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Fracture history of the Redwall Limestone and lower Supai Group, western Hualapai Indian Reservation, northwestern Arizona

by

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INTRODUCTION

The Hualapai Indian Reservation is located in northwestern Arizona, north of Highway 66 and south of the Lower Granite Gorge of the Colorado River (fig. 1). The study area encompasses the western half of the reservation between Peach Springs Canyon to the east, the Grand Wash Cliffs to the west, and the Colorado River to the north. Numerous large, northeast-trending tributaries of the Colorado River have dissected this area, known as the Hualapai Plateau.

The Hualapai Plateau, an erosional surface that formed during Paleocene time (Young, 1979), is capped predominantly by the Mississippian Redwall Limestone. Several isolated outcrops of the Mississippian Surprise Canyon Formation fill canyons as deep as 400 ft (122 m) eroded into the upper Redwall Limestone in late Mississippian time (Billingsley and Beus, 1985). Isolated remnants of the Pennsylvanian/Permian Supai Group crop out in the northern part of the Hualapai Reservation, and more extensively, north of Hindu Canyon. Tertiary basalt flows lie directly on the Redwall Limestone, although in a few areas, basalt caps erosional remnants of the Supai Group.

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

Three 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 western Hualapai Plateau. The Meriwhitica, Horse Flat, 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 northeast.

Recent mapping of the Hualapai Reservation has revealed the presence of over 900 collapse features, including 100 that have been identified as breccia pipes (Billingsley and others, in prep.; Wenrich and others, in prep.; 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 fragments with or without a matrix (Bryner, 1961). Exposures of pipes along canyon walls show that they are steep-sided features, which many workers believe originate in the Redwall Limestone (Wenrich and Sutphin, 1983; Sutphin and others, 1983; O'Neil and others, 1981; Baillieul and Zellinger,1980; Wenrich-Verbeek and Verbeek, 1980: Bowles, 1977). Upward enlargement of caverns within the Redwall prompted the collapse of overlying formations into the caves. Most of this collapse breccia within pipes consists of angular to subrounded fragments with a coarse sand matrix.

Sutphin and Wenrich (1983) and Wenrich (1985) suggest that the location of breccia pipes farther east on the Marble Plateau is controlled by northwest- and northeast-trending fracture zones in the Redwall Limestone that propagated upward from Proterozoic basement structures. They suggest that

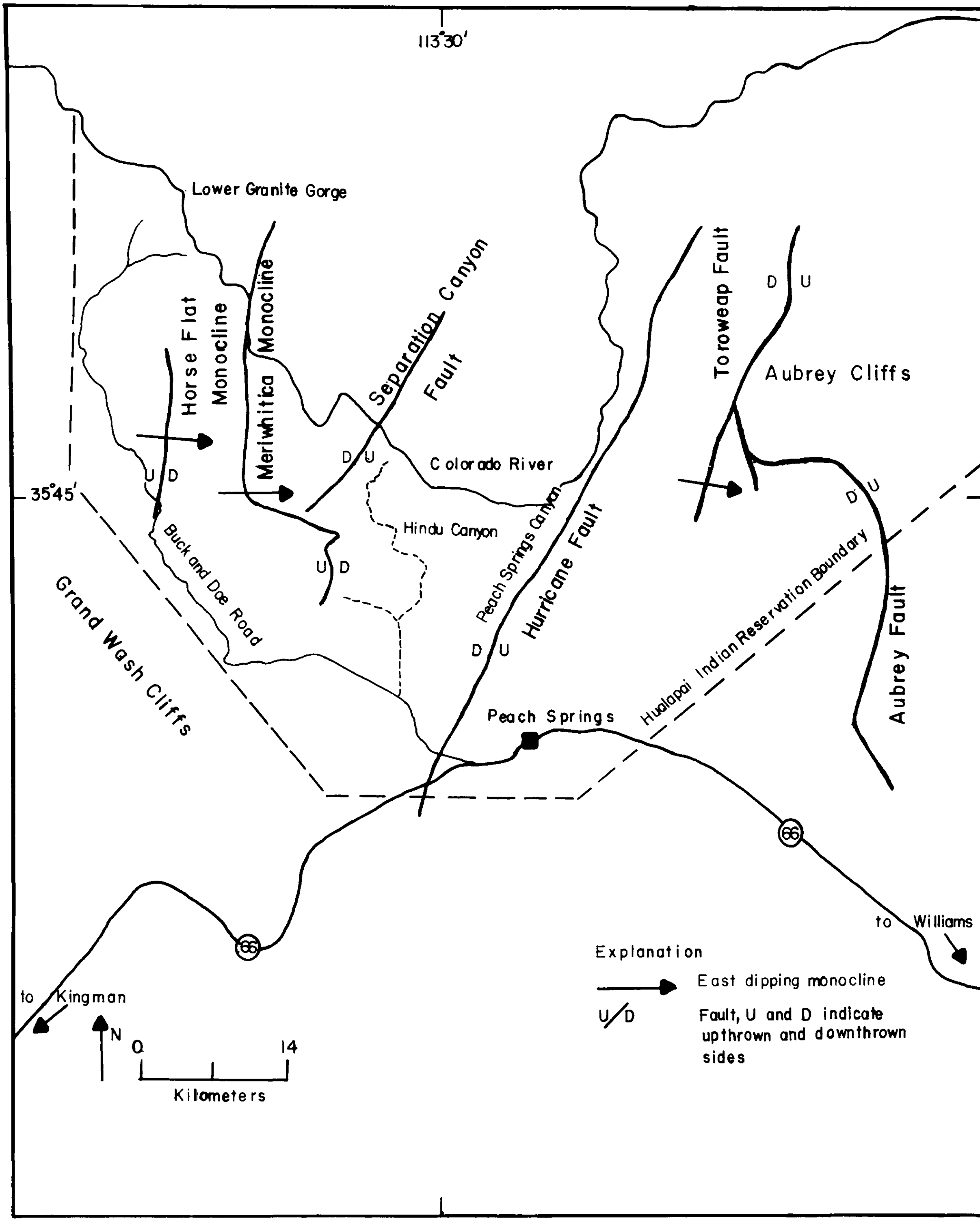

Figure 1 - Location map of the Hualapai Indian Reservation and major structural features, northwestern Arizona. (Modified from Huntoon, 1981, and Billingsley and Huntoon, 1983).

areas in which to focus exploration can be identified from the hypothesis that pipes are concentrated along these northeast and northwest trends.

This study of the Hualapai Plateau is a preliminary analysis of the fracture history of the Redwall Limestone and lower Supai Group. The study was designed to document the controls, if any, of Redwall Limestone fracture systems on the breccia pipes of that region.

METHODS

Sixty stations were studied in the western half of the Hualapai Reservation (fig. 2) The majority of stations (44) are in the Redwall Limestone. Less intensive examination of fracture systems within the Surprise Canyon Formation (1 station), the Supai Group (12 stations), and Tertiary basalts and gravels (3 stations) was also conducted to determine if the fracture history of the Redwall Limestone differs from that of the overlying formations.

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

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

Unraveling the fracture history of limestone is further complicated by the commonly extensive solutioning and consequent widening of either large, single fractures or a zone of closely spaced fractures. Terminating relationships among solution-widened fractures of different sets are commonly obscure when different joints, that once terminated on opposite sides of an older joint, 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 and the lower Supai Group.

FRACTURE PATTERN

This study indicates that the fracture pattern of the Redwall Limestone differs significantly from that of the overlying Supai Group on the Hualapai Plateau. The Redwall Limestone contains seven fracture sets, whereas the Supai Group contains five sets. Designation of sets is not only based on joint orientation, but also considers the 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. In addition, a

