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Fracture history of the Redwall Limestone, lower Supai Group, and Tertiary units on the Hualapai Indian Reservation, northwestern Arizona: Additional data to Open-File Report 87-359

by

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ABSTRACT

Paleozoic strata and Tertiary units on the Hualapai Plateau and western Coconino Plateau are cut by a complex fracture network that record at least eight different fracture events. The Mississippian Redwall Limestone was sliced by two early fracture sets prior to deposition of the overlying Supai Group. The Supai Group and Tertiary volcanic rocks and conglomerates appear to share the same fracture history. Breccia within pipes seems to have been fractured by the same events common to the Supai Group and Tertiary units. Ring fractures found in Supai rock directly adjacent to breccia pipes have not been observed in the underlying Redwall Limestone, which suggests that the limestone was fractured prior to formation of the pipes. Abundance and prominence of the various fractures sets varies spatially from the Hualapai Plateau to the western Coconino Plateau, although the relative-age relationships between the various sets remains constant.

INTRODUCTION

The Hualapai Indian Reservation is located in northwestern Arizona in the southwestern part of the Colorado Plateau physiographic province. The reservation is north of U.S. Highway 66 and south of the Lower Granite Gorge of the Colorado River (fig. 1). The main portion of this study (31 of 47 stations) focused on the eastern Hualapai Reservation, known as the Coconino Plateau. To augment a similar fracture study (Roller, 1987) conducted on the Hualapai Reservation, sixteen additional stations in the Redwall Limestone, Supai Group, and Tertiary units were located on the western half of the reservation known as the Hualapai Plateau.

The Permian Kaibab Limestone caps the Coconino Plateau (fig. 2), whereas the Mississippian Redwall Limestone caps the Hualapai Plateau, an erosional surface that formed during Paleocene time (Young, 1979). The Devonian Temple Butte Formation and the Cambrian Muav Limestone also crop out in the southwestern part of the reservation around Meriwhitica Canyon. Several isolated outcrops of the Mississippian Surprise Canyon Formation fill canyons as deep as 400 ft (122 m) that were eroded into the upper Redwall Limestone in late Mississippian time (Billingsley and Beus, 1985). Remnants of the Pennsylvanian/Permian Supai Group crops out sparsely in the northwestern part of the Hualapai Plateau and north of Hindu Canyon, and more extensively on the Coconino Plateau. Early and middle Tertiary basalt flows lie directly on the Redwall Limestone, Temple Butte Formation, and the Muav Limestone on the Hualapai Plateau. In only a few areas does basalt cap erosional remnants of the Supai Group. Tertiary gravels that filled ancient stream valleys crop out across the reservation.

Several large, high-angle, north- to north-northeast-trending fault zones cut the region, including the Aubrey, Toroweap, Hurricane, and Separation Canyon faults. A complex and lengthy history of both normal and reverse movement characterizes most of these faults. Deformation commenced in

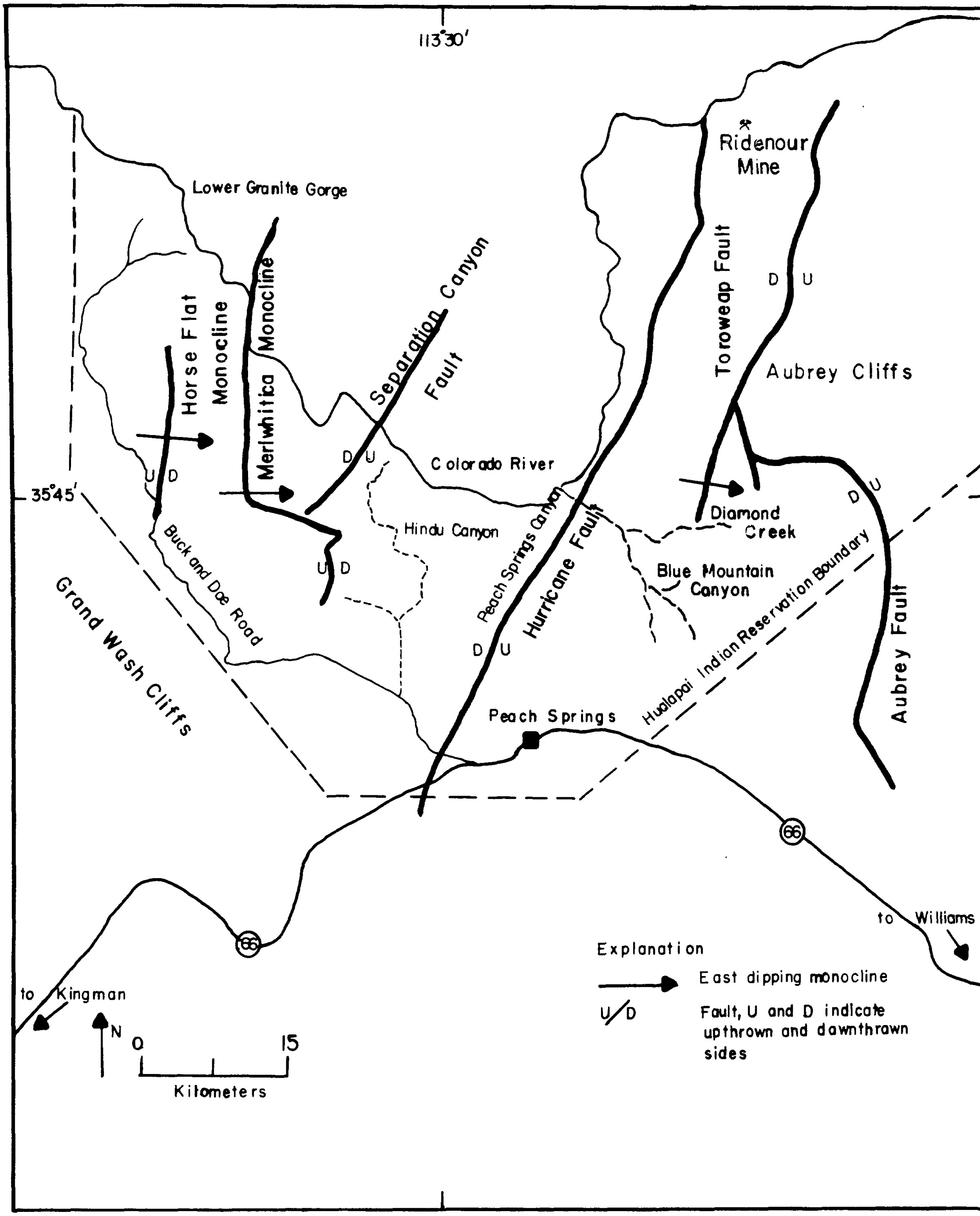

Figure 1 - Map of the Hualapai Indian Reservation and major structural features, northwestern Arizona. (Modified from Huntoon, 1981, and Billingsley and Huntoon, 1983)

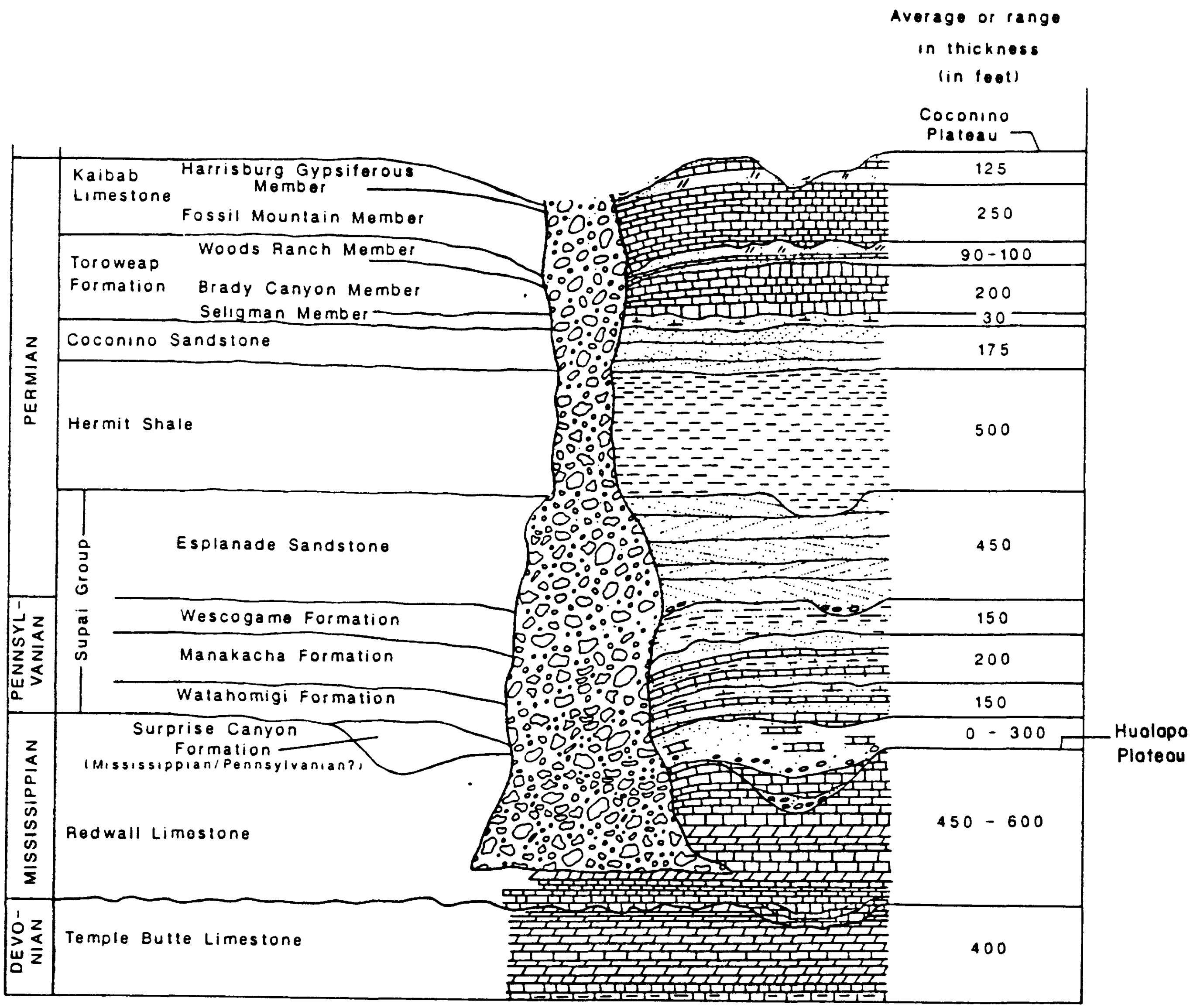

Figure 2 - Stratigraphic column of Paleozoic units that are exposed on the Coconino Plateau and Hualapai Plateau. (Adapted from Verbeek and others, 1988)

Proterozoic time for many of the faults, and some, such as the Hurricane fault, offset Holocene alluvial deposits (Huntoon, 1974; Shoemaker 1978). Huntoon (1974) noticed that some normal faults offset the Redwall Limestone and underlying units but not the overlying units.

Several large monoclines, believed by Young (1979) to have formed during two phases of deformation during the Late Cretaceous-to-Eocene Laramide Orogeny, have locally folded the Paleozoic sediments of the Hualapai and Coconino Plateaus. The Aubrey, Toroweap, Hurricane, Meriwhitica, and Peach Springs monoclines are thought by Huntoon (1974) to overlie high-angle reverse faults, which may be reactivated Proterozoic faults. The monoclines and inferred underlying faults trend north and north-northeast.

Recent mapping of the Hualapai Reservation has revealed the presence of over 900 collapse features, including about 100 that have been identified as breccia pipes (Billingsley and others, in prep.; Wenrich and others, 1986; Billingsley and others, 1986; Wenrich and others, 1986; Wenrich, 1985; Billingsley and Huntoon, 1983). Breccia pipes are generally cylindrical, vertical structures that wholly or partly contain angular to rounded rock fragments with or without a matrix (Bryner, 1961). Exposures of pipes along canyon walls show that the pipes are steep-sided features, which many workers believe originated as caverns in the Redwall Limestone (Wenrich and Sutphin, 1983; Sutphin and others, 1983; O'Neil and others, 1981; Baillieul and Zollinger, 1980; Wenrich-Verbeek and Verbeek, 1980; Bowles, 1977). Continued enlargement of caverns within the Redwall prompted the collapse of overlying formations into the caves filling the caverns with collapse breccia.

Solution caverns and passages subparallel to bedding are associated with areas of breccia pipes, especially in Blue Mountain Canyon. In Blue Mountain Canyon, the Redwall Limestone has been dissected by caverns and passages that are now clogged with numerous layers of white to gray, massive, and coarse- to very coarse-grained calcite crystals, some as large as 15 to 20cm across. The different layers of calcite suggest several episodes of fluid flow through the caverns. Age relations between breccia pipes and the caverns are unknown, but the two features could be related in time. Calcite-filled passageways might be the link between subhorizontal passages and the caverns that stoped upward to eventually form pipes.

Sutphin and Wenrich (1983) and Wenrich (1985) suggest that the location of breccia pipes in the Redwall Limestone farther east on the Marble Plateau was controlled by northwest- and northeast-trending fracture zones that propagated upward from Proterozoic basement structures. They propose that areas in which to focus exploration can be identified from the hypothesis that pipes are concentrated along these trends.

This study of the fracture pattern on the Hualapai Plateau is a continuation of a preliminary analysis (Roller 1987) of the fracture history of the Redwall Limestone, lower Supai Group, and Tertiary units. In addition to more fracture stations in the previously studied units, this study (1988) focused on six breccia pipes and adjacent Redwall Limestone to determine the controls, if any, of the Redwall Limestone fracture network on the location of breccia pipes.

