W80NE
N25W88SW	N77E90SE
N10E87NW	N75W78NE
N15E84NW	N85E90SE
N10E90SE	N85W87NE
N01E87NW	N81E84SE
N13E85NW	N72E78SE
N11E81NW	N70W82SW
N19E84NW	N72W73SW
N15E80NW	
N18E82NW	
N07E80NW	
N11E72NW	
N19W87NE	
N20W88NE	
N13W85SW	
N01W58SW	
N05W80SW	
N18W83NE	
N20W86SW	
N20W80SW	

STATION CUL5, COOLING JOINTS

n = 21

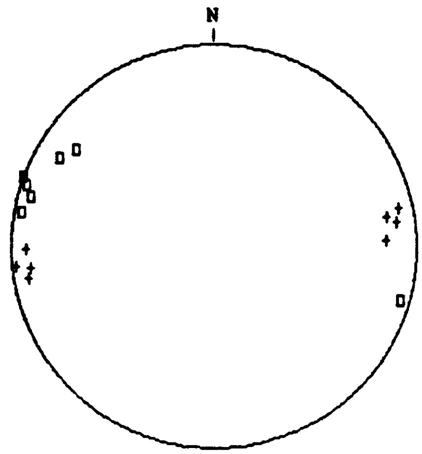


+ CUL5C1 n = 15
x CUL5C2 n = 6

Schmidt net, lower hemisphere projection

STATION CUL5, TECTONIC JOINTS

n = 16



+ CUL5T1 n = 9
□ CUL5T3 n = 7

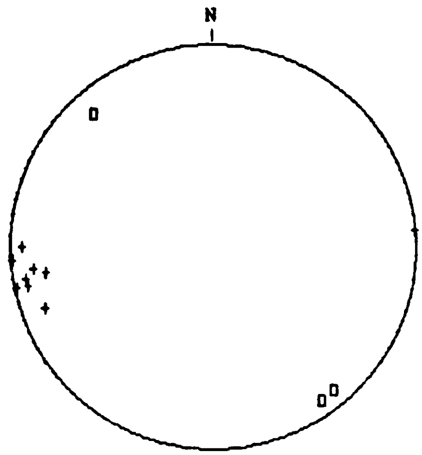
Schmidt net, lower hemisphere projection

CUL5C1	CUL5C2
N43W76NE	N69E82NW
N37W85NE	N51E83NW
N41W80NE	N42E82NW
N43W83NE	N35E86NW
N45W84NE	N39E86NW
N45W83NE	N27E89NW
N52W83NE	
N58W82NE	
N54W83NE	
N32W74NE	
N40W82NE	
N42W85NE	
N46W85NE	
N45W82NE	
N45W80NE	

CUL5T1	CUL5T3
N10W82NE	N18E87SE
N01W82NE	N30E77SE
N01W82NE	N35E72SE
N07W80NE	N16E85NW
N10W75SW	N15E83SE
N02W74SW	N10E86SE
N08W80SW	N20E90SE
N12W82SW	
N06W88NE	

STATION CUL6, TECTONIC JOINTS

n = 12



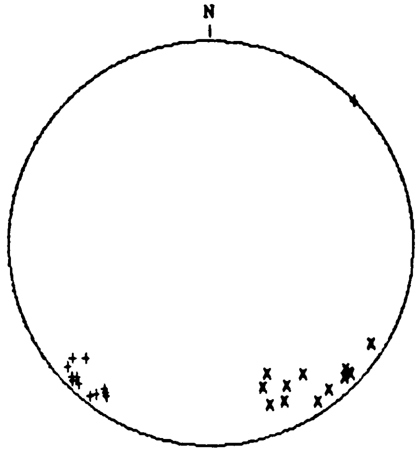
+ CUL6T1 n = 9
□ CUL6T3 n = 3

Schmidt net, lower hemisphere projection

CUL6T1	CUL6T3
N05W90SW	N50E81NW
N07W78NE	N55E82NW
N04W89NE	N48E77SE
N12W83NE	
N09W72NE	
N20W77NE	
N12W89NE	
N10W83NE	
N00E84SE	