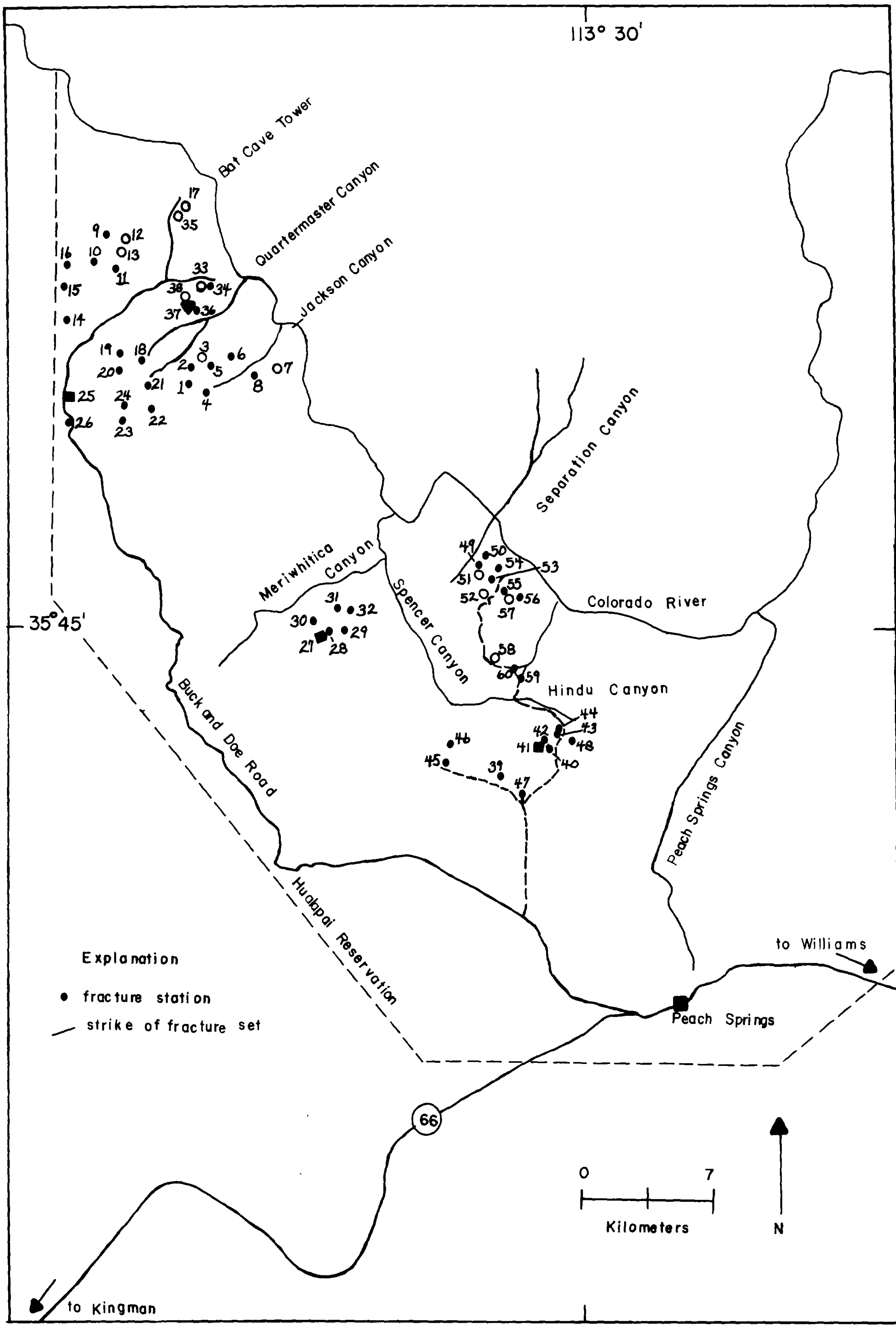

Figure 2 - Location map of stations. Black circles are stations in Redwall Limestone; triangle is Surprise Canyon Formation; open circles in lower Supai Group; squares in Tertiary basalts and gravels.

segment of a F1 joint that formed later by reactivation 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 more than five episodes of fracturing took place. This conclusion will be developed further in the following sections.

In the Redwall, joints of the two oldest sets (designated F1 and F2 respectively) strike N50E and N50W. Three younger sets (F3, F4 and F5) strike approximately east, north and N25W. In addition, there are two sets (F6 and F7) that have similar orientations to F1 and F2, but they are younger than F3, F4 and F5 joints as determined by age relations.

In contrast, joints of the two oldest sets (F3 and F4) in the Supai Group strike east and north, and joints of the younger sets strike N25W, N50E and N50W (F5, F6 and F7). The age relations at the one station studied in the Surprise Canyon Formation are not definitive, but it appears that the fracture sets might correlate with those of the underlying Redwall Limestone. These observations indicate that the northeast and northwest sets in the Redwall Limestone formed prior to jointing within the Supai Group. Therefore, F1 and F2 fracture sets do not exist in the Supai Group. Three stations studied in Tertiary basalts and gravels that cap the Redwall Limestone contain the five orientations that are seen in both the Redwall Limestone and the Supai Group.

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.

FRACTURE SETS OF THE REDWALL LIMESTONE

Recognition of fracture sets within the Redwall Limestone is straightforward at the majority of stations, although uncertainties do occur. 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). Dips were often difficult to measure precisely, as they varied as much as 20 degrees on either side of vertical along the same undulatory joint. It is commonly difficult to discern whether variable orientations actually reflect 1) a broad spread in orientation of the same set, 2) undulatory joint surfaces due to intense 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 (fig. 3). Widening of the fractures due to solution has destroyed the details. As an example, the relationship between joints whose orientations cluster around N25W with the north and N50W sets is not always clear. The N25W set is commonly 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 I placed the N20-30W joints into their own set.

Solution along subhorizontal fractures is pervasive in the Redwall Limestone. Numerous caves several meters across and high occur at the junction between large joints of the N50E and N50W sets and horizontal partings. Steep joints of all sets both crosscut and terminate against horizontal joints.

Low-angle joints (dips between 30 and 60 degrees) were observed at

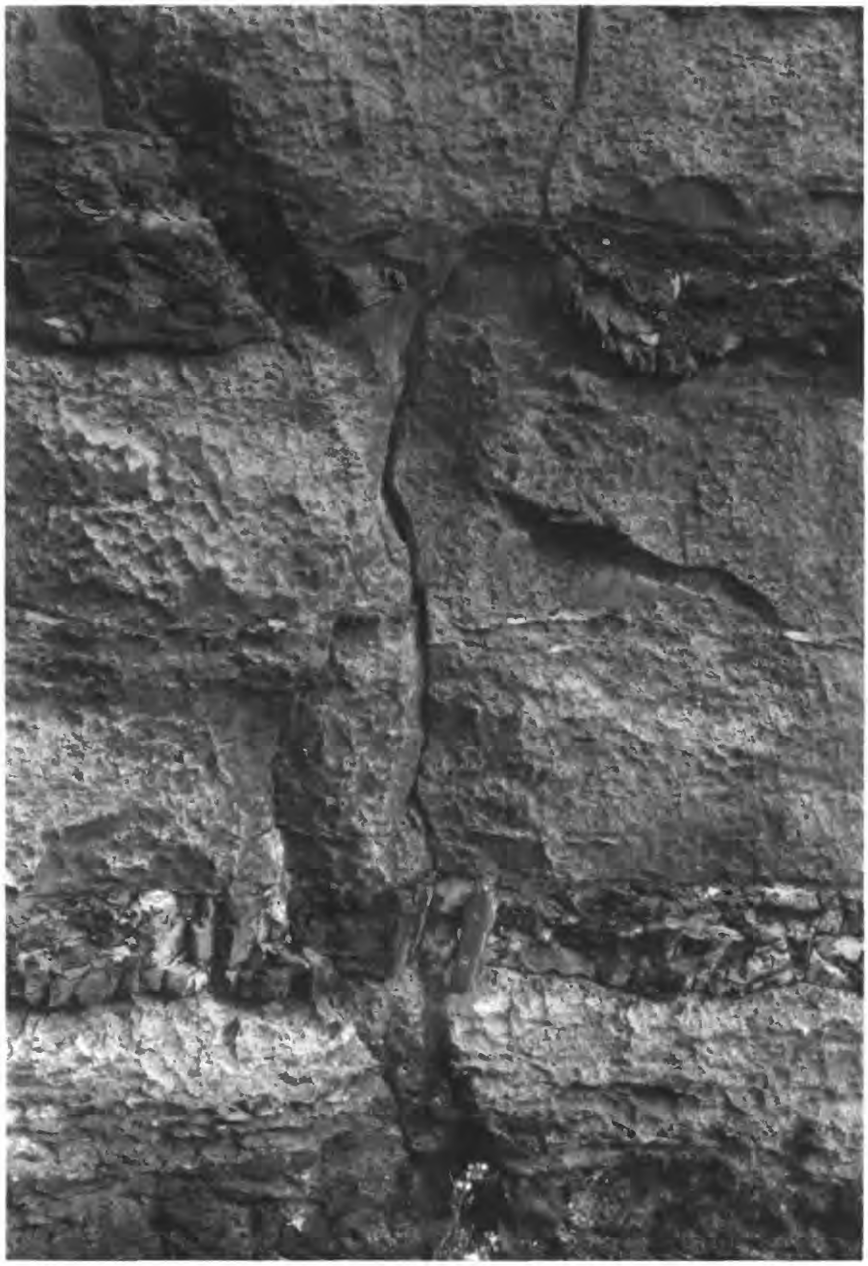

Figure 3 - Fractures are planar (parallel to knife) where they cut thin, dark layers of limestone but undulate along height of N45E fracture in highly pitted limestone at station #21 in Quartermaster Canyon quadrangle. Second fracture set is N55W.

several stations. These joints are commonly large and cut the steep joints and several meters of stratigraphic section; no shear offset is apparent.

Calcite occurs on joints of all the fracture sets throughout the study area, although not at every outcrop. The most common form of calcite is a white or gray, coarse-grained, lustrous filling. 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.

Fracture set 1 (F1)

Individual F1 joints strike N65E to N20E with mean averages about N50E (fig. 4). At some stations they tend to cluster between N30E and N45E, while at others they range from N50E to N65E; both extremes also exist at the same station. Dips are usually within 10 degrees of vertical on planar surfaces. Joints of this oldest set are present at all but one station in the Redwall Limestone and are always prominent and dominant (fig. 5).

Relative age relations at the majority of stations, as determined by the methods of Grout and Verbeek (1983), indicate that the N50E set is the oldest. It consistently truncates younger sets or the younger sets hook into the larger F1 fractures. At a few stations, however, fractures other than those of the N50E orientation truncate some of the N50E joints. These N50E joints are interpreted to be younger than the joints they terminate against, so they have been placed in the F6 fracture set.

Crosscutting of mineralized F1 joints by F2 joints is relatively common, and suggests that F1 was mineralized prior to F2 formation, which allowed the younger F2 fractures to propagate across the filled F1 fractures (fig. 6). White calcite and/or iron-stained calcite fills F1 joints; apertures most commonly range from 0.5 to 2.0 mm, but can be as much as 2 cm wide.

F1 joints are the largest and most consistently planar joints of all sets. Exposed lengths between 0.7 to 4.0 m, and heights from 0.6 to 4.0 m are typical. The large exposed heights and lengths might be the result of solution and the resultant coalescence of two or more very closely spaced joints. Whether the large measurements belong to an individual fracture is commonly difficult to tell for all the fracture sets in the limestone.

Fracture zones comprising several closely spaced joints cut tens of meters of section and are common in the study area. Solution along these zones has created voids as wide as 1 meter, which are typically open or partially filled by iron-oxide-stained calcite cement. Caverns are widespread along F1 trends plus at the junction between F1 and F2 joints. Zones of large calcite-filled vugs and calcite megacrystals appear to lie along northeast-striking fractures.

Fracture set 2 (F2)

Joints of the F2 set strike between N35W and N65W and cluster around N40W-N50W (fig. 7). Dips are frequently near vertical, although some undulatory surfaces vary greatly in dip. At station 10, dips of F2 were both very shallow and steep (between 51 and 85 degrees), changing from shallow to steep to shallow along the length of the outcrop within the same bed. Joints of all other sets at the station have steep dips only.