METHODS

Forty seven stations were studied across the Hualapai Reservation (figs. 3 and 4). The majority of stations (26) are in the Redwall Limestone. Of

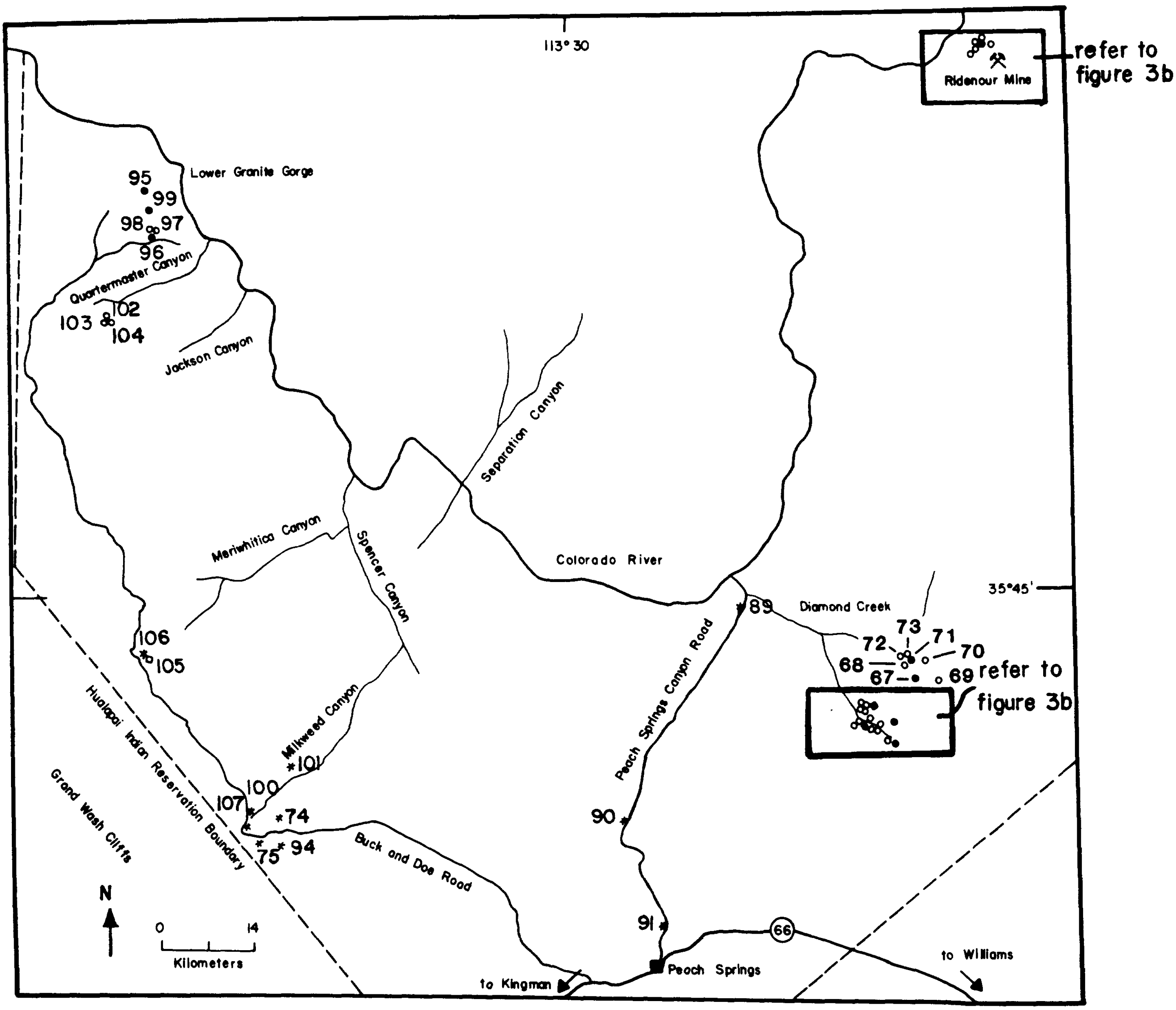

Figure 3 - Location map of stations, which start at #61 for continuity with Roller (1987). Open circles are stations in the Redwall Limestone; black circles are in the lower Supai Group, and asterisks designate Tertiary basalts and conglomerates.

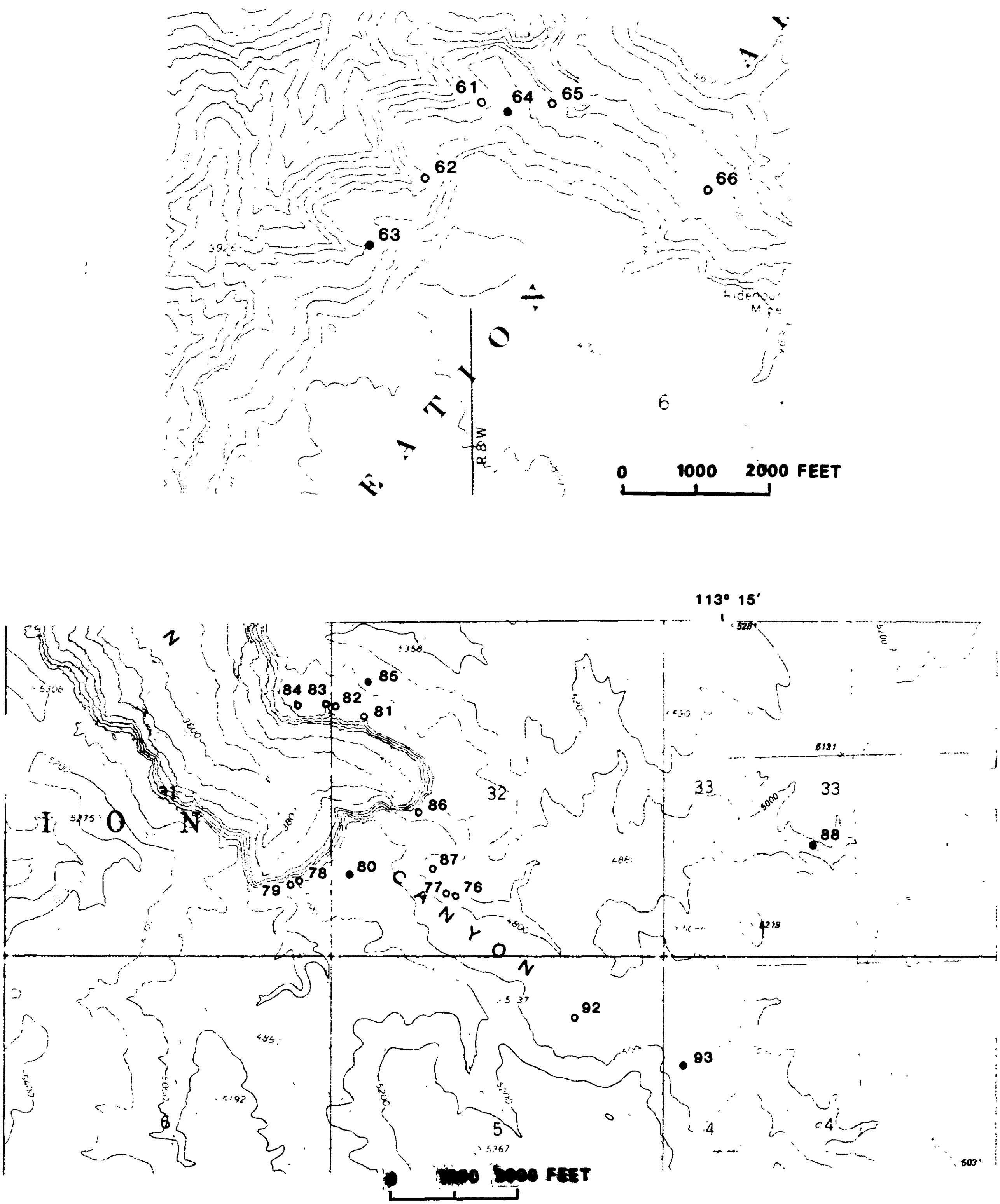

Figure 4 - Blow-up of station localities in the Ridenour mine area (upper map) and Blue Mountain Canyon (lower map). The Ridenour mine is located on the Vulcan's Throne SW 7½ minute topographic map, and Blue Mountain Canyon is found on Robbers Roost Canyon and Peach Springs NE 7½ minute topographic maps. Symbols are the same as in figure 3.

these 26 stations, 18 stations are in both breccia pipes and the adjacent country rock. Less intensive examination of fracture systems within the Supai Group (9 stations), and Tertiary basalts and gravels (10 stations) was also conducted to determine if the fracture history of the Redwall Limestone differs from that of these overlying formations as proposed in Roller (1987). Station numbers in this report start at #61, which is where the stations in the 1987 report left off.

At each station, fractures were separated into sets based on such characteristics as orientation, size and shape of the fracture plane, surface features, mineral fillings, and relative age. Terminating relationships between fracture planes establish relative ages of different sets at each station. A detailed and thorough discussion of these methods can be found in Grout and Verbeek (1983).

Designation of different fracture sets is based not only on joint orientation, but more importantly, the evaluation of relative-age relationships among joints of both similar and different orientations. Thus in this terminology, F1 refers to a discrete fracture episode. For example, a fracture that is parallel to F1 fractures, but is determined to be younger, is not an F1 fracture because it did not originate during the F1 event (fig. 5). In addition, a segment of an F1 joint that formed later by reactivation of the early joint by later stress is also not an F1 fracture, because it is younger than the F1 event. Therefore, although orientations of some of the sets in the Redwall Limestone and Supai Group are similar, the relative ages of the sets are different in the two units, so not all sets of similar orientations are correlative. Instead, in the Redwall Limestone, fractures of similar orientation developed at widely separated times, and at least nine episodes of fracturing took place. This conclusion will be developed further in the following sections.

Techniques used by Grout and Verbeek (1983) were developed in clastic rocks and appear to be applicable to limestones as well. However, weathering of joint surfaces in the limestone commonly destroys all vestige of surface features, such as plumose structures, twist hackle, or arrest lines that indicate an extensional origin for joints. Nevertheless, if both sides of open, curved fracture surfaces match across the opening, then no shear offset has occurred, and the fractures can be inferred to have formed from extensional processes. This is the case for the majority of fracture surfaces in the Redwall Limestone.

Understanding the fracture history of limestone is further complicated by the commonly extensive solutioning and consequent widening of either large, single fractures or zones of closely spaced fractures in the Redwall Limestone. Terminating relationships among solution-widened fractures of different sets are commonly obscure when two parallel joints that once terminated on opposite sides of an older joint now coalesce due to solution. The result is one apparently large joint that crosscuts the older joint, thus erasing the original terminating relationships between the two sets. Nevertheless, enough consistent relative-age information was found between fractures across the study area to formulate a working hypothesis for the history of fractures in the Redwall Limestone, the lower Supai Group, and Tertiary units.

In addition, undulating, irregular joint surfaces are common in limestone and cause changes in orientation along both the height (measured perpendicular to bedding) and the length (measured parallel to bedding of single fractures). It is commonly difficult to discern whether variable orientations actually reflect 1) an original wide spread in orientation of the same set,

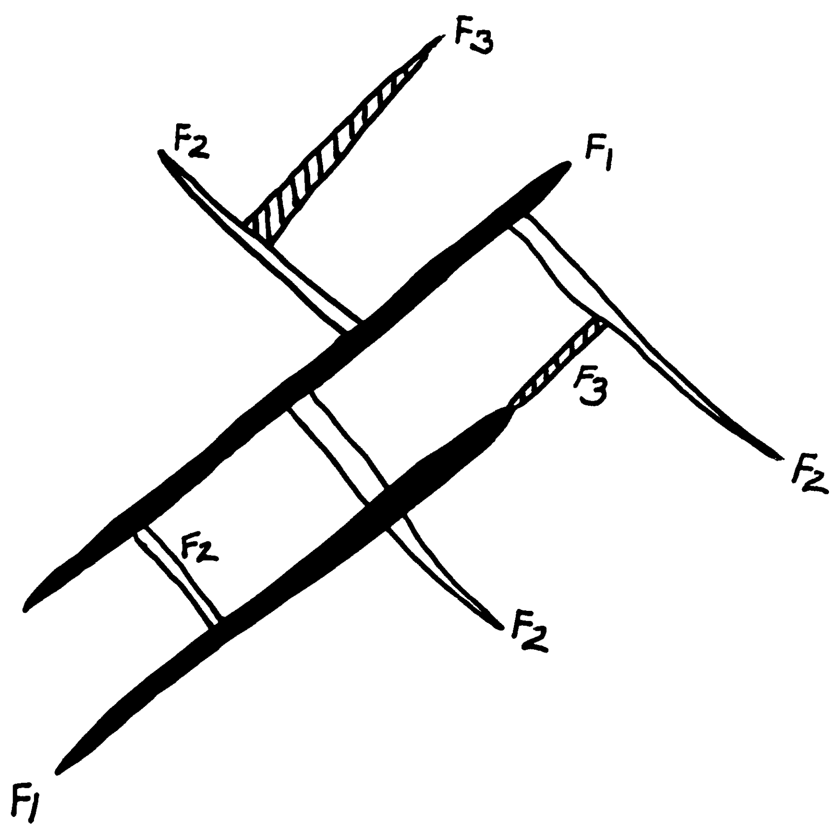

Figure 5 - Simplistic drawing shows a young fracture set (F3 in the drawing) that formed parallel to an earlier set (F1). Early F1 fractures truncate later F2 fractures, while the younger F3 fractures terminate against F2 fractures. These relationships can lead to apparent conflicting age relations if it is not understood that F1 and F3 fractures, although parallel in orientation, formed at distinctly separate times in the fracture history of the rock.

2) undulatory joint surfaces due to intense irregular weathering, or 3) several closely spaced but short joints of one set that are connected along steps whose orientation coincides with that of a different set. Widening of the fractures due to solution has destroyed the details. This widening of fractures sometimes created difficulties in determining the exposed height and length of individual fractures, so measurements were taken of "composite" heights and lengths. Composite measurements include the heights and lengths of several smaller joints that have coalesced into one large joint. Dips in the limestone are commonly difficult to measure precisely, as they often vary as much as 20 degrees on either side of vertical along an undulatory joint surface.

A continuous spread of orientations between fracture sets (commonly 30 to 40 degrees) is common amongst all of the sets at one time or another so that in areas of complex fracture networks, it is almost inevitable that some overlap in orientation occurs. As an example, the relationship between joints whose orientations cluster around N25W with the north and N50W sets is not always clear. Joints of the N25W set commonly are large and prominent, but at some stations, a continuous range in orientations between north and N50W occurs. A distinct clustering does exist at numerous stations, however, so the N20-30W joints are given set status. It is also sometimes difficult to discern whether N70-79E belongs to the northeast set or the east set when the entire spectrum of orientations are found at a station. This is why orientation alone is an insufficient guide to sets and why relative-age determinations are essential to understanding the number and sequence of fracture events. The combined use of orientation and relative ages serves to distinguish the various sets.

The 1987 study included joints with orientations of N16-39E in either the north set or the northeast sets. However, this grouping appears to be a set of its own because at 62% of the stations, both low northeast (N16 -39E) and higher northeast (N40-70E) joints exist. Age relations indiate that joints with low northeast orientations formed during two events, one after F2 fracturing and the other post F7 (N50W) fracturing. An insight into this situation might be gleaned from observations at several stations where joints with approximately N30E orientations curve along strike into larger joints with N60E orientations. Given that F1 (N50E) joints formed early in the Redwall Limestone, then at some later time, if the least principal stress direction was within 20 to 30 degrees of the F1 sigma 3, then a new set with low northeasterly orientations might use the terminations of the F1 joints as points of propagation, in addition to new fractures of the low northeasterly orientation forming in unbroken rock. The result would be twofold: a wide range of low northeast and northeast (F1) strikes could occur along strike of the same joint, and low northeast joints might also occur as shorter individual joints, not obviously connected to the earlier formed northeast joints. In the lower Supai and Tertiary units, the low northeast set (F2.5) is older than the N50E (F6) set, although at three stations, age relationships indicated that N35E joints are younger than F7 joints. These young N35E joints are designated F8 fractures.