STATION CUL7, COOLING JOINTS

n = 27

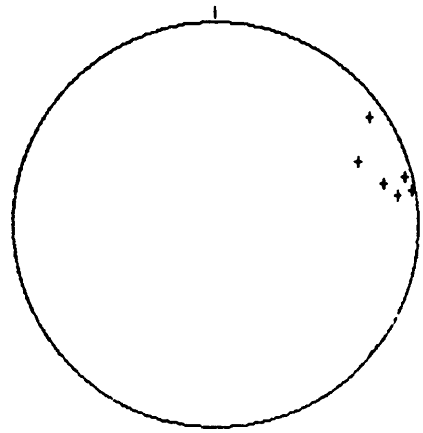


+ CUL7C1 n = 13
x CUL7C2 n = 13

Schmidt net, lower hemisphere projection

STATION CUL7, TECTONIC JOINTS

n = 6



+ CUL7T n = 6

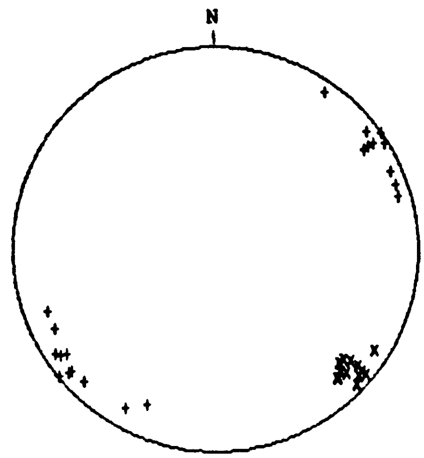
Schmidt net, lower hemisphere projection

CUL7C1	CUL7C2
N55W80NE	N45E83NW
N45W83NE	N43E83NW
N45W86NE	N56E84NW
N52W86NE	N65E75NW
N45W90SW	N70E74NW
N54W78NE	N51E82NW
N41W83NE	N62E69NW
N47W85NE	N67E60NW
N56W81NE	N70E65NW
N40W78NE	N43E84NW
N53W83NE	N32E83NW
N44W85NE	N55E68NW
N43W73NE	N43E80NW

CUL7T
N10W88SW
N09W80SW
N14W86SW
N24W66SW
N14W74SW
N35W82SW

STATION CUL8, COOLING JOINTS

n = 34



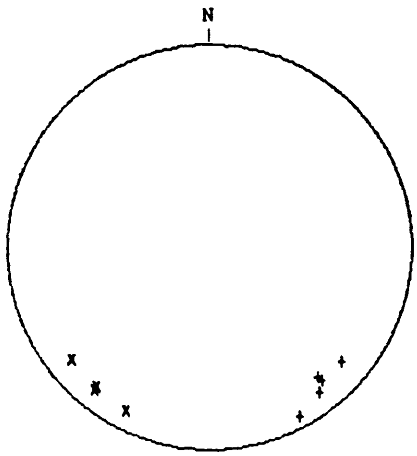
+ CUL8C1 n = 21
x CUL8C2 n = 13

Schmidt net, lower hemisphere projection

CUL8C1	CUL8C2
N26W77NE	N45E75NW
N32W88SW	N40E83NW
N24W84SW	N44E86NW
N38W84SW	N42E84NW
N35W90SW	N40E75NW
N39W89NE	N33E82NW
N40W82NE	N43E72NW
N33W84NE	N41E72NW
N45W81NE	N40E86NW
N66W73NE	N44E78NW
N35W79NE	N47E77NW
N34W82NE	N47E76NW
N40W84NE	N40E80NW
N20W77NE	
N34W80SW	
N34W83SW	
N34W77SW	
N55W84SW	
N20W84SW	
N16W83SW	
N60W79NE	