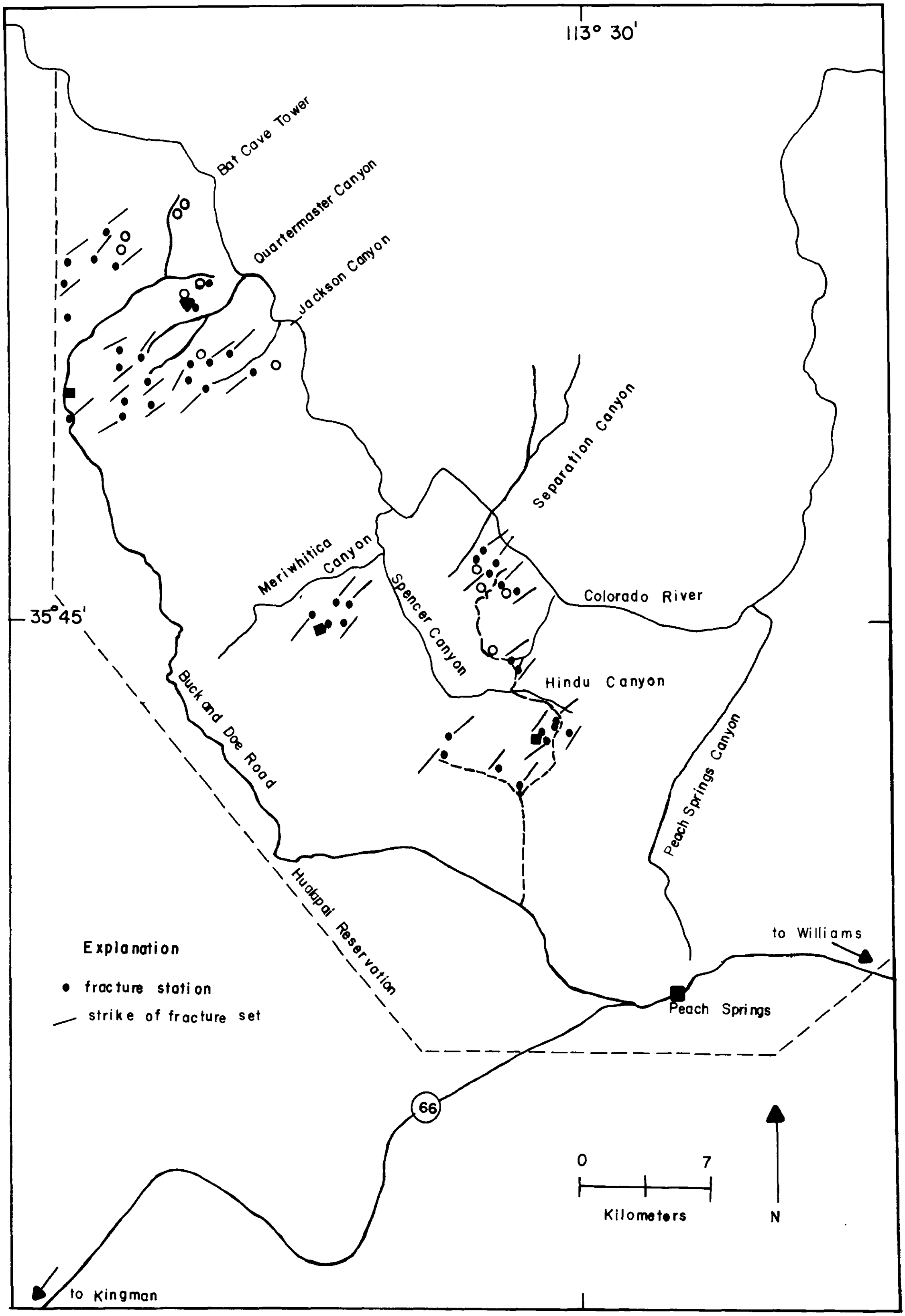

Figure 4 - Map of mean strikes for the F1 fracture set in the Redwall Limestone.

Figure 5 - Closely spaced N50E fractures west of station #29, Spencer Canyon quadrangle. Cluster of trees (arrow) occupies a wide fracture zone.

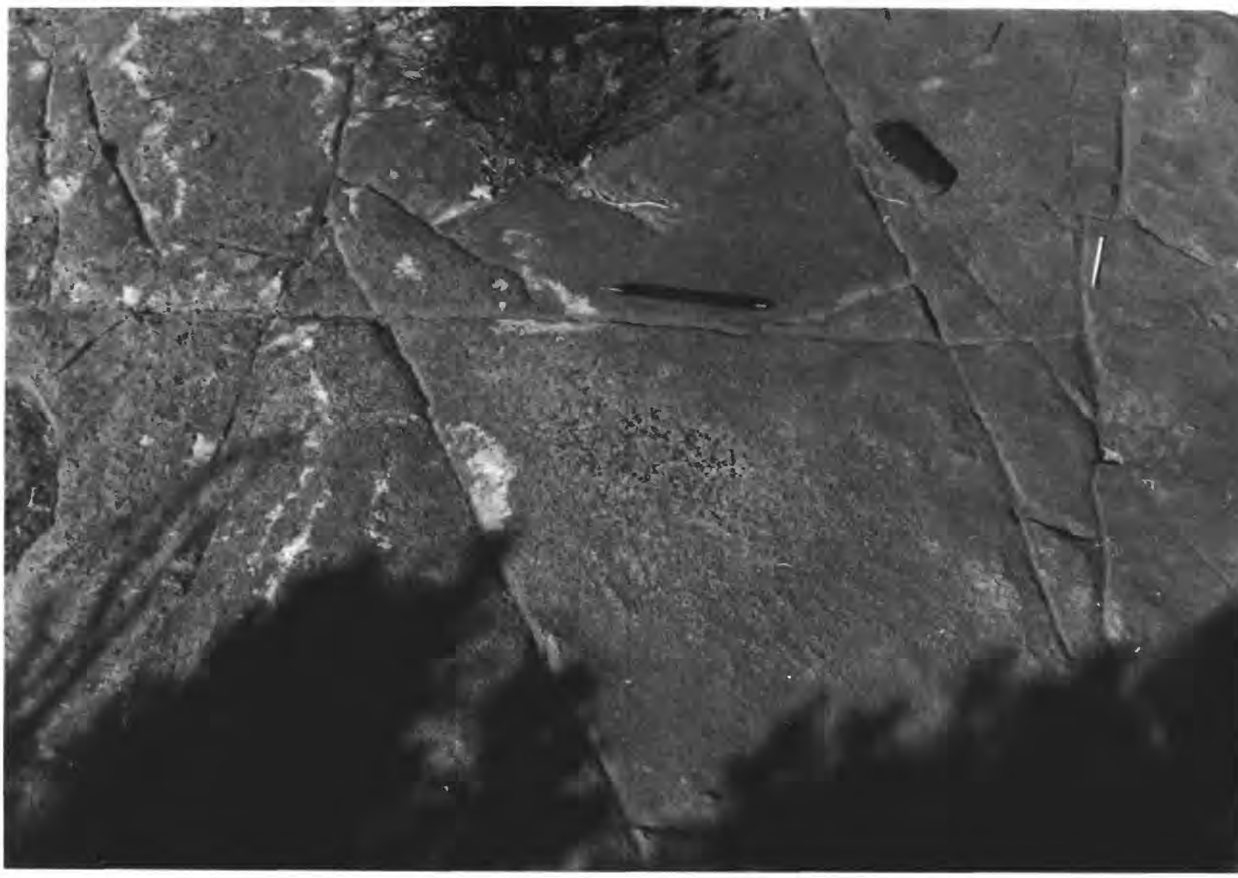

Figure 6 - N47E (F1) fracture (parallel to pencil) crosscut by N50W (F2) fractures (parallel to toothpick) and east (F3) fractures (parallel to knife) at station #28, Spencer Canyon quadrangle. Note that F3 fractures are short and connected along steps.