FRACTURE PATTERN

Roller (1987) indicated that the fracture pattern of the Redwall Limestone differs significantly from that of the overlying Supai Group and Tertiary units on the Hualapai Plateau. The 1987 study stated that the

Redwall Limestone contains seven recognizable fracture sets. This report agrees with the findings of 1987, but it also shows that the fracture history of units on the Hualapai Plateau is more complex than previously shown. It appears, based on relative-age relations, that there have been several episodes of reactivation or fracturing parallel to earlier sets in the Redwall Limestone. The number of sets as determined by this study (1988) has increased to nine: F2.5 (N28E) is now separated out from orientations included in F1 based on relative age determinations, and F8 (N38E) is a set that parallels F2.5 orientations but was determined to be younger than F1 - F7 fractures. Reactivation of joints has also occurred within Supai Group and Tertiary units. The Supai Group and Tertiary units now contain a minimum of seven differentiable sets, plus an uncertain number of reactivated sets.

In the Redwall, joints of the two oldest sets (designated F1 and F2 respectively) strike N50E and N50W (Roller, 1987). Four younger sets (F2.5, F3, F4 and F5) strike approximately N28E, east, north, and N25W. In addition, there are three still younger sets (F6, F7, and F8) that have orientations similar to F1, F2, and F2.5 respectively, but are demonstrably younger than F3 through F5 joints. In contrast, the two oldest sets of the Redwall Limestone (F1 and F2) are missing in the lower Supai Group: F2.5 - F8 are common to both formations. Joints of the two oldest sets in the lower Supai Group strike N30E (F2.5), east (F3) and north (F4), and joints of the younger sets strike N25W, N50E, N50W, and N30E (F5, F6, F7, and F8 respectively). Although N50E and N50W joints are found in both the Redwall Limestone and the lower Supai Group, it can be domonstrated by relative age determinations that N50E and N50W joints in the Supai are younger than F2.5 - F5 joints. Ten stations studied in Tertiary basalts and gravels that cap the Redwall Limestone also contain seven sets (F2.5 - F8) common to both the Redwall Limestone and the Supai Group, but their fracture history is similar to that of the Supai Group.

Another interesting outcome of this years study is that the most prominent sets in the Redwall Limestone on the Hualapai Plateau are not, for the most part, the dominant sets in the Redwall on the Coconino Plateau. It appears that the relative ages of the sets have remained the same from one side of the plateau to the other, but due to a differential stress gradient across the plateaus, different fracture sets are of varying prominence from place to place. On the Hualapai Plateau, northeast (F1) and northwest (F2) fractures are consistently dominant, but on the Coconino Plateau, the younger N80E (F3) and N10W (F4) are commonly the most prominent sets in the Redwall Limestone. These field observations are substantiated by aerial photographs of the Redwall surface. Fracture orientations observed on photographs in the Hindu Canyon area of the Hualapai Plateau include N45W, N45E, and N20W. N45E fractures are the longest and most prominemt on the photographs. The N20W fractures are locally abundant and large. In constrast, north of Blue Mountain Canyon, observed orientations include N10W, east, N40-55E, and N45W. The N10W and east fractures are the most strongly displayed in the aerial photographs on the Coconino Plateau.

Solution along subhorizontal fractures is pervasive in the Redwall Limestone. Numerous open caves several meters across and high occur at the junction between large joints of the N50E, N50W, N10W and N25W sets and horizontal partings.

Joints are well developed in all members of the Supai Group. Unlike the weathered surfaces of joints in the Redwall Limestone, delicate plumose structures, twist hackle, and arrest lines, characteristic of extension joints, are beautifully displayed on joint surfaces in the clastic units of the Supai Group. The lower Supai, however, contains several thick limestone units whose joint surfaces have not retained surface features. All sets contain coarse-grained pink to white calcite cement along joint surfaces.

The fracture set nomenclature is based on both orientation and age relations, so the earliest Supai Group fracture set is designated F2.5 (N30E) to match the F2.5 (N28E) fracture episode in the Redwall Limestone. This is a new set designation for the Supai Group and Tertiary units as well as the Redwall Limestone. In Verbeek and others (1988), they observed in the Ridenour Mine area that the north set (their F1) is older than the N70E set, which is their F2 set. This F2 fracture set ranges from N60E to N79E, and averages N70E (Verbeek and others, 1988). Orientations of their F2 fracture set overlap with both my F3 set (N75E to N75W) and F6 (N40E to N75E). The often prominent N86E set (F3) and newly designated F2.5 (N30E) that I measured in the lower Supai Group do not have an exact correlatives in the upper Supai Group in the Ridenour Mine area.

Fracture measurements were taken at eight stations in both cliff exposures and stream beds in Tertiary basalts that cap the Redwall Limestone and Muav Limestone. At many of the stations, a clear distinction exists between fractures formed from extensional forces and those formed during cooling of the basalt. Extensional fractures cut several meters of section and have fairly planar, smooth surfaces in cross section, and are laterally continuous for several meters along strike in plan view (fig. 6). Fracture zones, which contain numerous closely-spaced joints, were observed with orientations of northwest, northeast, and N25W joints. These criteria suggest that these are not cooling joints. At some stations, it was not certain if relatively short (less than a meter long), sinuous fractures were extension joints or cooling joints. It is possible that some fractures measured include a mixed population of both types of joints, although an attempt was made to measure only those that appeared to be extension joints.

F2.5 through F8 fracture sets that cut the Redwall Limestone and the Supai Group also cut Tertiary basalt and conglomerate. Fractures within the N50W and N50E sets are not F1 and F2 sets, but are of the F6 and F7 fracture episodes. East fractures are commonly the most prominent, planar, and largest of fractures (see fig. 6). At stations #94 and #106, however, the east set was not prominent at all, and terminated against north, northeast, and low northeast fractures. The fracture history of the Redwall Limestone and Supai Group both appear to be complex and suggest multiple episodes of reactivation along most orientations, and this is substantiated by age relationships in Tertiary basalts.

Two thick (6-25 m), early-middle Tertiary conglomerate outcrops were studied in Peach Springs Canyon. The six fracture orientations that cut the basalt also cut the entire section of conglomerate. Fracture lengths and heights are up to several meters, and spacing ranges from 0.5 to several meters. At station #90, fractures were apparent, but they were not as abundant or closely spaced as at station #89, possibly because the gravels at #90 are massive and the thickness of the unit is great, approximately 25 meters thick. In constrast, layering ranged from 0.5 to 2m thick at station #89, which agrees with the observation of Grout and Verbeek (1983) that units with thin layering are more highly fractured than more massive units.

Below is a description of the fracture sets in terms of orientation, relative age, and geometry for the Redwall Limestone, Surprise Canyon Formation, Supai Group, and Tertiary basalts and gravels.

Figure 6 - Long (up to 5m), relatively planar N80W (F3) joint of extensional origin cuts Tertiary basalt at station #101 near Milkweed Spring.

Fracture set 1 (F1) Redwall Limestone

The average orientation for F1 is N57E, with a range between N46E-N68E (fig. 7). On the western Hualapai Plateau, F1 joints were present at all but one station, and they were always the largest and most planar joints. The situation is different on the Coconino Plateau, specifically in the Blue Mountain Canyon area. N57E fractures remain the oldest set, but spatially they vary in relative prominence. They are either poorly developed or are totally absent at several stations in the Redwall Limestone on the eastern part of the reservation. Instead, N80W (F3) and/or N10W (F4) joints are commonly the most prominent joints in the Redwall as well as in the overlying lower Supai rocks. However, in Redwall Limestone that bordered breccia pipes #369 (adjacent to station #96) and #876 (adjacent to station #78), N57E joints were prominent and closely spaced. This was also true with F2 (N55W) joints near the pipes. This will be described further in the section on breccia pipes and possible explanations will be discussed in the conclusion section.

Exposed lengths of subvertical F1 joints range from 10cm to 1m, with exposed heights of 15cm to 1.2m. Composite lengths and heights are larger, up to 10m and 15m respectively. It is commonly difficult to tell if the large measurements belong to an individual fracture due to solution and the resultant coalescence of two or more very closely spaced joints, which is so common in the Redwall limestone. Average spacing for F1 joints is approximately 10-40cm locally, with spacing up to several meters across some outcrops where F1 is poorly developed.

Crosscutting of mineralized F1 joints by F2 joints is relatively common, indicating that F1 was mineralized prior to F2 formation, which allowed the younger F2 fractures to propagate across the filled F1 fractures.

Fracture zones comprising several closely-spaced joints that cut tens of meters of section are widespread on the western Hualapai Plateau, but are not as common on the Coconino Plateau. Because F1 is not well developed on the Coconino Plateau, fewer fracture zones have formed from the coalescence of numerous closely spaced joints. However, solution along the few fracture zones that were observed has sometimes created zones up to 1 meter wide, which are either open or partially filled by iron-oxide-stained calcite cement.

Fracture set 2 (F2) Redwall Limestone

Subvertical F2 joints strike an average of N55W (fig. 8). Analogous to the F1 fractures, the prominence of F2 fractures varies across the reservation. F2 joints are found at a majority (37 of 44) of stations, and on the Hualapai Plateau they are planar and prominent. However, many of the outcrops studied on the Coconino Plateau contain only a few N55W joints, and these are commonly not prominent, which is similar to the F1 fracture network. For example, at stations #61-#66 north of the Ridenour Mine, N55W joints are planar, closely-spaced, the dominant set, and are older than east (F3), north (F4), and northeast (F6) joints at three stations, but at two stations N55W joints are undulatory, short and weakly developed, and they terminate against the east (F3) north (F4) sets. These weakly developed joints belong to the F7 (F50W) fracture set as defined by relative age relations.

In the Blue Mountain canyon area, early N55W (F2) joints were observed at 8 out of 14 stations. At the remainder of the stations, they either were not observed or were judged younger than F2 joints by relative-age

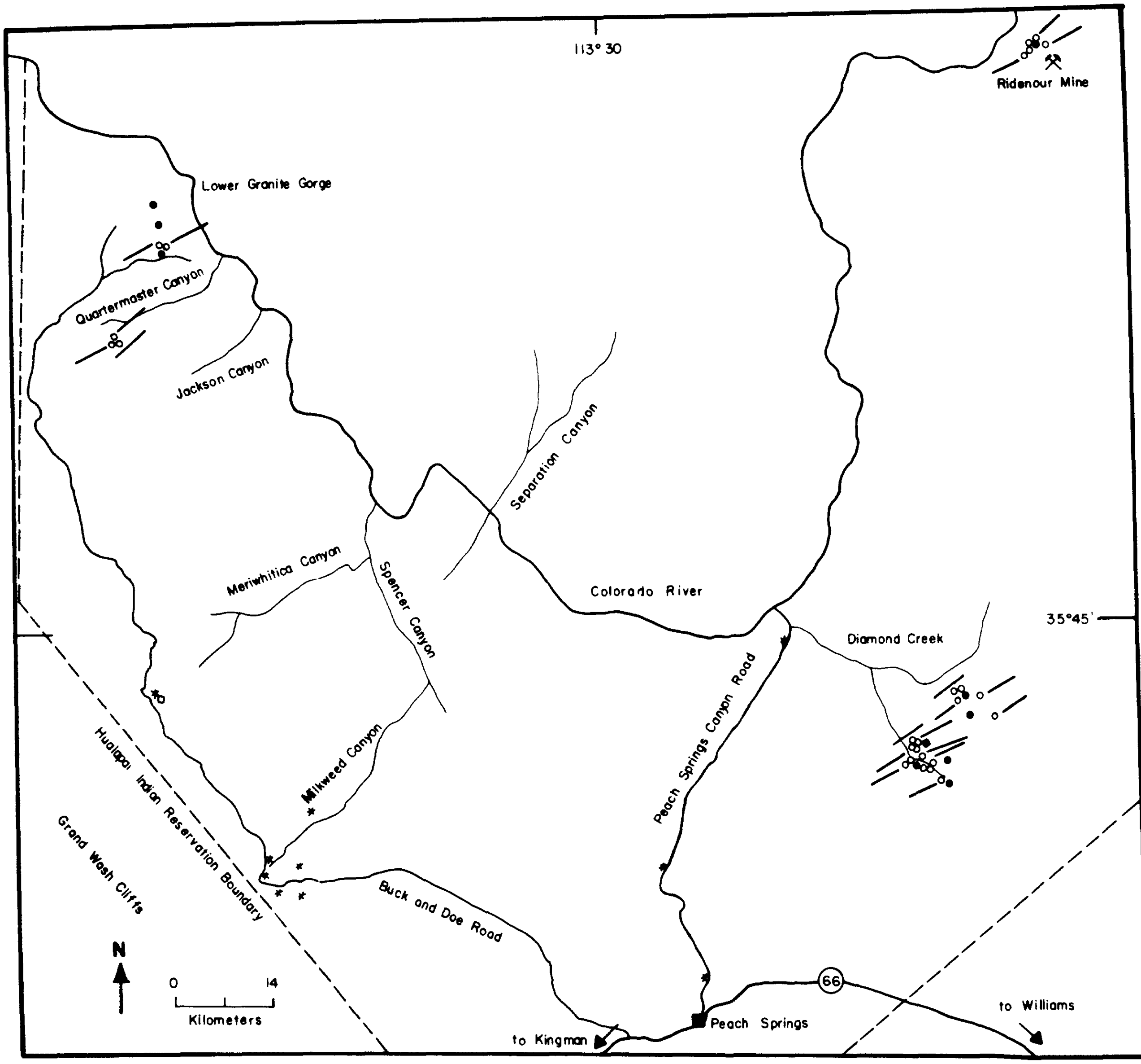

Figure 7 - Map of mean strikes for the F1 fracture set in the Redwall Limestone. Overall average for F1 is N50E.