STATION CUL9, COOLING JOINTS

n = 9

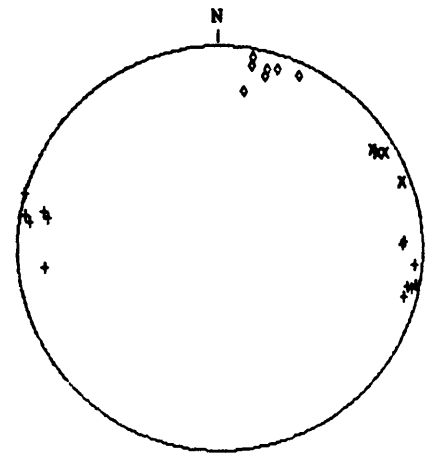


\+ CUL9C1 n = 5
x CUL9C2 n = 4

Schmidt net, lower hemisphere projection

STATION CUL9, TECTONIC JOINTS

n = 25



\+ CUL9T1 n = 14
x CUL9T2 n = 4
◇ CUL9T4 n = 7

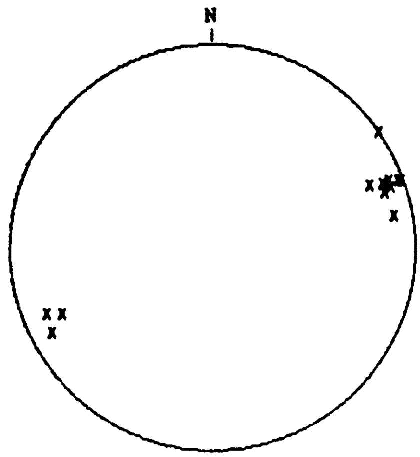
Schmidt net, lower hemisphere projection

CUL9C1	CUL9C2
N62E84NW	N63W80NE
N50E72NW	N39W77NE
N50E75NW	N51W80NE
N41E75NW	N51W78NE
N53E79NW	

CUL9T1	CUL9T2	CUL9T4
N12E86NW	N33W79SW	N75W77SW
N05E86NW	N30W83SW	N80W81SW
N10E75SE	N20W85SW	N75W81SW
N02W80SW	N31W80SW	N80W85SW
N11E88NW		N81W67SW
N15E83NW		N65W83SW
N01W79SW		N72W82SW
N06W76NE		
N12E78SE		
N10E87SE		
N12E84NW		
N16E90SE		
N08E84SE		
N12E84NW		

STATION CUC1, TECTONIC JOINTS

n = 12



x CUC1T2 n = 12

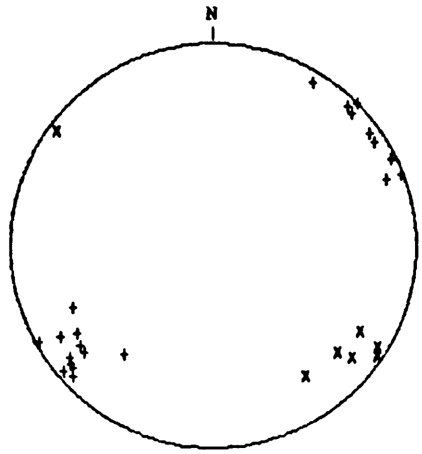
Schmidt net, lower hemisphere projection

CUC1T2

N21W82SW
N20W87SW
N19W82SW
N21W79SW
N28W70NE
N24W70NE
N35W90SW
N20W89SW
N10W80SW
N18W78SW
N22W72SW
N22W77NE

STATION CUC2, COOLING JOINTS

n = 28



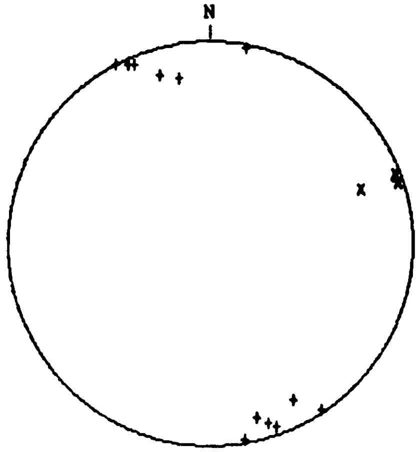
+ CUC2C1 n = 21
x CUC2C2 n = 7

Schmidt net, lower hemisphere projection

CUC2C1	CUC2C2	CUC2C3
N33W84SW	N31E73NW	N13E83NW
N40W81NE	N34E87NW	N09W84SW
N29W88NE	N32E85NW	N02E83NW
N26W87SW	N39E77NW	N03E82NW
N21W89SW	N41E70NW	
N21W80SW	N36E85SE	
N40W86NE	N55E68NW	
N33W69NE		
N38W79NE		
N36W84SW		
N45W90SW		
N24W65NE		
N46W85SW		
N31W77NE		
N37W71NE		
N51W59NE		
N40W72NE		
N59W84SW		
N43W84NE		
N41W81NE		
N44W84SW		