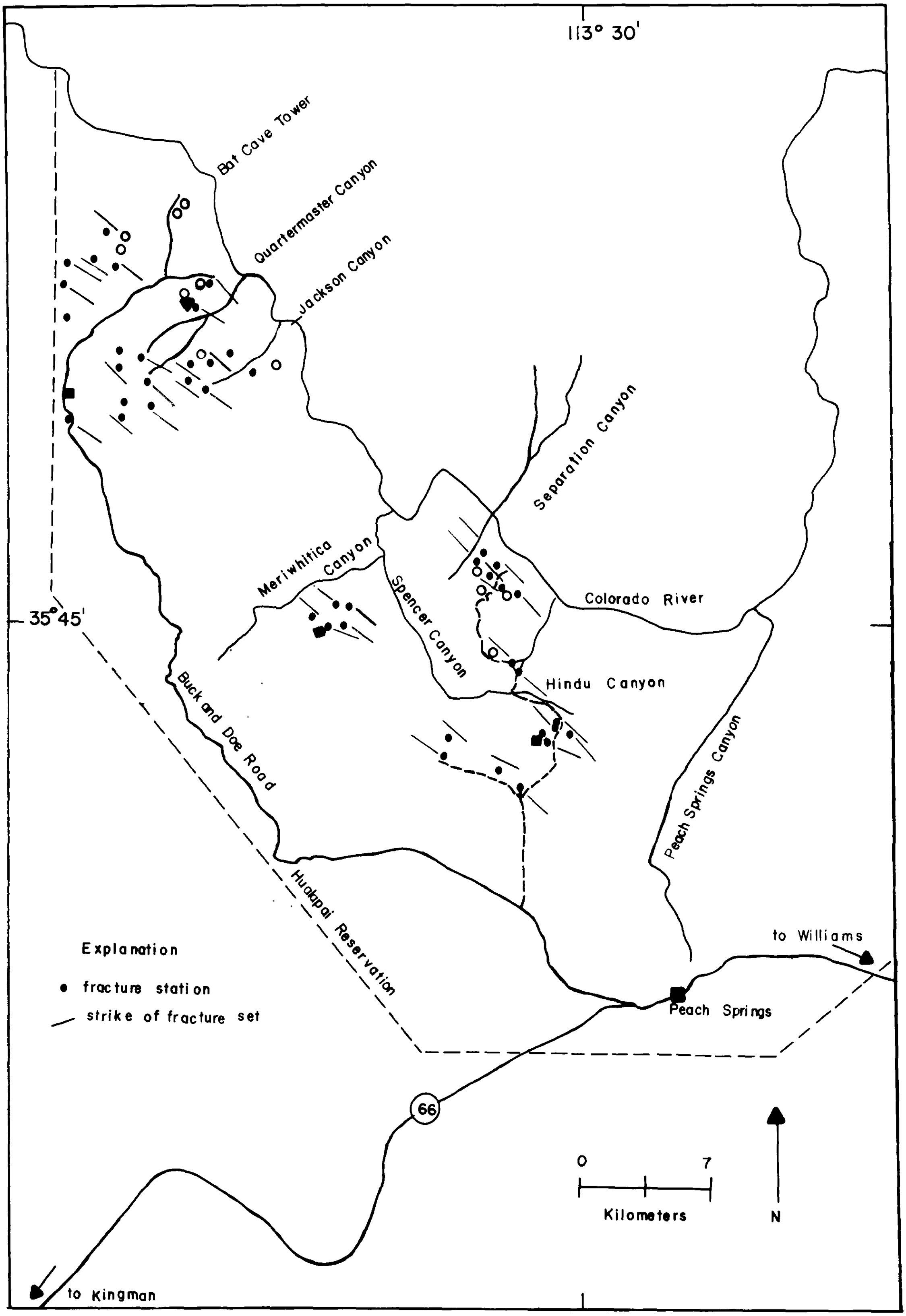

Figure 7 - Map of mean strikes of the F2 fracture set, Redwall Limestone.

F2 joints are found at a majority (37 of 44) of stations. Along with F1 joints, F2 joints are usually planar and are a prominent and large set with exposed heights of 0.5 to 3.0 m and lengths of 0.5 to 4 m. Fracture zones as much as 1 m wide, but normally 10 to 40 cm wide, are abundant; composite heights and lengths of 4 to 5 meters are common. Average spacing of individual joints outside fracture zones is about 20 to 40 cm.

F2 joints termintate or hook into F1 joints. Gray and white calcite and iron-stained calcite fracture fillings are present, although not at all stations. At station 11, an early formed calcite filling was later brecciated and recemented by an iron-stained cement, suggesting reactivation along the northwest joint set. This suggests that the iron-stained cement is younger than the white and gray cement.

Fracture set 3 (F3)

F3 joints range in strike from N70W to N70E but the mean centers around N88W to N85E (fig. 8). They are not abundant fractures at many of the stations in the Redwall Limestone, although they are well expressed at some stations (29 out of 44), and large, possible fracture zones of F3 joints often form cliff faces on the order of 100's of meters in the Redwall Limestone. These zones are important in controlling canyon wall topography and possibly fluid flow as shown by abundant springs and plants on the cliff faces.

Individual F3 fractures are smaller and more undulatory than those of the F1 and F2 sets. Exposed heights range from 30 cm to 2.5 m and exposed lengths from 40 cm to 5.1 m. Spacings of individual F3 fractures average between 30 and 60 cm, where they are best developed, to several meters where they are least abundant. Even where they are not prominent, they commonly form zones up to 1 meter wide that cut several meters of section.

Fracture set 4 (F4)

F4 joints range in strike between N19E and N15W and generally dip subvertical (fig. 9). F4 joints are commonly undulatory with exposed heights of 0.3 to 1.2 m and exposed lengths of 0.3 to 2.2 m. Similar to F3 joints, individual spacings range from close, averaging 20-40 cm, to several meters apart where poorly developed. Fracture zones are often 20 to 40 cm wide and are commonly opened by solution.

Fracture set 5 (F5)

F5 joints commonly have orientations close to both the northwest and north sets. The average strike of joints of the F5 set is about N25W (fig. 10). The N20W-N30W fracture set is not everywhere abundant, although locally the joints can be quite large and prominent. At several stations, a distinct break exists between orientations of N25W and the F2 and F4 set, so fractures of N25W are placed in a separate set. (fig. 11).

Closely spaced fracture zones are common with composite heights (presumed convergence of several individual fractures) as much as 15 m and lengths as long as 30 m. Many straight, steep drainages and clefts in the Redwall Limestone trend N25W and cut 100's of meters of stratigraphic section.

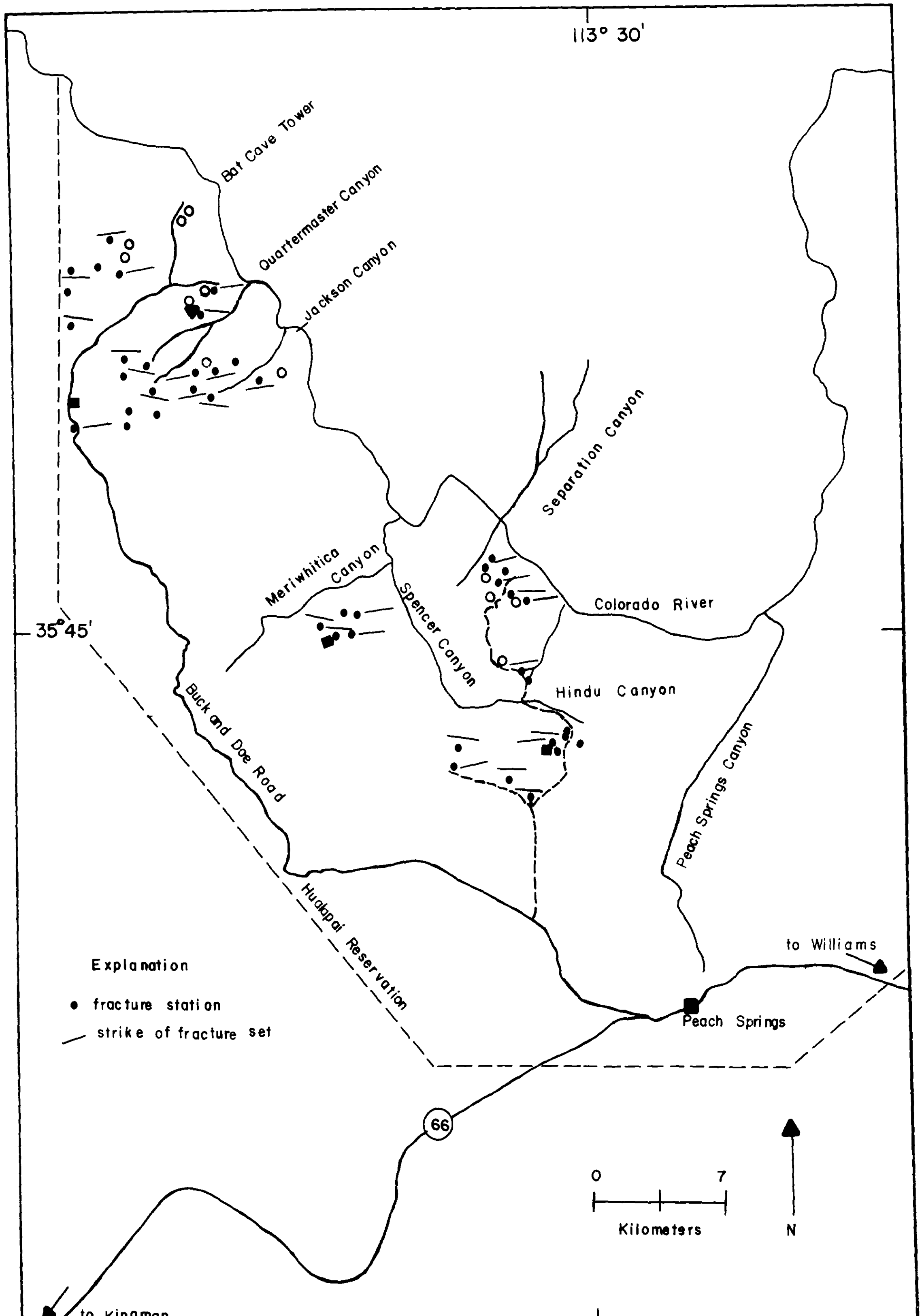

Figure 8 - Map of mean strikes of the F3 fracture set, Redwall Limestone.