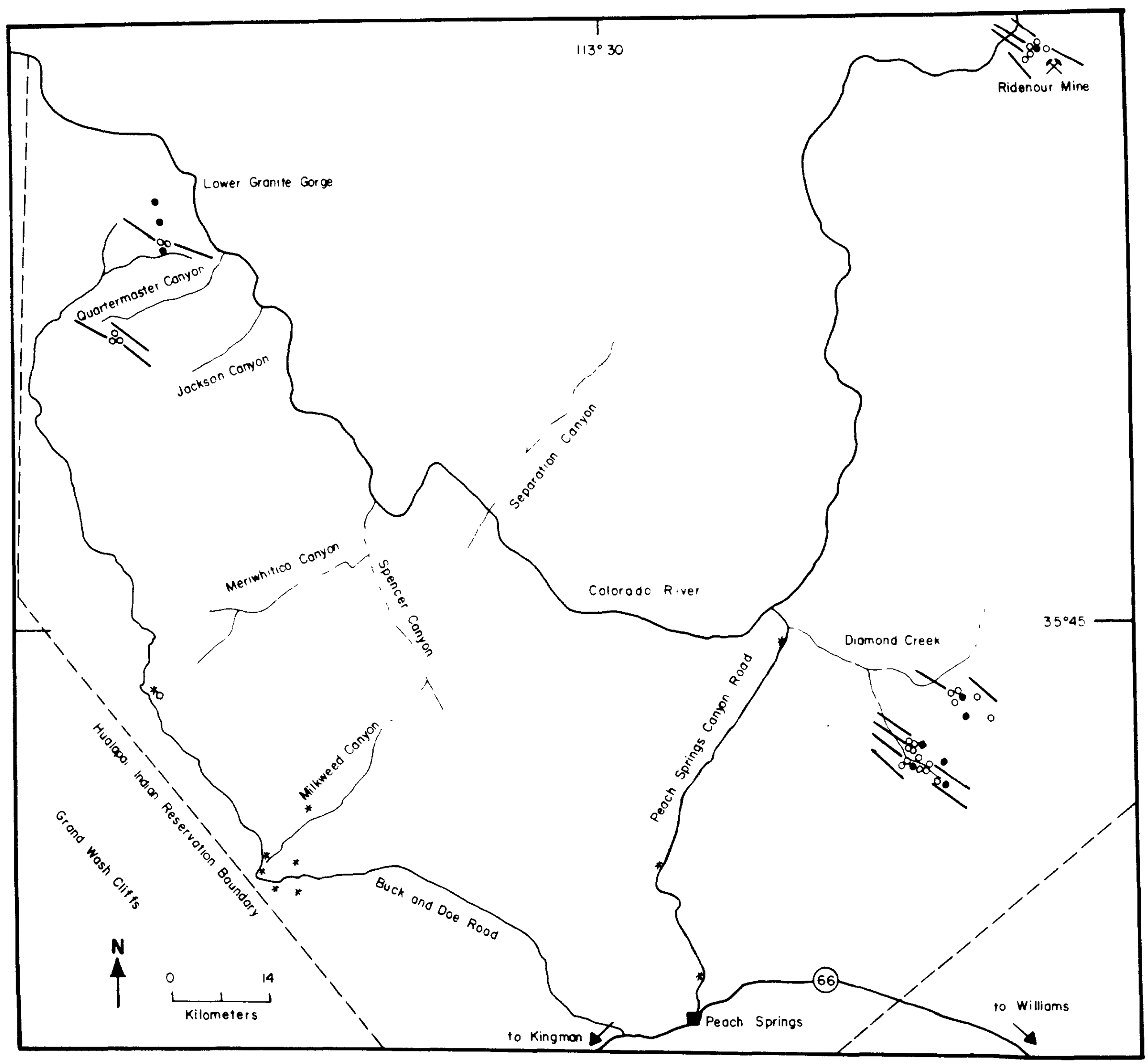

Figure 8 - Map of mean strikes for the F2 fracture set in the Redwall Limestone. Overall average for F2 is N51W.

relationships. Figure 9 shows a photograph of a planar N55W joint (parallel to the pencil) that is filled with Redwall Limestone breccia, which shows that the joint formed prior to brecciation.

Exposed heights of 0.2 to 1.3m and lengths of 0.15 to 0.7m are common. Composite heights and lengths of 2.5 to 2 meters respectively were measured. Average spacing of individual joints outside fracture zones is from 5-20cm locally, averaging 40-70cm, with spacing of up to 1-5m across the outcrop where F2 joints are not well developed. Fracture zones as wide as 20 to 50cm wide were observed.

Fracture set 2.5 (F2.5) Redwall Limestone

Fracture set 2.5 (F2.5) was included in the F1 set in the 1987 report, but it is given set status in this report because it occurs at 62% of the stations studied, along with the F1 (N57E) set. It is designated set 2.5 so that sets F3 through F7 of this report refer to the same sets described in Roller (1987). Fifteen relative age relations show that these fractures are younger than F1 and F2 fractures and older than F4 through F8. F2.5 fractures range from N20E to N37E and average N28E (fig. 10).

At several outcrops, it was observed that N20-30E (F2.5) joints curved into N55E joints along strike. One possible explanation for this observation is that the least principle stress direction (sigma 3) during F2.5 time was close but not quite perpendicular to sigma 3 of the F1 event, so new fractures formed using the tips of F1 fractures as points of propagation. The new set has orientations close to those of the F1 set, but formed at a later time.

Fracture set 2.5 (F2.5) Supai Group

Age relations indicate that joints with orientations averaging N30E (fig. 10) occurred both early (F2.5) in the fracture history of the lower Supai Group and late (F8). The 1987 fracture report did not distinguish this N30E set from the higher northeast set, but with more age relation observations, it is now evident that an early N30E fracture set does exist. Subvertical F2.5 fractures were observed at five of the nine lower Supai stations.

Along the base of a 25m high sandstone cliff west of the Ridenour Mine, N30E fractures have exposed heights of 6m and exposed lengths of 2.5m average. Layering in most Supai outcrops measured is much thinner, from 30cm to several meters. F2.5 fractures terminate against bedding planes, so exposed heights average 40cm and composite heights average 2.5m. Exposed lengths average 30-60cm. Average spacing of joints is 0.4-1m. F2.5 is also a prominent set at the two Supai stations measured in the Quartermaster Canyon area.

Fracture set 2.5 (F2.5) Tertiary units

F2.5 fractures were measured in both Tertiary gravels, the Peach Springs tuff (18my) and olivine basalts (fig. 10). Subvertical F2.5 fractures were observed at two out of ten stations; at three other stations, the age relations are ambiguous.

Figure 9 - Photograph of N55W joint (parallel to pencil) that defines zone filled with breccia. Breccia consists of Redwall Limestone with cemented, comminuted, red Surprise Canyon Formation or Supai Group sediment as matrix. Wall of N55W joint is lined with 2mm thick white crystalline calcite and altered Redwall Limestone with large calcite rhombs bordering the breccia zone. N10W joints (middle right to lower left of photograph) cut the breccia.

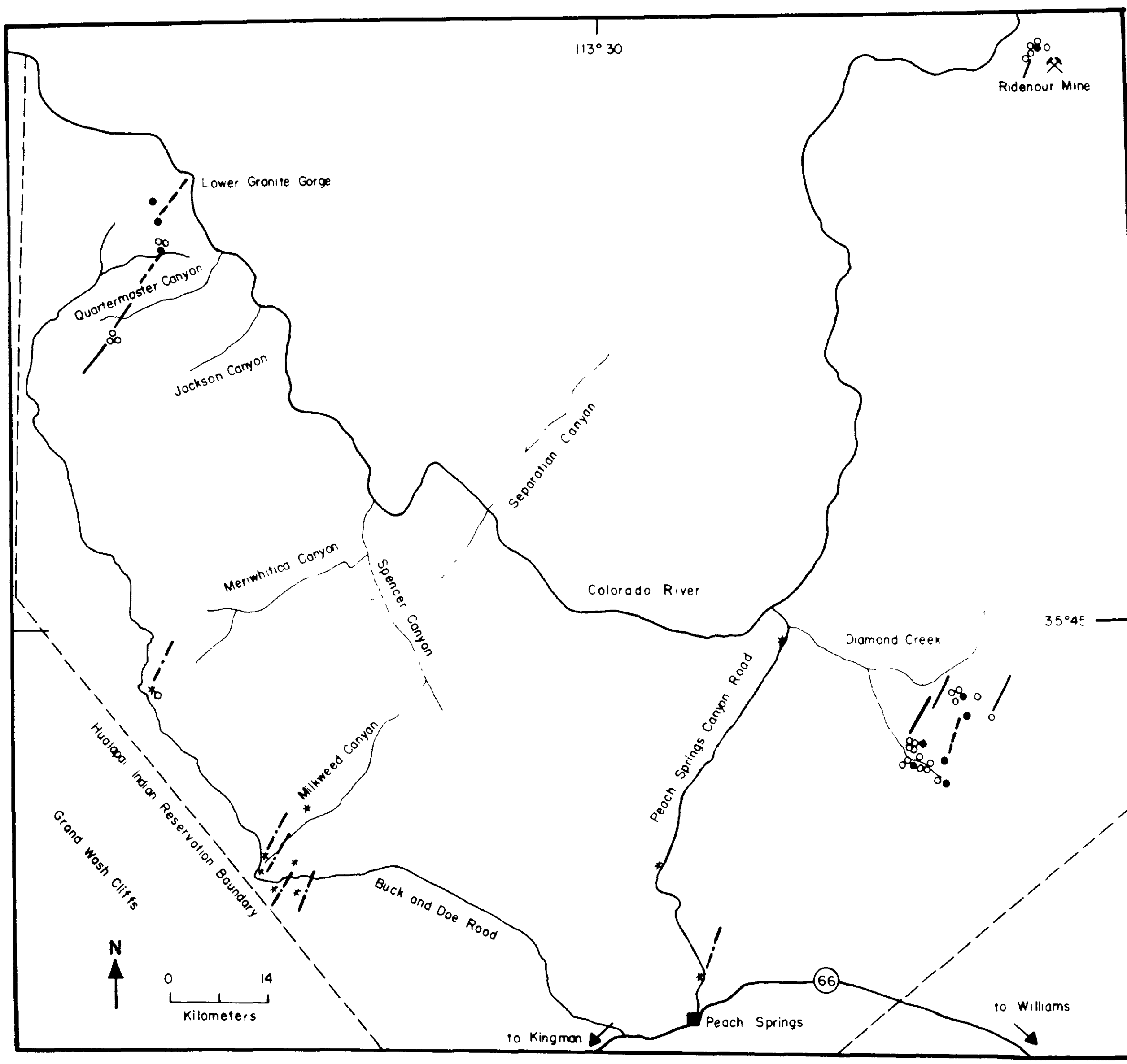

Figure 10 - Map of mean strikes for F2.5 fracture sets in the Redwall Limestone (solid lines), Supai Group (dashed lines), and Tertiary units (lines of dashes and dots). Overall average strike of F2.5 for the Redwall Limestone is N28E; Supai Group is N31E; Tertiary units are N32E.

F2.5 fractures have composite heights of 0.6-3m and composite lengths of 0.4-2.5m. Average spacings across the outcrop are 30-50cm, and can be several meters where they are not well developed. Where they are well developed, F2.5 joints are relatively planar (fig. 11).

Fracture set 3 (F3) Redwall Limestone

Subvertical joints of F3 range in strike from N81E to N87W with the mean centering around N87E (fig. 12). They are not abundant at many of the stations in the Redwall Limestone on the western Hualapai Plateau, although they are well expressed at some stations (29 out of 44). In contrast, F3 joints are often very well developed and prominent on the Coconino Plateau, especially in the Blue Mountain Canyon area. Exposed heights range from 0.2 to 1m and exposed lengths range from 0.1 to 1m. Where F1 and F2 are well developed, F3 fractures tend to be short segments that terminate against the earlier formed joints. Composite heights and lengths range from 1.0 to 2.5m and 0.7 to 4.5m respectively. Spacings of individual F3 fractures average between 20 and 50cm where they are best developed to several meters where they are least abundant.

Fracture set 3 (F3) Supai Group

Strikes of F3 joints range from N84E to N89E; average strike is about N86E in this study (fig. 12) and was N86W in the 1987 study. Dips are subvertical. F3 joints range from planar in clastic units to undulatory in limestone layers. Exposed heights range from 0.3-5m and exposed lengths from 0.2-2m. Similar to the Redwall Limestone, the larger lengths and heights may be composite dimensions resulting from solution along fractures. Spacings average 20-50cm where F3 is well expressed to several meters where only a few F3 fractures are present. Fracture zones up to 30cm wide are locally abundant.

Joints of the east (F3) and the north (F4) sets are commonly the largest and most prominent joints in the Supai Group, especially in the Blue Mountain Canyon area. At some outcrops, F3 joints were not abundant but nevertheless were very large and widely spaced. This is often the case with the oldest fractures.

Fracture set 3 (F3) Tertiary units

F3 fractures range from N87W-N87E and average 90 degrees (fig. 12). They were observed at seven out of ten stations. At many of the stations in olivine basalt, F3 fractures are the most prominent joints and are planar. Average lengths range from 0.7-1.5m and average heights range from 0.4-1.5m. Composite lengths are up to 7.0m and composite heights are up to 3.5m. Average spacing is 20-50cm where F3 is the prominent and abundant fracture set, and spacing increases to several meters where they are not well developed.

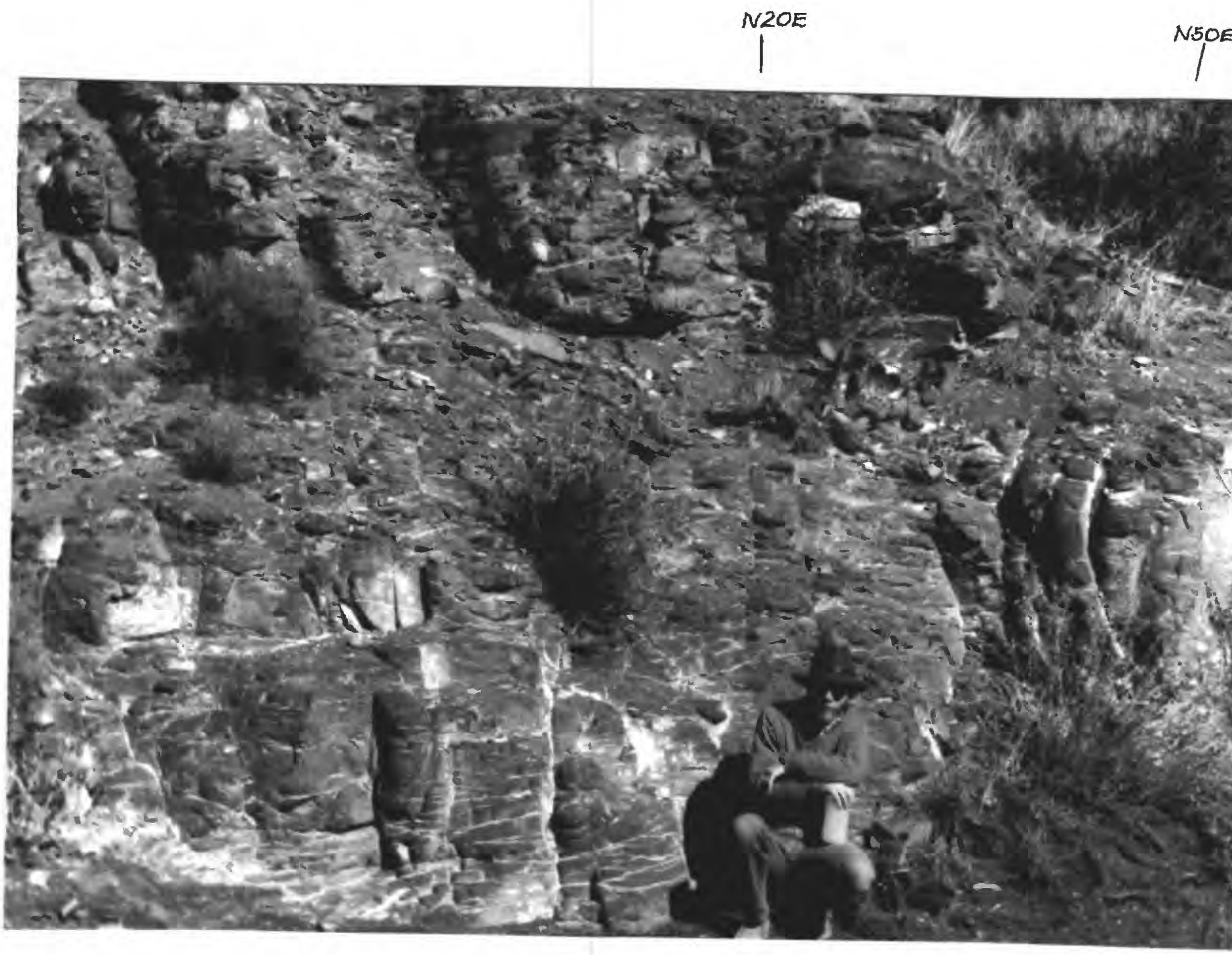

Figure 11 - Set of joints directly behind person in Tertiary basalt strike N20E (F2.5). N50E (F6) joints are well expressed to the right of the person. Station #94.