STATION CCR1, COOLING JOINTS

n = 16

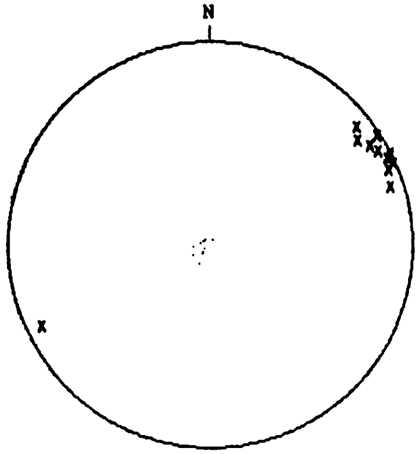


+ CCR1C1 n = 12
x CCR1C2 n = 4

Schmidt net, lower hemisphere projection

STATION CCR1, TECTONIC JOINTS

n = 22



x CCR1T2 n = 12
· CCR1SH n = 10

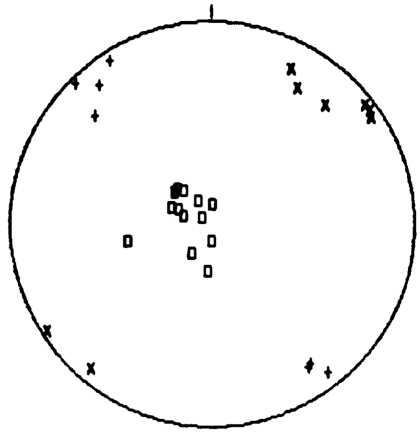
Schmidt net, lower hemisphere projection

CCR1C1	CCR1C2
N73E76SE	N20W68SW
N65E87SE	N21W87SW
N79E72SE	N18W87SW
N80W88SW	N20W87SW
N67E86SE	
N56E88NW	
N72E82NW	
N62E76NW	
N62E90SE	
N70E85NW	
N75E78NW	
N80E88NW	

CCR1T2	CCR1SH
N39W82SW	N45W04NE
N29W84SW	N50E03SE
N33W88SW	N08W07NE
N27W90SW	N29W08NE
N26W82NE	N06E04SE
N32W82SW	N47W05NE
N35W78SW	N21E03SE
N24W89SW	N31W03NE
N18W83SW	N71W02SW
N23W85SW	N60W09NE
N26W87SW	
N26W89SW	

STATION CCR2, COOLING JOINTS

n = 28



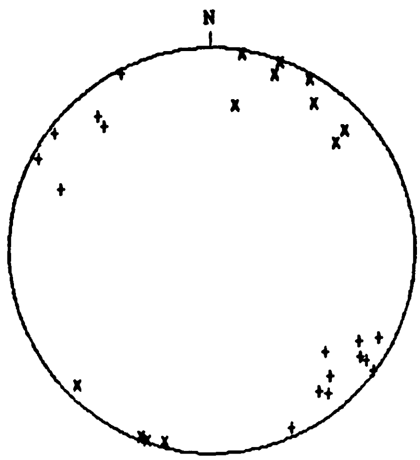
+	CCR2C1	n = 7
x	CCR2C2	n = 8
□	CCR2C3	n = 13

Schmidt net, lower hemisphere projection

CCR2C1	CCR2C2	CCR2C3
N55E73NW	N47W70SW	N11W35NE
N51E78SE	N34W84SW	N87W07NE
N46E87SE	N36W86SW	N90E08SE
N52E82NW	N50W83NE	N23E18SE
N56E74NW	N33W87NE	N37E05SE
N58E85SE	N58W68SW	N18E13SE
N43E68SE	N63W75SW	N40E20SE
	N38W85SW	N84W19NE
		N55W14NE
		N46E20SE
		N59E11SE
		N50E18SE
		N25E15SE

STATION CCR3, COOLING JOINTS

n = 28



+ CCR3C1 n = 16
x CCR3C2 n = 12

Schmidt net, lower hemisphere projection

CCR3C1	CCR3C2
N50E76SE	N70W81SW
N49E70SE	N81W62SW
N37E89NW	N70W88SW
N53E76NW	N60W87SW
N47E74NW	N45W84NE
N28E86SE	N71W89NE
N36E83NW	N76W87NE
N22E69SE	N69W88NE
N28E82NW	N81W88SW
N37E86SE	N55W77SW
N42E64NW	N41W70SW
N36E79NW	N42W77SW
N63E88SE	
N32E74NW	
N51E80NW	
N66E85NW	