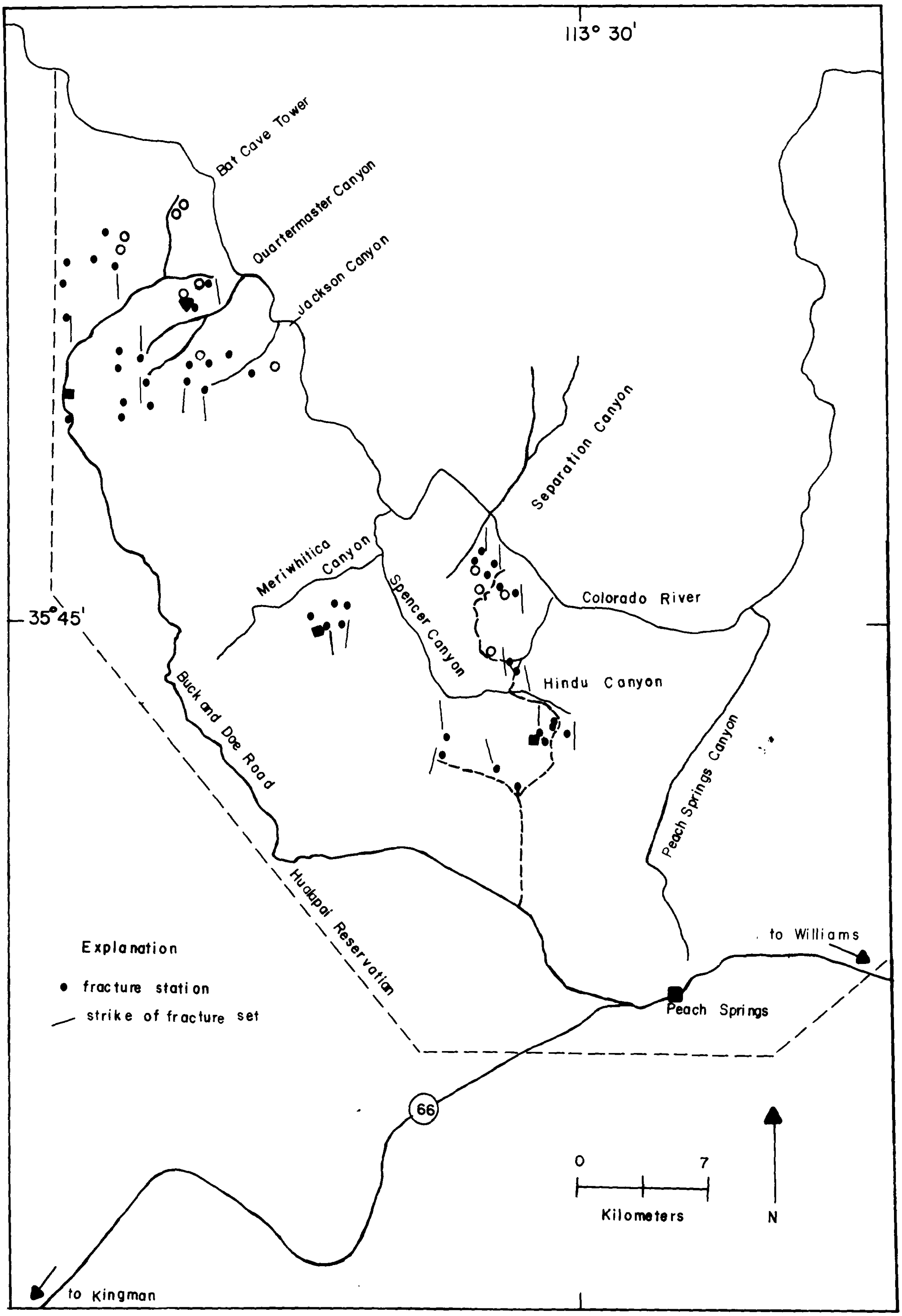

Figure 9 - Map of mean strikes of the F4 fracture set, Redwall Limestone.

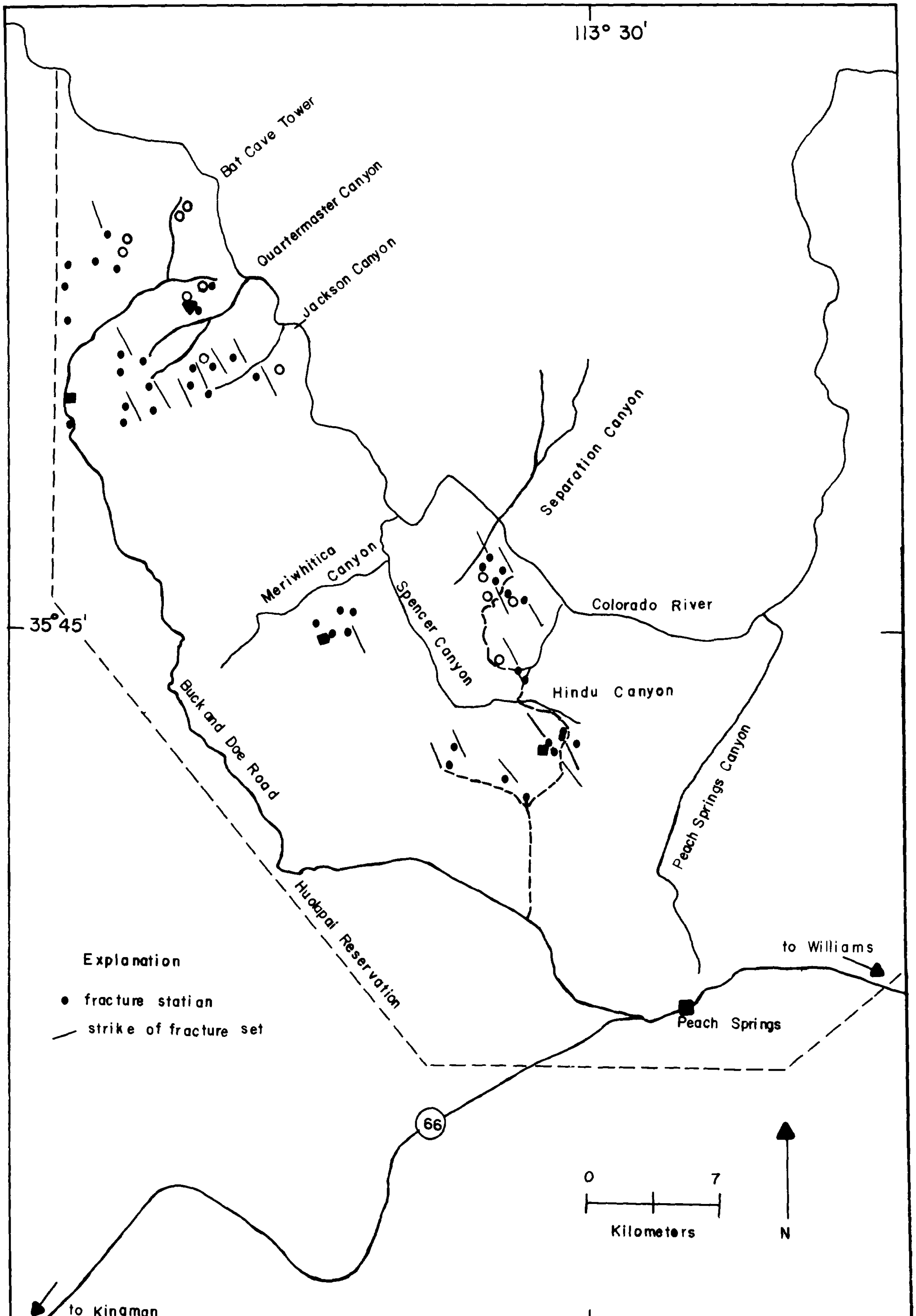

Figure 10 - Map of mean strikes of the F5 fracture set, Redwall Limestone.

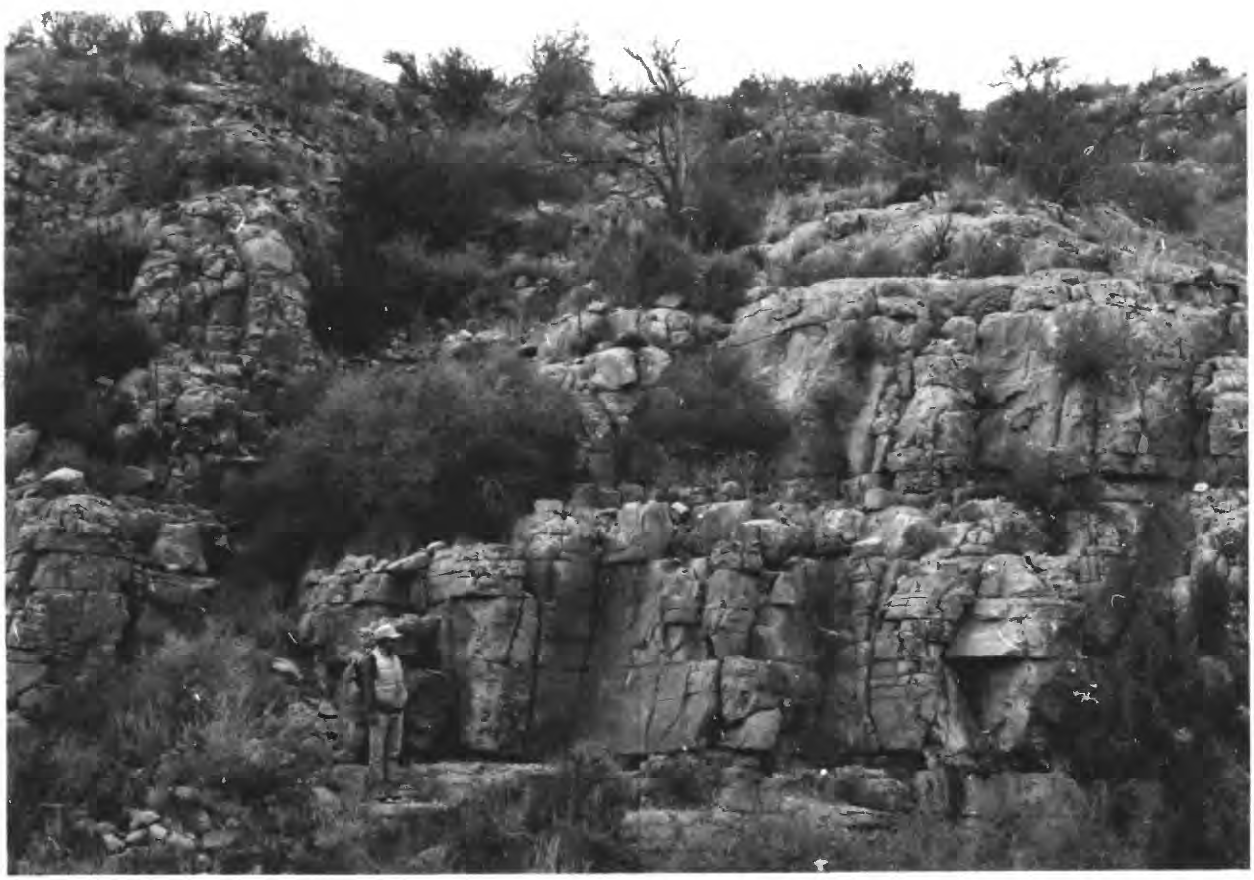

Figure 11 - Person's left arm parallels large and abundant N25W (F3) fractures about 1/2 mile north of station #24, Quartermaster Canyon quadrangle. Joints of the other set, N60E, (F1) are also large.

Fracture set 6 (F6)

Joints of fracture set 6 strike an average of N50E, subparallel to F1 joints in the Redwall Limestone. F6 terminates against older fractures, and the F6 joints are commonly short (less than 20 cm). They 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.