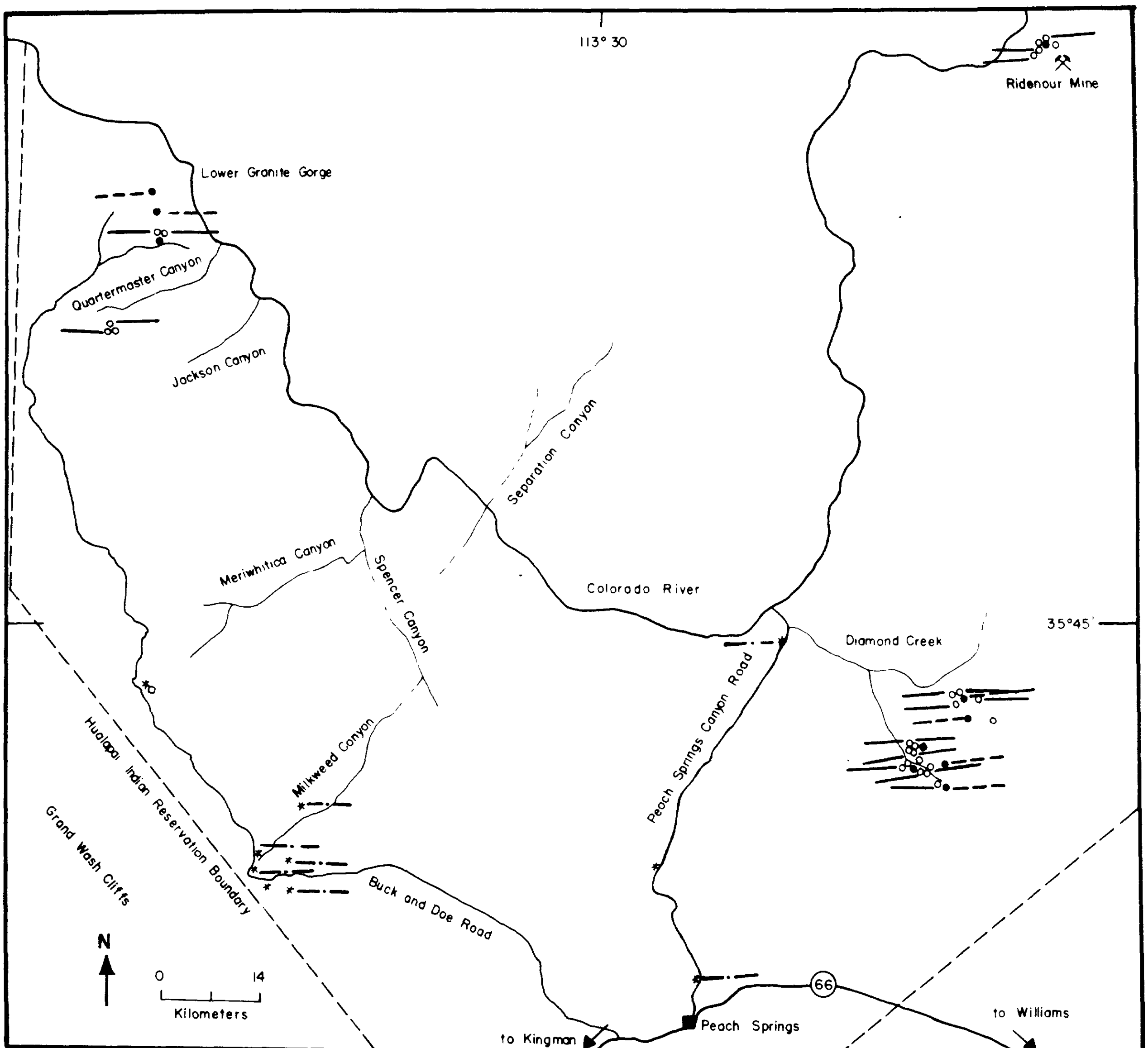

Figure 12 - Map of mean strikes for F3 fractures sets in the Redwall Limestone (solid lines); Supai Group (dashed lines); and Tertiary units (lines of dashes and dots). Overall average strike for F3 fractures in the Redwall Limestone is N87E: Supai Group fractures average N86E; average for Tertiary units is 90 degrees.

Fracture set 4 (F4) Redwall Limestone

F4 joints range in strike between N02E and N14W and average N7W (fig. 13). They usually dip subvertically. In the Blue Mountain Canyon area they are often the most prominent set along with F3 joints. F4 joints have exposed heights of 0.2 to 0.9m and exposed lengths of 30 to 40cm. Composite lengths and heights are up to 2m. Similar to F3 joints, individual spacings range from close, averaging 20-30cm, to several meters apart where poorly developed. Abundant fracture zones with composite lengths of 50m and up to 1m wide were observed at several stations. Joints in these zones are filled with several generations of calcite, with some calcite crystals up to 2cm long, and locally with Redwall breccia and red silty filling.

At one locality between station #69 and #70, fractures trending N10W are partially filled with finely laminated, red, quartz- and calcite-rich siltstone layers cemented by calcite. The siltstone consists of resedimented Surprise Canyon or Supai sediments that were deposited into the irregular shaped N10W fracture zones.

Fracture set 4 (F4) Supai Group

F4 joints strike from N03E to N13W, averaging N6W (fig. 13). In many places, these joints comprise the most prominent set. Joint surfaces are planar to broadly curving to undulatory. Exposed heights range from 0.30-1.4m and exposed lengths range from 0.5-2.7m. Composite lengths are up to 6m and composite heights range from 5-7m. Average spacing where F5 is prominent is 30-80cm. Calcite fills joints with apertures around 1-2mm.

Fracture set 4 (F4) Tertiary units

F4 joints range from 04E-03W, and average north (fig. 13). They were observed at eight out of ten stations. Average heights are 0.2-0.3m and average lengths are 0.2-1m. Composite heights and lengths are up to 5m. Spacing averages 25-60cm and was commonly several meters. These joints are usually planar and are a prominent set in the Blue Mountain Canyon area.

Fracture set 5 (F5) Redwall Limestone

F5 joints have average strikes of N27W (fig. 14) and range from N25W to N30W. This N20W-N30W fracture set is not developed everywhere, although locally the joints can be quite large and prominent.

Composite heights are up to 2.5m and lengths as long as 3m. Many straight, steep drainages and clefts in the Redwall Limestone trend N25W and cut hundreds of meters of stratigraphic section, especially on the Hualapai Plateau.

This set was observed at only one of the six Redwall stations north of the Ridenour Mine (station #63) and it was not well developed. The set is also not well developed at the northern-most stations in the Diamond Creek area, but becomes more prevalent around Blue Mountain Canyon and on the western Hualapai Plateau.

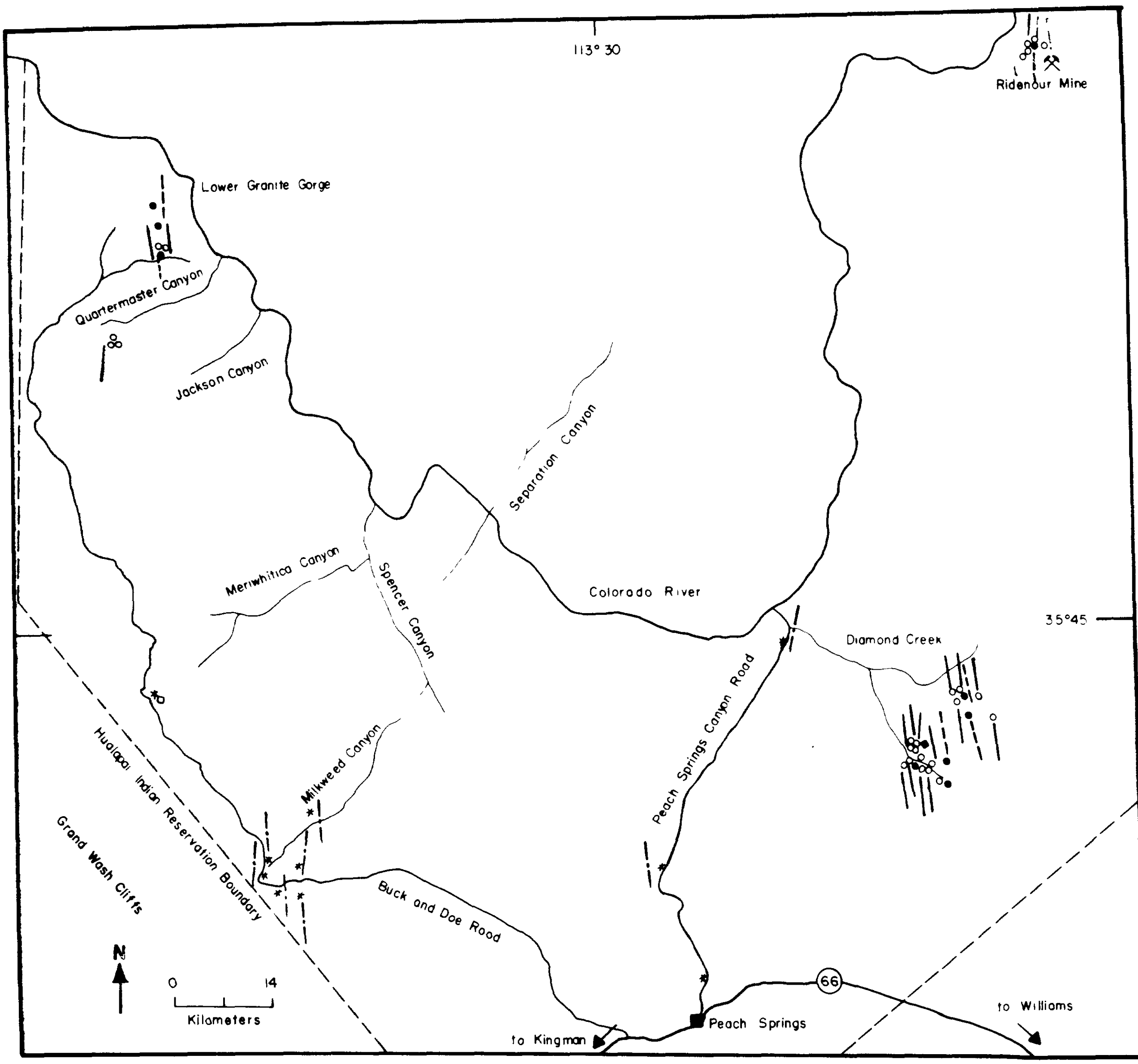

Figure 13 - Map of mean strikes for F4 joints in Redwall Limestone (solid lines), Supai Group (dashed lines), and Tertiary units (lines of dashes and dots). Overall average for F4 in the Redwall Limestone is N7W; Supai Group is N6W; and Tertiary units is north.

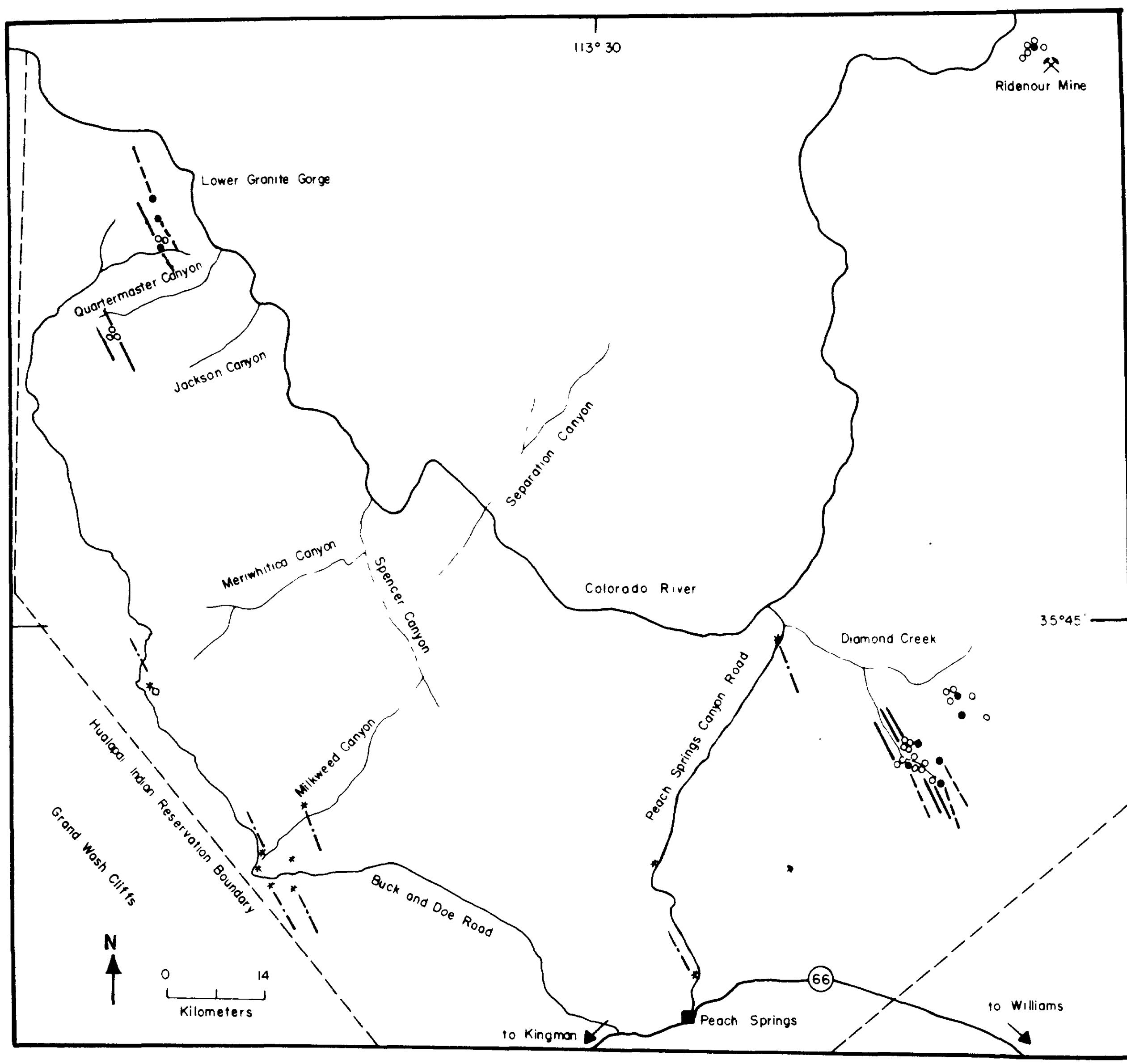

Figure 14 - Map of mean strikes for F5 fracture sets in the Redwall Limestone (solid lines); Supai Group (dashed lines); and Tertiary units (lines of dashes and dots). Overall average for the F5 set in the Redwall Limestone is N27W; average for the Supai Group is N26W; average for Tertiary units is N26W.