Fracture set 7 (F7)

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

FRACTURE SETS OF THE SURPRISE CANYON FORMATION

One station in the Surprise Canyon Formation was studied in the Quartermaster Canyon area. Two sets of east- and north-striking sets are most conspicuous, particularly in the basal conglomerate that contains abundant limestone clasts. Joints of both sets have heights and lengths as much as 1.5 m and 1.2 m respectively. Average spacings for the east-striking joints are 1.0-1.5 m in the conglomerate, and less in silty shale layers. Spacings are less for the north-striking joints and average 60-80 cm in conglomerate and 20-40 cm in the shale layers. Both the N50E and N25W sets are evident in the Surprise Canyon Formation, but the joints are less abundant and generally smaller than the east and north sets.

Age relations between the fractures from this station suggest that the number of fracture sets in the Surprise Canyon Formation may be the same as in the Redwall Limestone, because it appears from terminating relations that both older and younger joints of the N50E orientation exist in the Surprise Canyon Formation. More fractures need to be studied in the Surprise Canyon Formation to verify this preliminary observation.

FRACTURE SETS OF THE SUPAI GROUP

Joints are well developed in all members of the Supai Group. Unlike the weathered surfaces of joints in the Redwall Limestone, delicate plumose structures and twist hackle, 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. Most of the stations measured in the Supai were in these lower limestone layers. All sets contain coarse-grained pink to white calcite cement along joint surfaces.

Joints of the oldest fracture set in the Supai Group strike on an average of N85W in constrast to the oldest set (N50E) in the Redwall Limestone. The fracture set nomenclature is based on both orientation and age relations, so the earliest Supai Group fracture set is designated F3 to match the F3 fracture episode in the Redwall Limestone.

Fracture set 3 (F3)

F3 joints strike between N70E and N70W; average strike is about N85W (fig. 12). Dips are subvertical. F3 joints range from planar in clastic units to undulatory in limestone layers. Exposed heights range from 0.5 - 4.5 m and exposed lengths from 0.3 - 4 m. As with the Redwall Limestone, the larger lengths and heights may be composite dimensions resulting from solution along fractures. Spacings average from 20 - 30 cm where F3 is well expressed to several meters where only a few F3 fractures are present. Fracture zones from 10 to 50 cm wide are abundant.

The east set is the oldest, as seen from termination relationships in 80% of the stations. At the other 20%, the north (F4) set truncated the east set. East fractures are consistently older than N25W (F5), N50E (F6) and N50W (F7) in the Supai Group.

Joints of the east and the north sets are commonly the largest and most abundant joints in the Supai Group, especially in the northwestern part of the reservation near Quartermaster Canyon. Many drainages follow an eastly course where they cut through the Supai.

Fracture set 4 (F4)

F4 strikes from N19E to N15W (fig. 13). Joint surfaces range from planar to broadly curving to undulatory. Exposed heights range from 1.0 -1.3 m and exposed lengths range from 0.2 - 3.5 m. Average spacing where F4 is prominant is 30 - 50 cm. Fracture zones as much as 2 meters in height cut through the section.

Fracture set 5 (F5)

As with the Redwall Limestone, it was sometimes difficult to decide whether the N25W joints belong to F2 or F4 sets, but at several stations a distinct break in orientations exists, so I again placed the N25W joints in a separate set. They range in strike from N15W to approximately N35W and average N25W (fig. 14). At the breccia pipe south of Bat Cave tower, they are prominent fractures, with abundant white and pink coarse-grained calcite filling fractures up to 2 mm wide.

Fracture set 6 (F6)

The average strike of F6 joints is N50E (fig. 15). These joints typically are not prominent except at stations north of Hindu Canyon where they constitute the most abundant joint set along with F7. At these stations, however, joints of the N50E set were determined to be younger than the east- and north-trending fractures that were less abundant (spacings on the order of meters), but very large where developed.

Fracture surfaces are planar, where small, to undulatory where larger. Exposed heights range from 0.2 - 2 m and exposed lengths from 0.2 to 2.5 m. The larger joints are probably composite. This is especially evident at station 57, where one joint several meters long consists of closely spaced en echelon joints with individual lengths of 20 - 40 cm. Average spacings of F6 joints are close, 20 - 40 cm, where F6 joints are most prominent; elsewhere

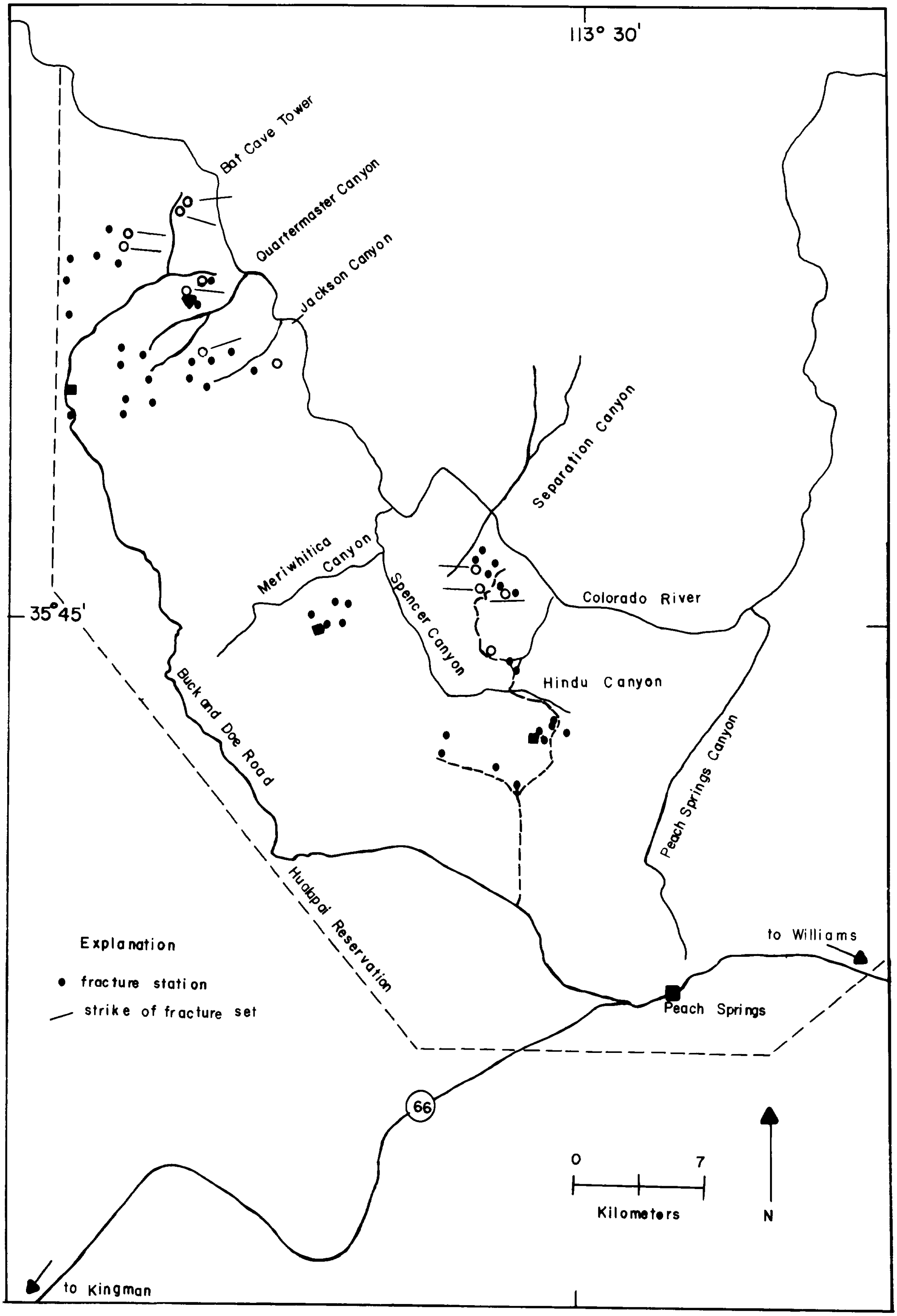

Figure 12 - Map of mean strikes of the F3 fracture set, lower Supai Group.