Fracture set 5 (F5) Supai Group

F5 joints range in strike from N20W to N31W, and average N26W (fig. 14). They have exposed heights and lengths of 0.2-1m and 0.2-3m respectively, and composite heights and lengths of 1.5-2.5m and 2-7m. In a study of the Esplanade Sandstone of the upper Supai Group in the Ridenour Mine area, Verbeek and others (1988) did not observe this set at the numerous stations studied. They did, however, note its presence approximately 1 mile southwest of the mine during photogeologic fracture mapping of the Esplanade platform (Verbeek and others, 1988). This is another example of fracture sets that vary spatially in prominence across the region.

Calcite-filled joints with apertures less than 5mm are common. Average spacing between F5 joints is 10-50cm, increasing to several meters where they are less well developed. At station #93, F5 joints are very planar but conflicting age relations were observed at this outcrop between N26W (F5) and N86E (F3) joints. The N26W joints have the longest composite lengths at this station and are closely-spaced in fracture zones.

Fracture set 5 (F5) Tertiary units

F5 fractures occur at seven out of ten stations (fig. 14). They average N25W and have exposed heights and lengths of 0.4-1.5m and 0.4-0.7m, respectively. Composite heights and lengths are up to 3.0m and 5.0m, respectively. Average spacing ranges from 0.2-1.5m. These fractures are prominent sets at a few stations where they are also very planar. Fracture zones are 20cm wide and contain numerous closely-spaced joints.

Fracture set 6 (F6) Redwall Limestone

Joints of fracture set 6 strike an average of N50E, subparallel to the older F1 joints. F6 joints terminate against older fractures and are commonly short (less than 20cm), which is typical of young joints. These joints appear to be more common on the Coconino Plateau than on the Hualapai Plateau (fig. 15), which consistently exhibits well-developed, large early F1 fractures. F6 joints may represent a combination of reactivation along F1 trends, and/or fractures that formed parallel to F1 trends but at a later time than F1. More work is necessary to clearly sort out the F6 history. They were not observed at all stations.

At stations #61-#66, northwest of the Ridenour mine, both F1 and F6 joints were observed based on relative age relations. It is sometimes difficult to separate the younger N50E joints from the older ones in limestone where few age relations exist and seemingly conflicting age relationships are common.

Fracture set 6 (F6) Supai Group

The average strike of F6 joints is N58E (fig. 15). These joints are commonly sparse but are locally well developed in lower Supai units, such as at stations #80, #88, and #99 where they are one of the dominant joints

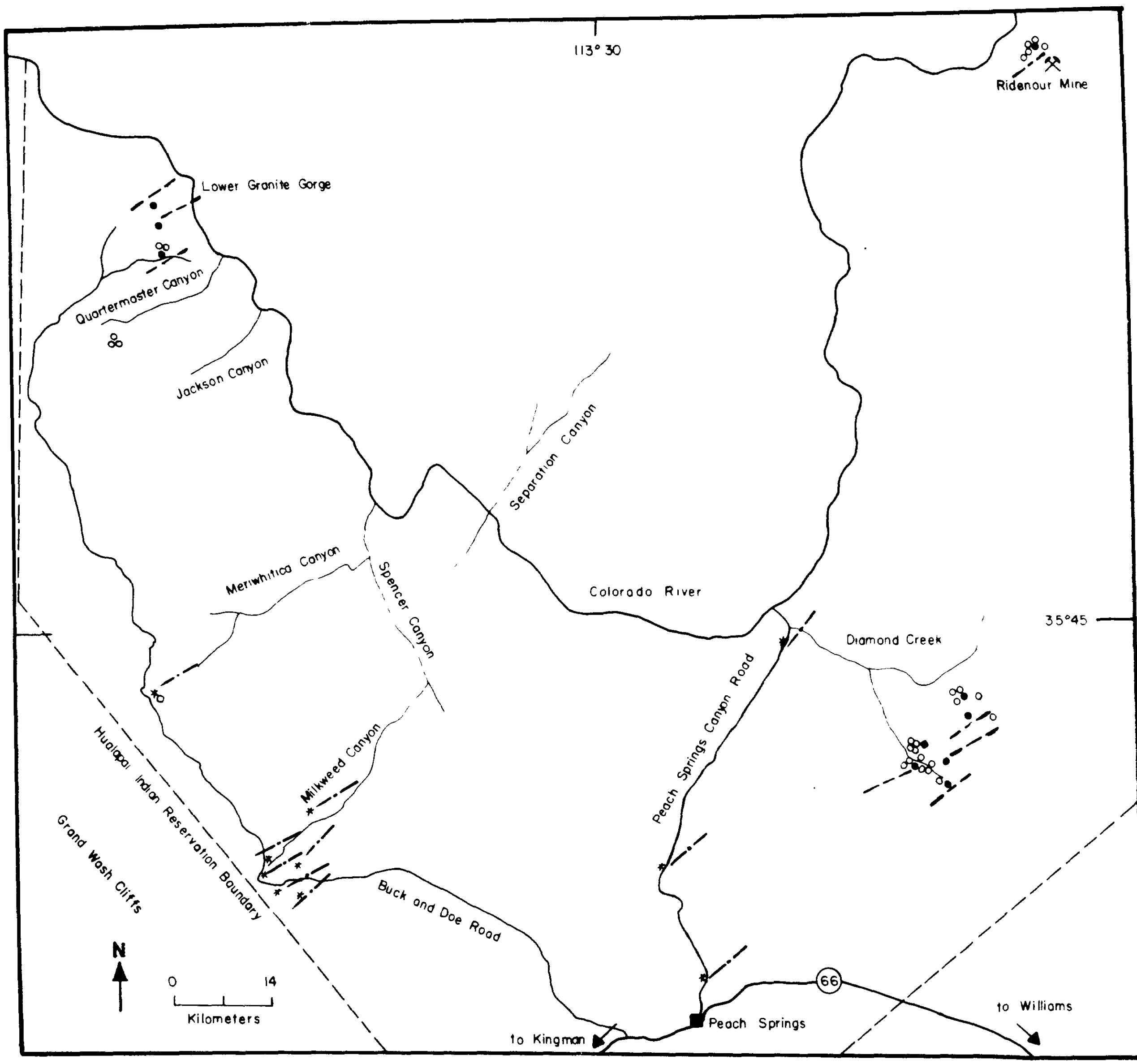

Figure 15 - Map of overall strikes for the F6 fracture set in the Supai Group (dashed lines) and Tertiary units (lines of dashes and dots). Overall average for F6 fractures in the Supai Group is N58E and average for Tertiary units is N56E. Too few measurements for F6 were taken in the Redwall Limestone to warrant representation on the map.

sets. In zones with very long composite lengths, the individual segments are very undulatory. Although this set is one of the younger sets, it is commonly well developed locally whereever the older sets have wide spacings. This was also observed in the 1987 study. At station #95, F6 joints terminated against subhorizontal parting joints.

Fracture surfaces are planar to undulatory. Exposed heights range from 0.2-2m and exposed lengths from 0.2-2.5m. Composite heights and lengths range from 0.6-3.5m to 0.2-10m. Average spacing of F6 joints is 20-30cm where well developed to several meters in outcrops where they are sparse. Fracture zones are relatively common with numerous closely spaced joints within a 15-30cm wide zone.

Fracture set 6 (F6) Tertiary units

F6 joints average N50E and were observed at all ten Tertiary stations (fig. 15). They have exposed heights and lengths that average 0.3-1.5m and 0.4-1.5m, respectively. Composite heights and lengths are up to 8m and 6m, respectively. Average spacing of F6 joints is 0.2-1m. At station #106, F6 joints are prominent and planar, although they often exhibit irregular surfaces. Fracture zones are common.

Fracture set 7 (F7) Redwall Limestone

Joints of fracture set 7 have orientations similar to those of the F2 set. F7 joints tend to be short and terminate against fractures F1 through F6.

Fracture set 7 (F7) Supai Group

The average strike of F7 joints is N54W (fig. 16), and ranges from N47W to N62W. Other characteristics are similar to those of F6 joints in terms of prominence, height and length, and spacing.

Fracture set 7 (F7) Tertiary units

Fracture 7 joints occur at seven of the ten stations. The average strike of F7 joints is N50W (fig. 16). Exposed heights average 0.4-1m and exposed lengths average 0.4-1m. Composite heights and lengths average 0.3-2m and 0.5-2.5m respectively. Average spacing of F7 joints is 0.2-1m and is often several meters spacing where F7 joints are not well expressed. These young joints are usually undulatory (fig. 17).

Fracture set 8 (F8) Redwall Limestone, Supai Group, and Tertiary units

Fracture set 8 has similar orientations of F2.5, but has been determined to be younger than all previous sets based on relative age relationships. These joints have irregular surfaces and are small both in terms of exposed height and length. They are bound by subhorizontal uplift joints. This fracture set was also observed by Verbeek and others (1988) in the upper Supai

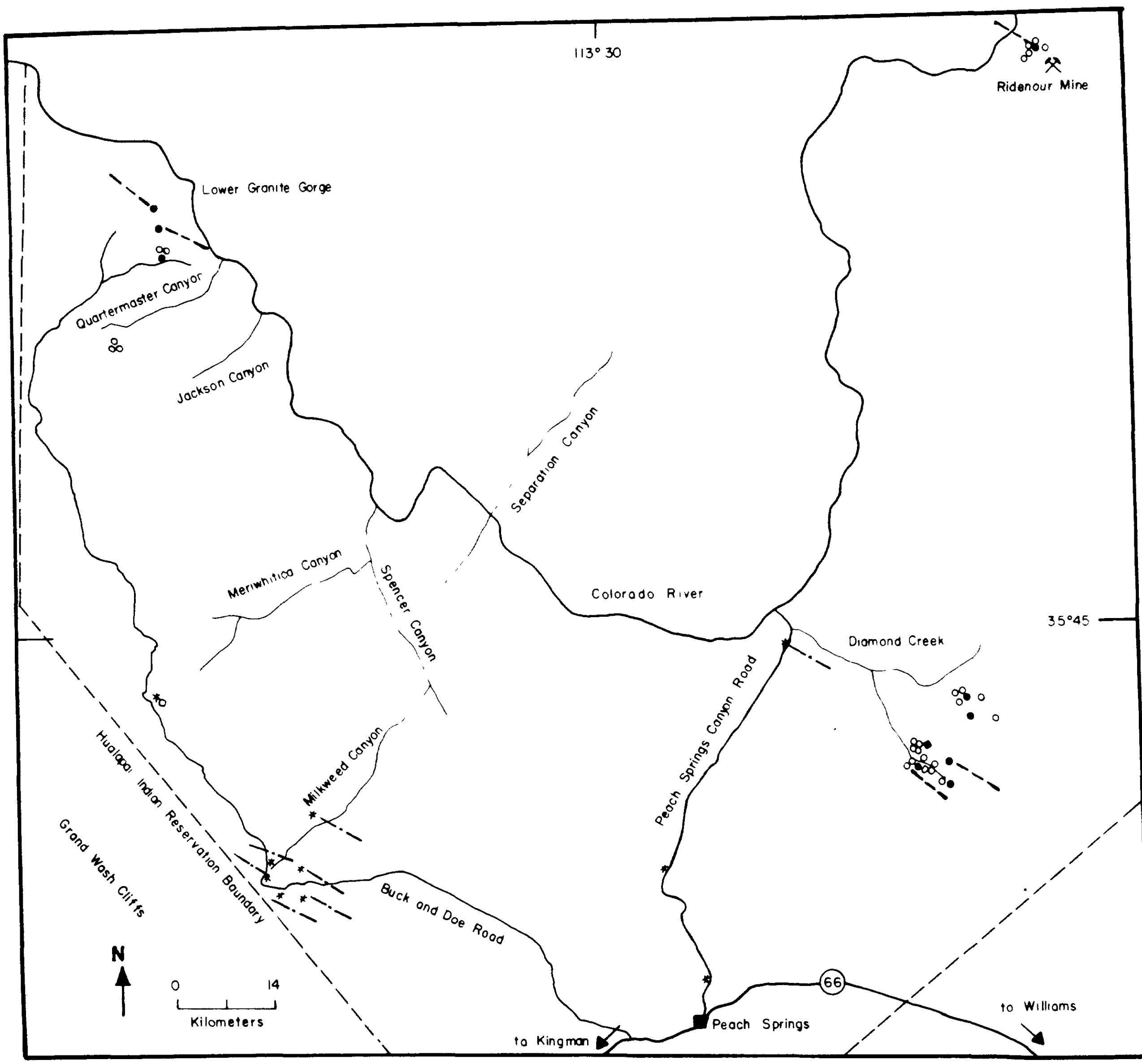

Figure 16 - Map of mean strikes for the F7 fracture set in the Supai Group (dashed lines) and Tertiary units (lines of dashes and dots). Overall average strike for the Supai Group is N54W and average for Tertiary units is N59W.

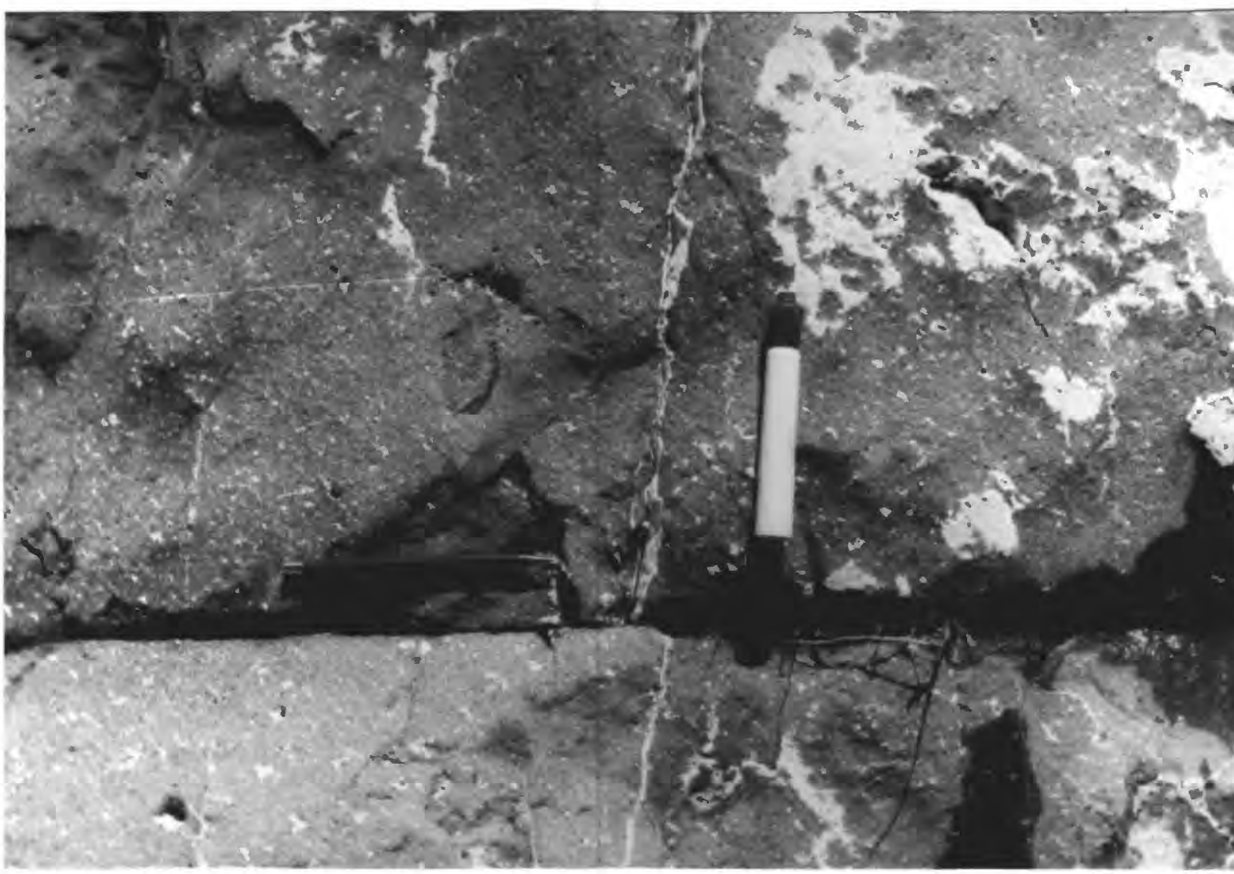

Figure 17 - Caliche-filled N50W (F7) joints parallel to the magic marker are terminated by a planar N50E (F6) joint that parallels the pencil. Station #94 in Tertiary basalt.

Group near the Ridenour Mine, and this F8 set occupies the same relative age position in their fracture history of the Ridenour Mine area.

Mineralization along joints

All joint sets in the Redwall Limestone contain calcite cement, usually consisting of a lustrous, white to gray coarse-grained calcite. Two types of calcite cement can also occur in the same fracture, and typically, the gray or white variety is found with an iron-stained one. The iron-stained calcite was observed both in the middle of the opening and lining the fracture. In addition to terminations of younger joints by earlier joints, crosscutting of joints is prevalent in the Redwall Limestone and shows that many early joints were closed by cementation prior to formation of later joints.

No cement unique to the two early sets in the Redwall was observed, nor was there any cement that was common in proximity to or within breccia pipes. The only exception is within pipe #874 (near station #84): limonite and goethite nodules were locally ubiquitous and a thin (2mm) black (goethite?) filling coated a very small area of a subhorizontal fracture in a solution cavern. This was the only case of cement other than calcite observed to fill joints in the Redwall Limestone.

Several F2 joints at station #61 contained angular limestone pieces (1-4cm long) that were cemented by a caliche matrix. This feature could have formed either by very closely spaced anastomosing fractures that coalesced and branched apart isolating pieces of limestone or could be brecciated limestone that was later cemented by caliche.

Coarsely crystalline white calcite was observed to fill fractures of all seven sets in the lower Supai Group and Tertiary units. Aperatures ranged from 0-3mm wide.

FRACTURES IN COLLAPSE BRECCIAS WITHIN THE REDWALL LIMESTONE

Stations adjacent to and within six breccia pipes were studied to determine if early F1 and F2 joints in the Redwall Limestone controlled the formation of the pipes, as hypothesized by Sutphin and Wenrich (1983), Wenrich and Sutphin (1988), and suggested by the results of Roller (1987). The results of studying these six pipes are not conclusive with regards to controlling pipe formation, but some interesting observations were made that, with more detailed work, might aid in answering this question. It was possible to examine only the upper exposed sections of most of the breccia pipes because much of the breccia is exposed on sheer cliff faces that are not readily accessible. An exception is pipe #369 (from Billingsley and others, 1986) in the lower Supai (station #96), which is well exposed and easily accessible.

Stations #78 and #79 are not in a pipe proper but are in the Redwall Limestone on opposite sides of pipe #876 south of Blue Mountain Canyon. Very little of the actual breccia pipe was accessible. In this area, east (F3) and north (F4) fractures are generally the most prominent sets in both the Redwall Limestone and lower Supai Group. F1 and F2 joints are either weakly developed, nonexistent, or prominent only very locally. However, at stations #78 and #79, F1 and F2 joints are prominent, planar, and closely-spaced, on the order of 10-20cm versus several tens of centimeters to meters at surrounding stations. Redwall outcrops at these two stations look like rubble due to very close density of fracture spacing of the northeast (F1) and northwest (F2) joints (fig. 18).

Densely-spaced F1 and F2 joints also occur at station #97 next to pipe #369. Figure 19 shows a photograph of prominent, densely-spaced joints in proximity to the breccia pipe. The fracture density in the cliff wall several hundred meters away from the breccia pipe is reduced. North (F4) fractures are most obvious in the photo, but F1 and F2 fractures are also well developed and closely-spaced.

Breccia visible at pipe #369 is composed of lower Supai limestone blocks (Watahomigi Formation). Most of the joint surfaces in the breccia are very irregular and the few that are planar have both subvertical dips or relatively shallow (42 to 65 degrees) dips. The most prominent sets in the breccia are N20-40E (F2.5) and N20-30W (F5). Less prominent north (F4), northeast (F6) and northwest (F7) joints cut the breccia. Immediately adjacent to the pipe, however, and approximately 5 meters below station #98, northwest (F2) joints (based on relative age determinations) in the Redwall Limestone are very densely spaced (1-15 cm) and prominent (fig. 20). Spacing of F2 joints increases to several meters away from the pipe.

One possible scenerio is that a densely-spaced early F1 and F2 fracture system in the Redwall Limestone localized and concentrated fluid flow, which initiated cavern formation along these early fracture networks. Some of these caverns later developed into pipes. A densely-spaced subvertical, nearly perpendicular fracture network would encourage formation of rectangular blocks of Redwall Limestone like the blocks of rubble observed adjacent to several pipes. This bears on the apparent absence of ring fractures in the Redwall Limestone and the existence of ring fractures as the first fracture network to be imposed in the overlying Supai Group as is well-documented by Verbeek and others (1988). Verbeek and others (1988) have documented in detail that mineralized ring fractures associated with the Ridenour Mine pipe formed in unjointed upper Supai rock (Esplanade Sandstone) immediately adjacent to the breccia pipe. Ring fractures are unlikely to form or be well-defined in rock that is already jointed. Several large ring fractures were observed in Supai rock just outside of breccia pipe #369 approximately 100m above the densely-spaced northwest fractures in the Redwall Limestone. No ring fractures were observed in the underlying Redwall Limestone.

Summary

Table 1 summarizes the orientations of the different fracture events within the Redwall Limestone, Supai Group, and Tertiary units on the Hualapai and Coconino Plateaus. The two oldest fracture sets in the Redwall Limestone, have no correlatives in terms of both orientation and relative age among joint sets in the Supai Group. Thus, the fracture histories of the Redwall Limestone and Supai Group overlap only in part. Fracture sets 2.5 through 8 of the Redwall Limestone appear to correlate with fracture sets 2.5 through 8 of the Supai Group: the orientations agree and the relative ages are in identical sequence. Therefore, these suggested correlations are almost certainly correct.

All six orientations of fractures cut breccia within collapse structures in the Redwall Limestone and Supai Group. These fractures also cut the Tertiary basalts and gravels. No definitive age relations of the fracture sets, however, were observed for the breccia, so the suggested correlations of sets and inferred similarities of fracture histories are based only on fracture orientations.

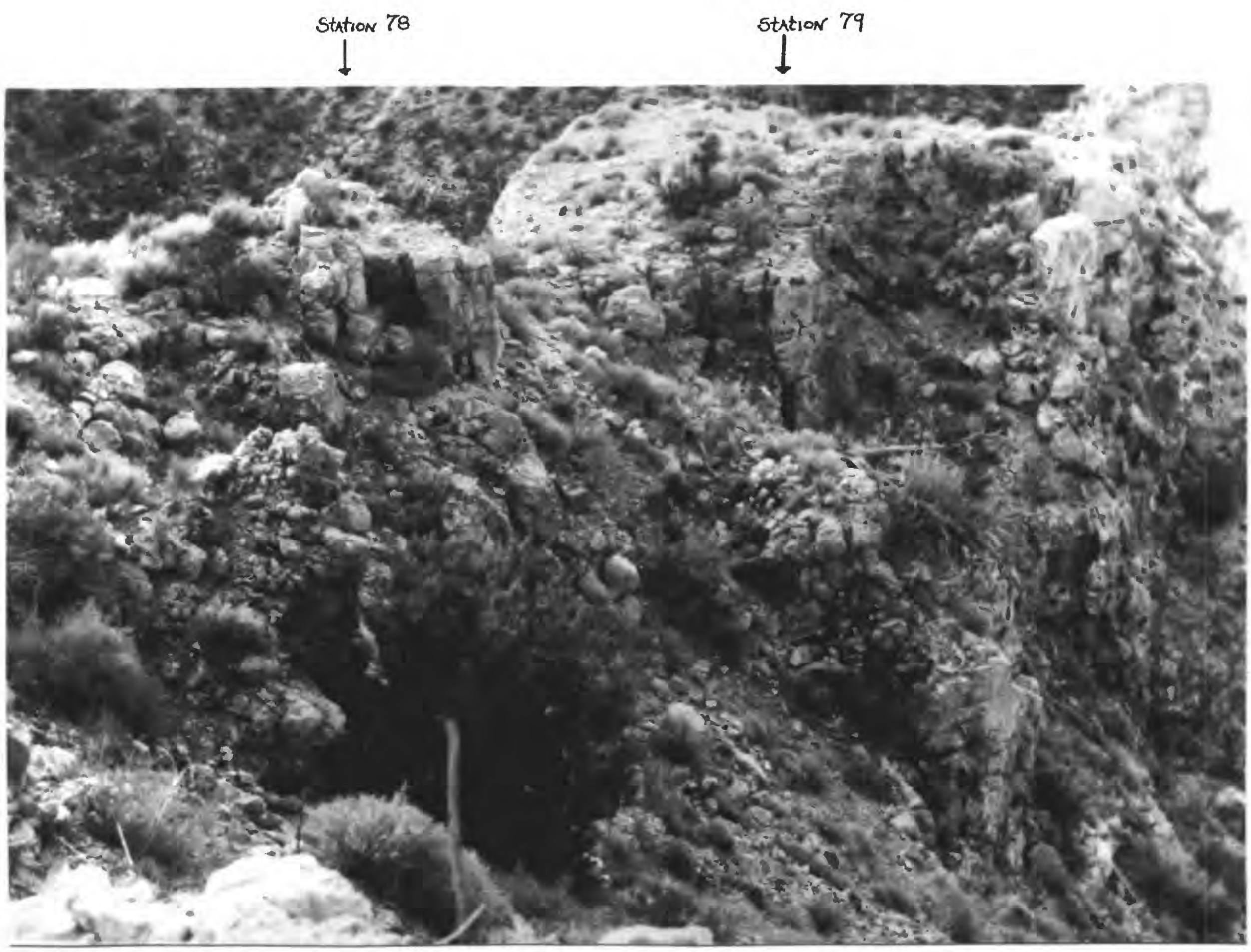

Figure 18 - View of stations #78 and #79 and pipe #876 south of Blue Mountain Canyon. Closely-spaced northeast (F1) and northwest (F2) joints give the outcrop a rubbly appearance.

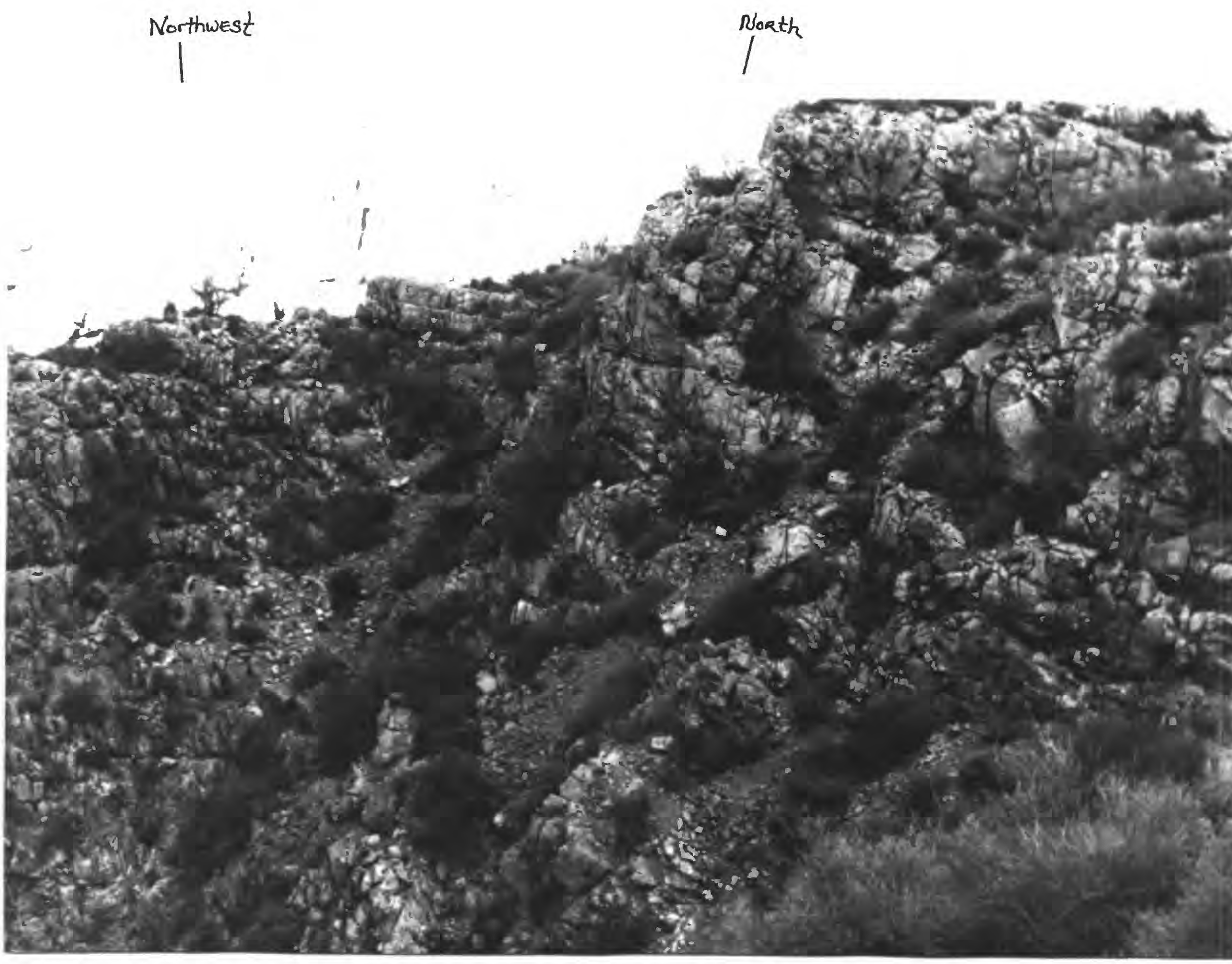

Figure 19 - Prominent north-striking joints (F4) and closely-spaced northwest-striking joints (F2) at station #97 near pipe #369.