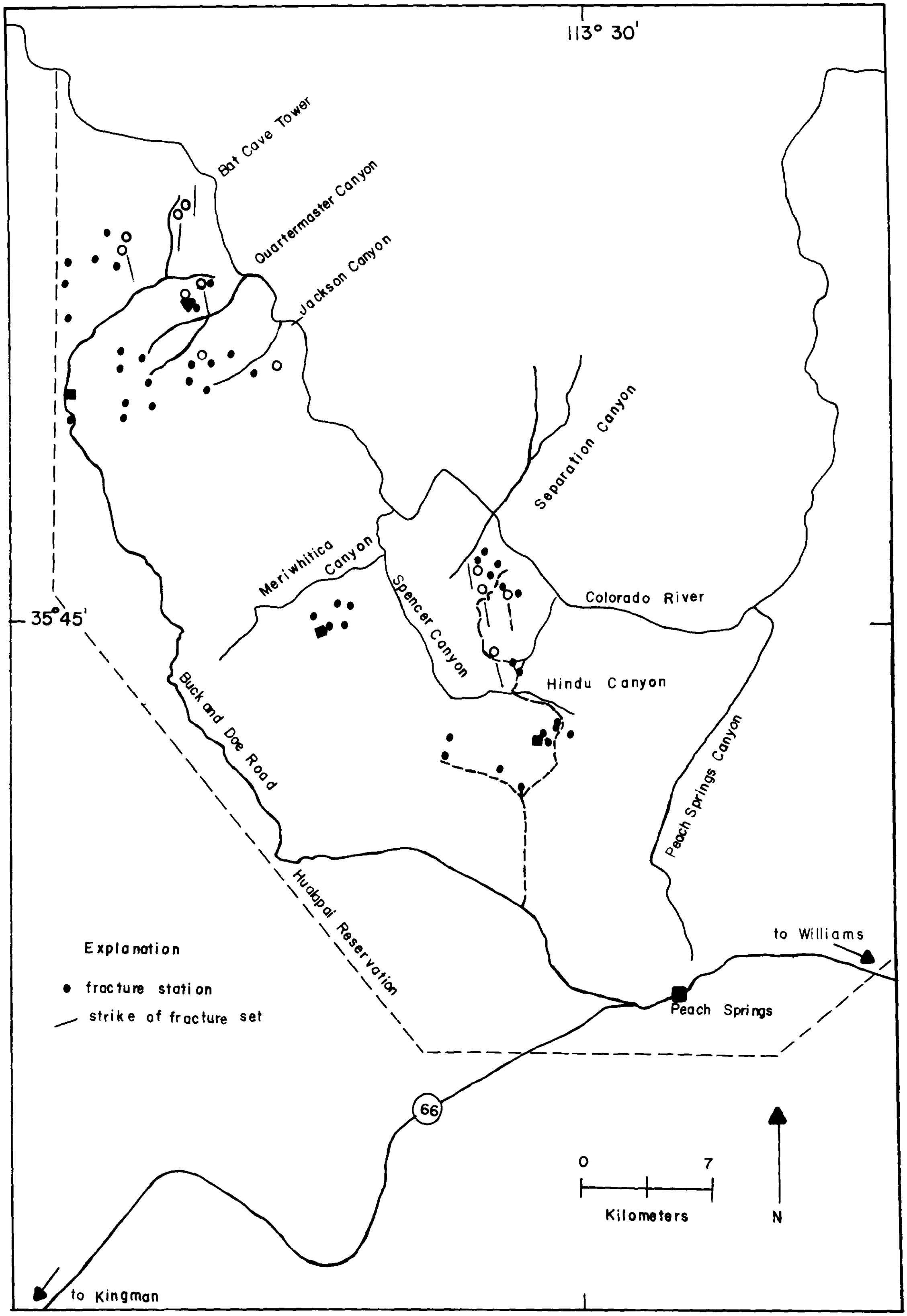

Figure 13 - Map of mean strikes of the F4 fracture set, lower Supai Group.

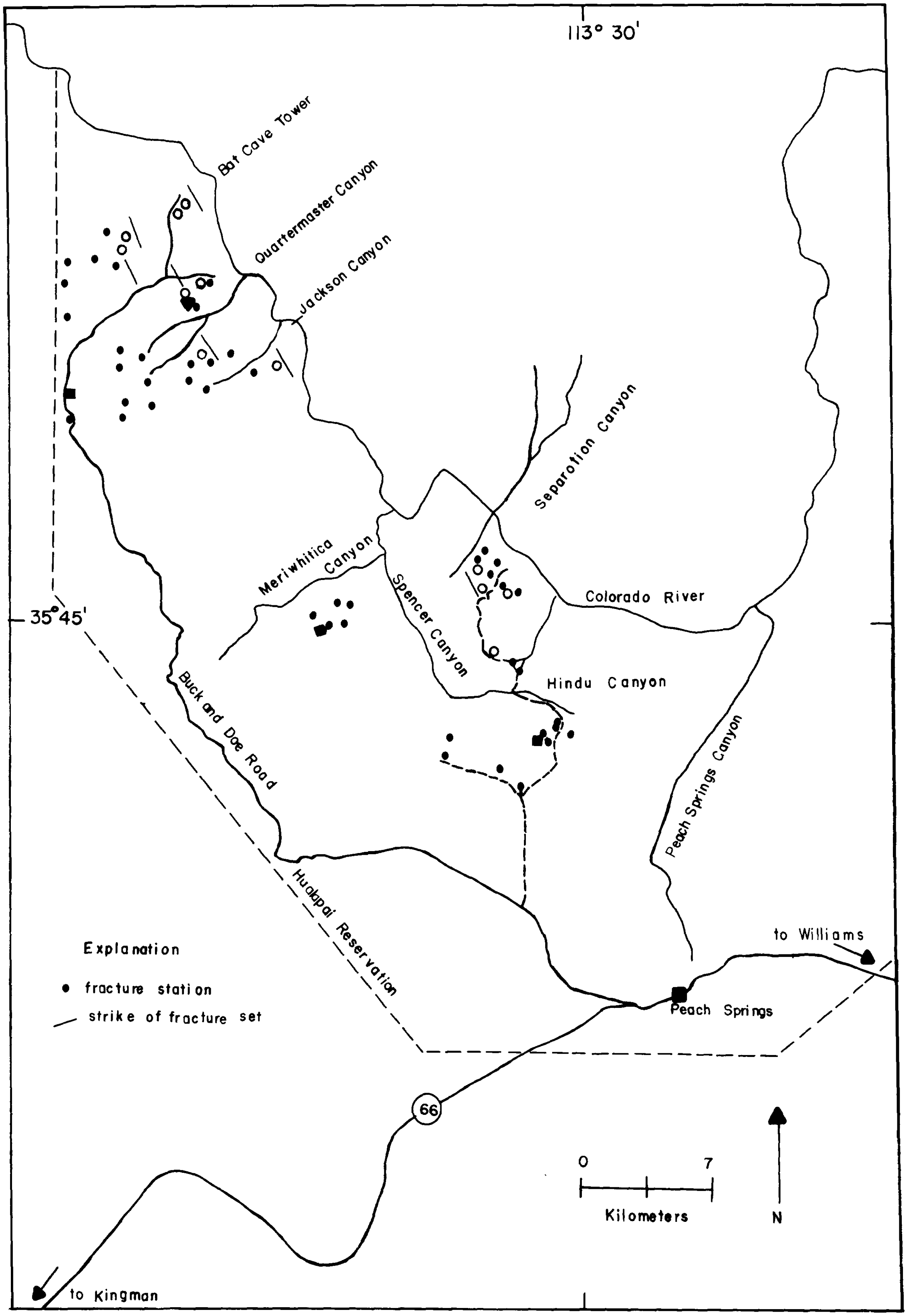

Figure 14 - Map of mean strikes of the F5 fracture set, lower Supai Group.

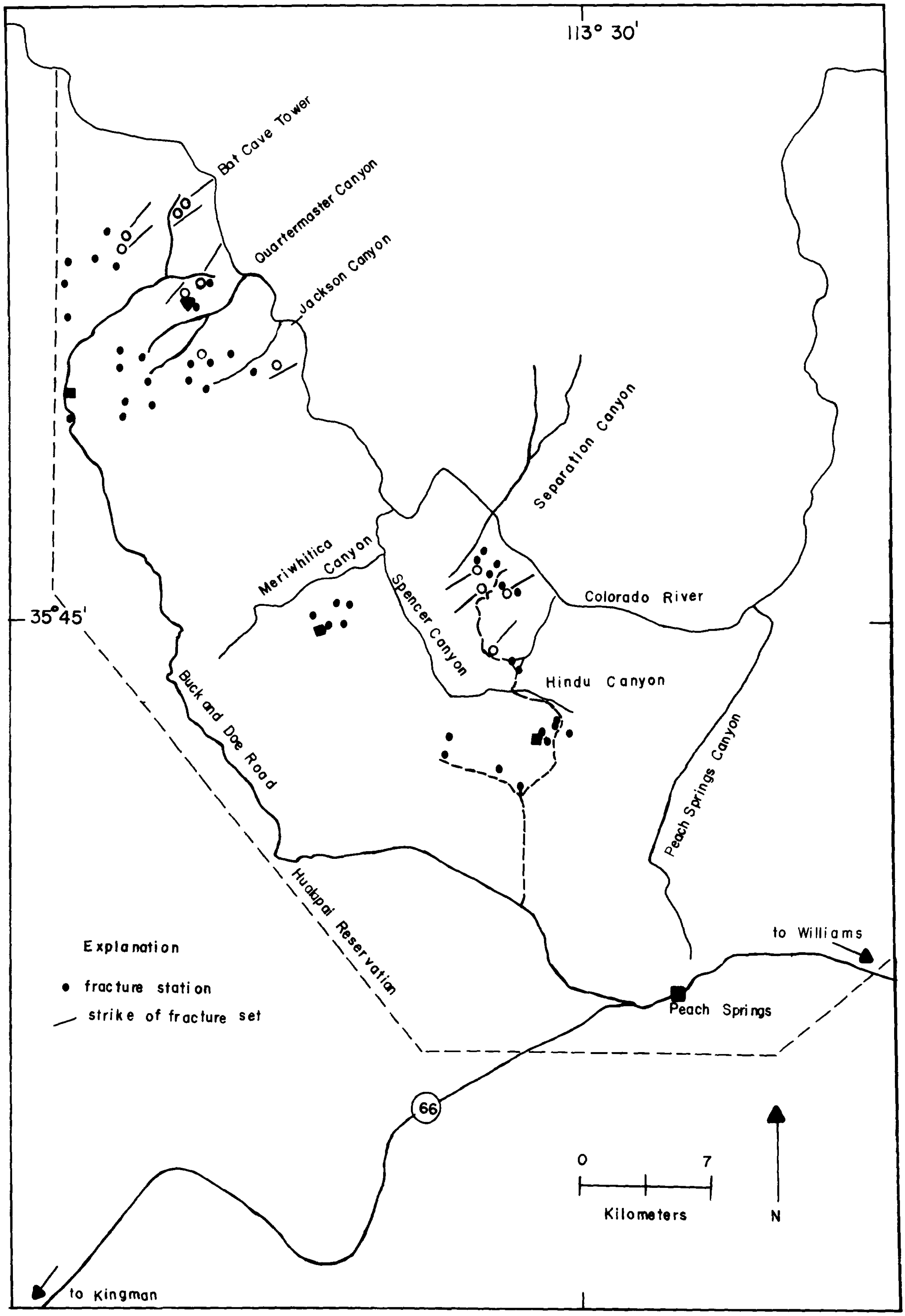

Figure 15 - Map of mean strikes of the F6 fracture set, lower Supai Group.

spacings are on the order of meters.

Fracture set 7 (F7)

The average strike of F7 joints is N50W (fig. 16). Other characteristics are similar to those of F4 joints in terms of prominence, height and length, and spacing.