Figure 20 - Closely-spaced northwest-striking joints (F2) parallel to the hammer immediately adjacent to pipe #369. Outcrop is Redwall Limestone.

Table 1 - Summary of average strikes and suggested correlations for fracture sets F1 through F8 for the Redwall Limestone, lower Supai Group and Tertiary units.

GEOLOGIC UNIT	FRACTURE SET								
	F1 (oldest	F2	F2.5	F3	F4	F5	F6	F7	F8 youngest)
Redwall Limestone	N50E	N51W	N28E	N87E	N7W	N25W	N50E	N50W	N28E
Lower Supai Group	n.f	n.f	N30E	N86E	N6W	N26W	N58E	N54W	N30E
collapse breccia in Supai Group	n.f	n.f	N30E	N86E	N6W	N25W	N58E	N54W	N30E
Tertiary units	n.f	n.f	N35E	east	north	N25W	N50E	N50W	N35E
Upper Supai Group (Verbeek and others, 1988)	n.f	n.f	n.f	n.f	N2W	ap*	N68E	N60W	N35E

n.f. = not found

*ap = this set was not observed in the immediate vicinity of the Ridenour Mine, but is a relatively prominent set on aerial photographs approximately one mile southwest of the mine. Age relations were not observed between this set and the other sets, so the placement of this set in the fracture history scheme is based on conjecture.

TECTONIC IMPLICATIONS OF THE HUALAPAI AND COCONINO PLATEAU FRACTURE PATTERN

Paleozoic strata and Tertiary units on the Hualapai and Coconino Plateaus have been subjected to numerous stresses that initiated joint development. Although I do not attempt to determine the event responsible for each fracture set, it is reasonable to propose that the early northeast- and northwest-trending fracture sets (F1 and F2) in the Redwall Limestone, which do not have correlatives in the Supai Group, formed prior to deposition of the Supai Group. As mentioned in the 1987 report, residual stress from the Antler Orogeny, that caused gentle upwarping during regional uplift at the end of Mississippian time (Skipp, 1979), might have imposed the early northwest and northeast fracture network upon the Redwall Limestone. Karst features, including sinkholes, caverns, and solution breccia were also widespread in the Redwall Limestone during the late Mississippian (McKee, 1979; Billingsley, 1986), and it is possible that karst development was promoted by an extensive fracture network.

Fracture sets 2.5-8 cut the lower Supai Group, breccia, and Tertiary units, which shows that a great deal of fracturing has occurred in relatively recent time, at least post 18my (age of Peach Springs Tuff). Thus a large part of the fracture history of the Hualapai region does not overlap in time with deformation events that produced the large monoclines that fold Paloeozoic strata on the Hualapai Indian Reservation during the late Cretaceous to early Tertiary.

The southwest margin of the Colorado Plateau has been uplifted two to three miles since the Cretaceous, and more than 3000 feet of uplift has occurred along the Grand Wash Fault in the last 5 million years (Wenrich and others, 1986). It would be reasonable to expect that this large amount of uplift has affected the rocks of the Hualapai Plateau either directly as McGill and others (in press) suggest (see below) or possibly millions of years later as Ramsay and Huber (1987) suggest. Ramsay and Huber (1987) state that it is doubtful that joints form during major tectonic events but most likely are related to the last phases of orogenic activity or to a "release of stored orogenic elastic strains during periods of uplift, perhaps millions of years after the main tectonic event." However, McGill and others (in press) propose that normal faults in the Grand Canyon area affect regional stress fields and cause fracturing of rocks over wide regions that are not faulted. Locally, the faults cause densely-spaced jointing close to the fault traces. If faulting does cause some fracture formation, the extensive record of recurrent movement along major faults on the Hualapai and Coconino Plateaus (Billingsley and others, 1986) might have produced a very complex fracture system composed of many reactivated joints or segments parallel to earlier-formed fractures during the late Tertiary.

POSSIBLE CONTROLS OF BRECCIA PIPE LOCATIONS BY FRACTURES

It remains premature to state definitively that early F1 and F2 fractures in the Redwall Limestone controlled pipe formation, although the following observations support the suggestion: 1) Northeast (F1) and northwest (F2) fracture sets were imposed upon the Redwall Limestone prior to fracturing within the Supai Group. At what time the fracturing of the Supai Group rocks occurred is not known from the available data, but the fact that all of the Tertiary units studied also contain the same sets as the Supai Group introduces the possibility that the Supai was not fractured until tens of millions of years after it was deposited, perhaps during uplift of the Colorado Plateau in the late Tertiary. 2) The close association of pipes and the Surprise Canyon Formation (Billingsley, 1986; Wenrich and others, 1986) supports the notion that cavern development within the Redwall Limestone occurred shortly after deposition and lithification, prior to and/or synchronous with deposition of Surprise Canyon sediments in river valleys and caverns. Rivers and karst features are both dependent on large water discharge, which is facilitated by a fractured and porous rock unit. 3) A map of underground passageways and caverns in the Redwall Limestone west of Peach Springs Canyon shows five pipes that are all located in northwest (F2)- and northeast (F1) - striking passages (Wenrich and Sutphin, 1989). Numerous passageways with N05E, N15W, and N30E trends were also mapped, but no pipes were found along these trends. 4) Ring fractures appear to be well developed in Supai rocks adjacent to pipes, but none have been observed in the Redwall Limestone. If the Redwall already contained a network of fractures then the ring fractures, which form as a sort of pressure release in unjointed rock, would not form in the Redwall as it was already fractured. 5) Four stations studied in the Redwall adjacent to pipes exhibited anomolously closely-spaced early formed fractures . The closely-spaced joints may have concentrated fluid flow, thus localizing groundwater movement and promoting solution and cavern development.

Wenrich and others (1986) state that with a few exceptions, breccia pipes on the Hualapai Plateau appear to be distributed irregularly (fig. 21) compared to the Marble Plateau where a strong northeast and northwest distribution has been mapped (Sutphin and Wenrich, 1983). Alignments that were noted on the Hualapai Plateau include N40E, N50W, and N10-20W trends. The apparent irregular distribution of pipes on the Hualapai Plateau does not necessarily preclude the possiblity of early fracture control of cavern formation. Figure 22 is a simplistic illustration showing a network of northeast and northwest fractures in the Redwall Limestone. In this diagram, it is assumed that caverns occur at both the junction of two major fractures and along single fractures, as observed in the cavern map in Wenrich and Sutphin (1989). Pipe locations can either appear totally irregular if the pipes are spaced far apart or in areas where several pipes occur, one could connect pipes in virtually all orientations described in this report - northeast, northwest, N25E, northerly, N25W, and easterly. The impression is of a seemingly irregular distribution when in fact pipe locations in this illustration were originally controlled by early fractures. If one looks at just the mineralized pipes (squares with circles) on the Hualapai Plateau (see fig. 21), one sees two distinct northerly trends with at least four pipes (Bat Tower area and north of Plain Tank Flat) in addition to several easterly, northwesterly, and northeasterly trends. Thus it is possible that the early northeast and northwest fractures did control cavern location even though the distribution pattern appears irregular.

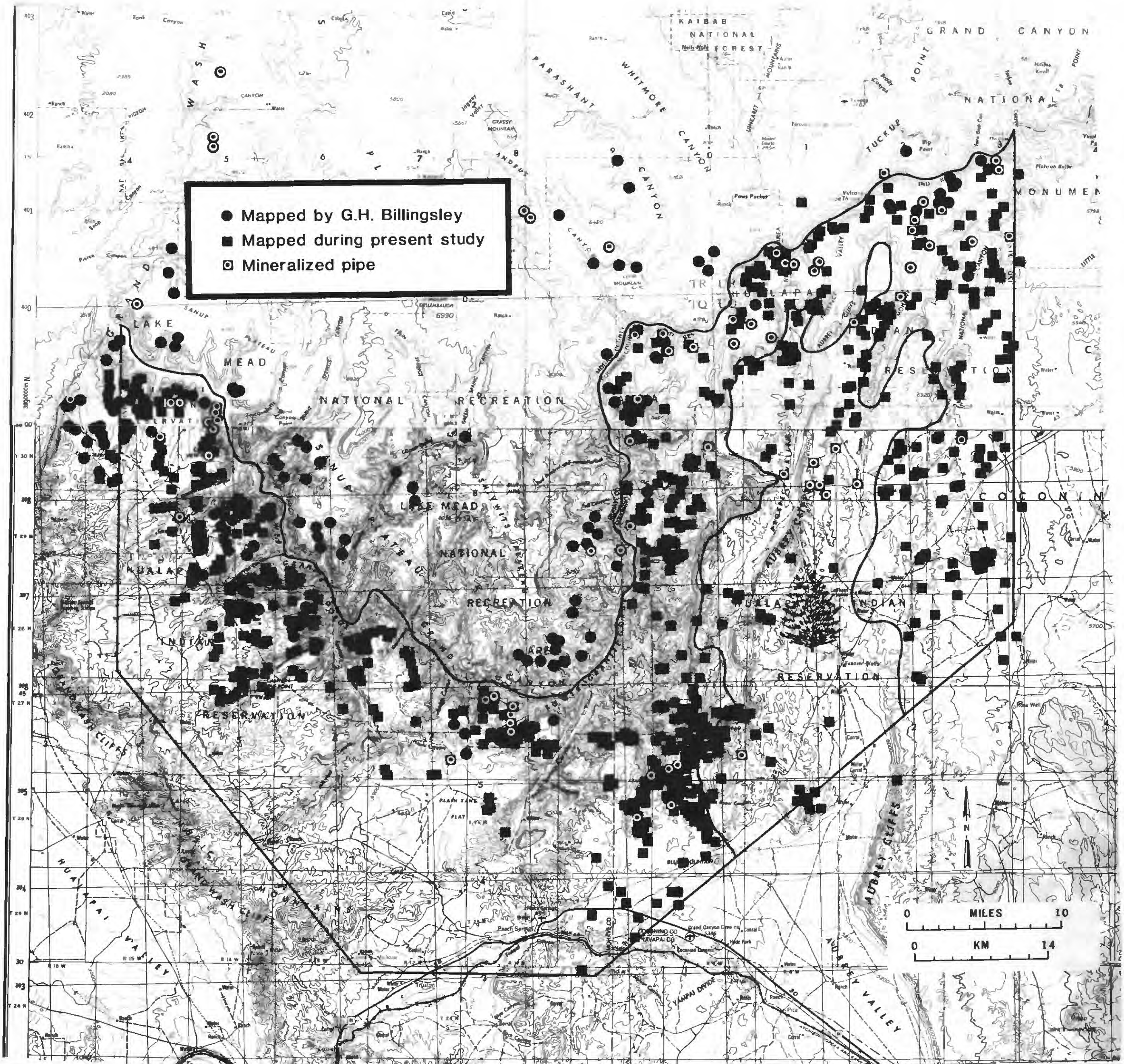

Figure 21 - Map of collapse features, including known and suspected breccia pipes, on the Hualapai Indian Reservation. The tree on the eastern side of the reservation represents heavily forested areas within which collapse features are difficult to detect. Some of these collapse features were mapped by G. H. Billingsley prior to 1982; the majority were mapped by K. J. Wenrich, G. H. Billingsley, and H. B. Sutphin during 1982-1988. Taken from Wenrich, Billingsley, and Van Gosen (1986).

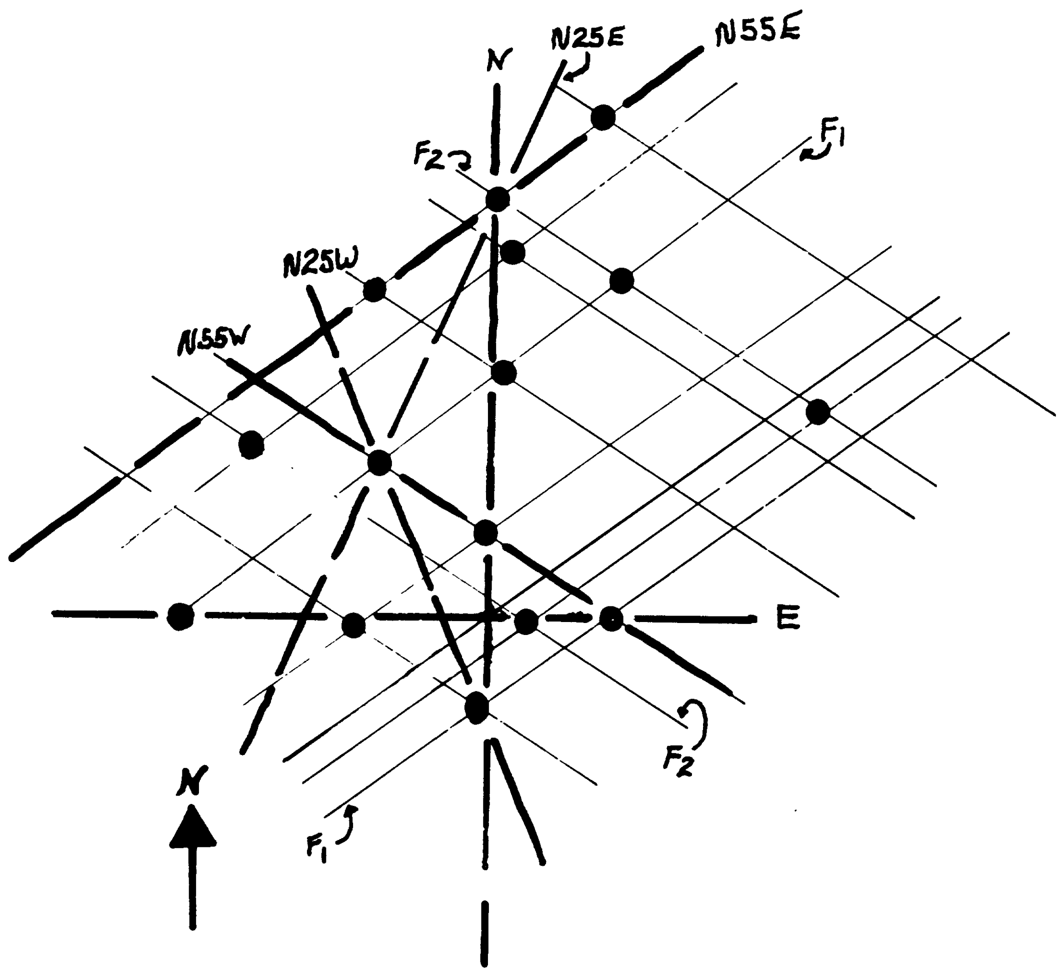

Figure 22 - Simplistic illustration showing how early northeast (F1) and northwest (F2) fractures in the Redwall Limestone could control breccia pipe locations at depth in the Redwall Limestone, although the surface expression of the pipes, when connected by lines, shows numerous orientations that imply that an irregular distribution of pipes exists.

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