FRACTURES THAT CUT COLLAPSE BRECCIAS WITHIN THE REDWALL LIMESTONE AND SUPAI GROUP

Two breccia zones were studied in detail to determine which joints cut the breccia and thus which fractures postdated breccia formation. One station is in the Redwall Limestone south of Hindu Canyon. Here the breccia is along a horizon, probably stratigraphically controlled, rather than in a vertical pipe. Measurements taken over a 1 km area show that the five fracture orientations identified in the Redwall Limestone cut the breccia. The northeast and northwest fractures in the breccia may not be part of the F1 and F2 fracture sets, but rather relate to F6 and F7 events.

The other station is in a classically shaped breccia pipe in the Supai Group. As with the Redwall station, all five joint orientations cut the breccia. Many of the joints are short and undulatory, reflecting the heterogeneous nature of the breccia (figs. 17 and 18). Because the joints are so irregular and undulatory, no good age relationships could be discerned for joints that cut the breccia.

FRACTURE SETS OF TERTIARY BASALT AND CONGLOMERATE

Measurements were taken at two stations in the basalt that caps the Redwall Limestone. The joints cut 3 - 4 meters of basalt and have fairly planar and smooth surfaces (fig. 19). Their planar character and consistency of orientation suggest that these are not cooling joints. Joints of the N50E, N50W, east, north, and N25W sets that cut the Redwall Limestone and the Supai Group also cut the Tertiary basalt.

Thick (6-7 m), early Tertiary gravels with abundant limestone clasts overlie the Redwall Limestone south of Hindu Canyon. The gravels are 400 ft (122 m) above Hindu Canyon. The Tertiary gravels studied were probably deposited in a proximal reach of a tributary to Hindu Canyon. The five fracture orientations that cut the basalt also cut the entire section of conglomerate. Fracture lengths are also very large, up to several meters.

SUMMARY OF FRACTURE PATTERNS AND TECTONIC IMPLICATIONS

Table 1 summarizes the characteristics of fracture sets within the Redwall Limestone, Surprise Canyon Formation, Supai Group, and some of the Tertiary units on the western Hualapai Plateau. The two oldest fracture sets in the Redwall Limestone, and possibly the Surprise Canyon Formation, appear to 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 3 through 7 of

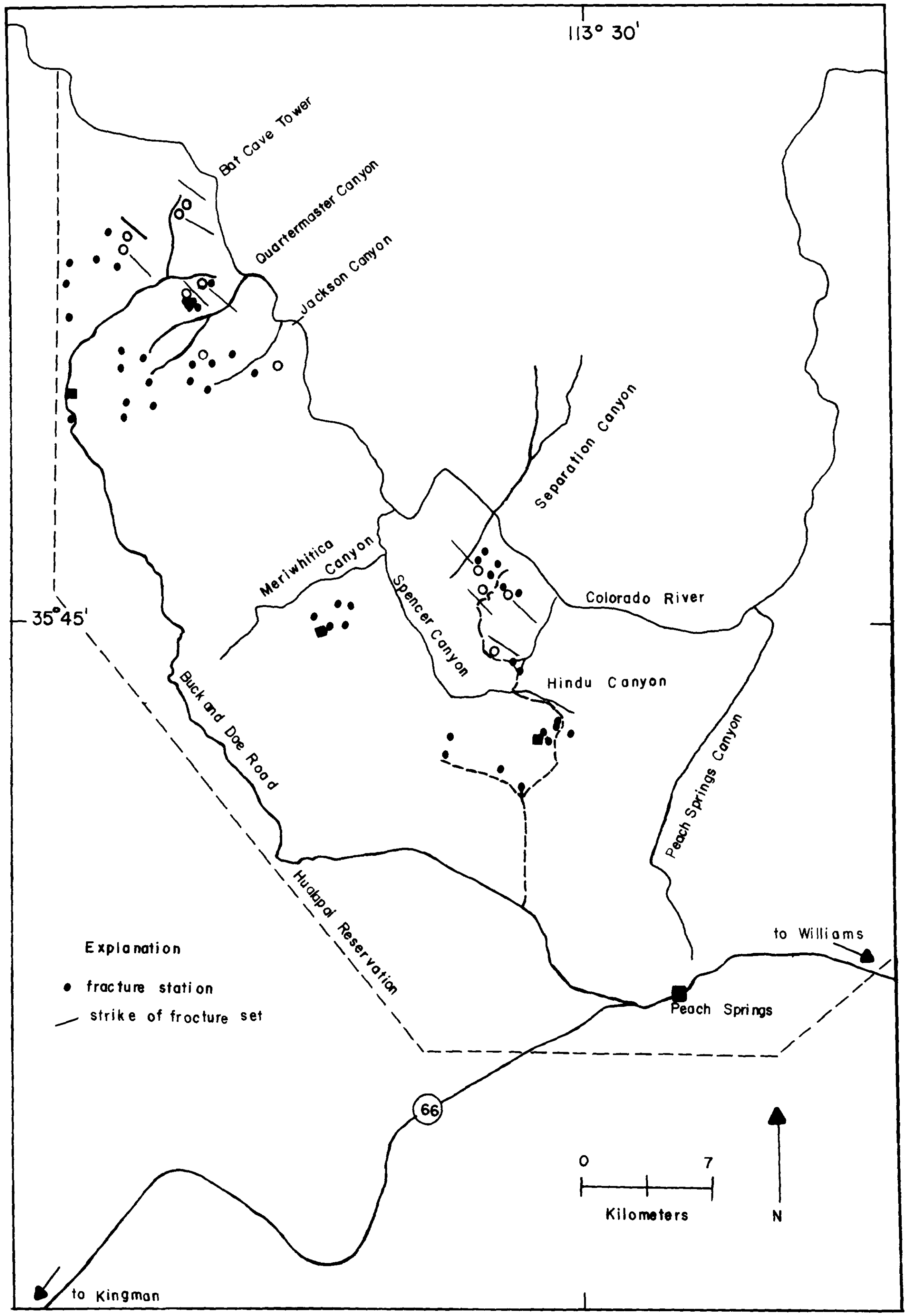

Figure 16 - Map of mean strikes of the F7 fracture set, lower Supai Group.

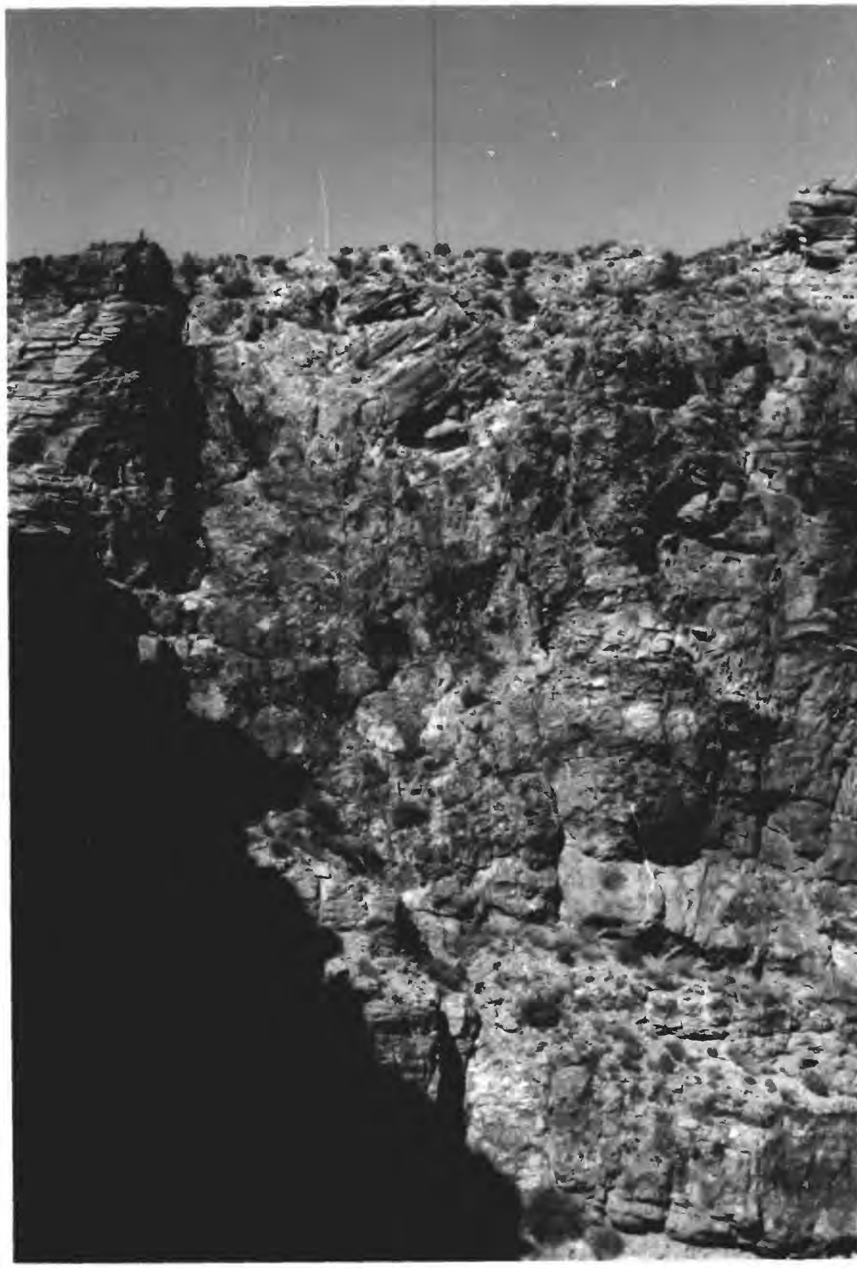

Figure 17 - Breccia pipe in the lower Supai Group south of Bat Cave tower below station #17, Bat Cave quadrangle. East-striking joints (F3) perpendicular to the plane of the photo cut the breccia. View is towards the west.

Figure 18 - Same location as figure 17, but looking north. North-striking joints (F4) are visible cutting the breccia.

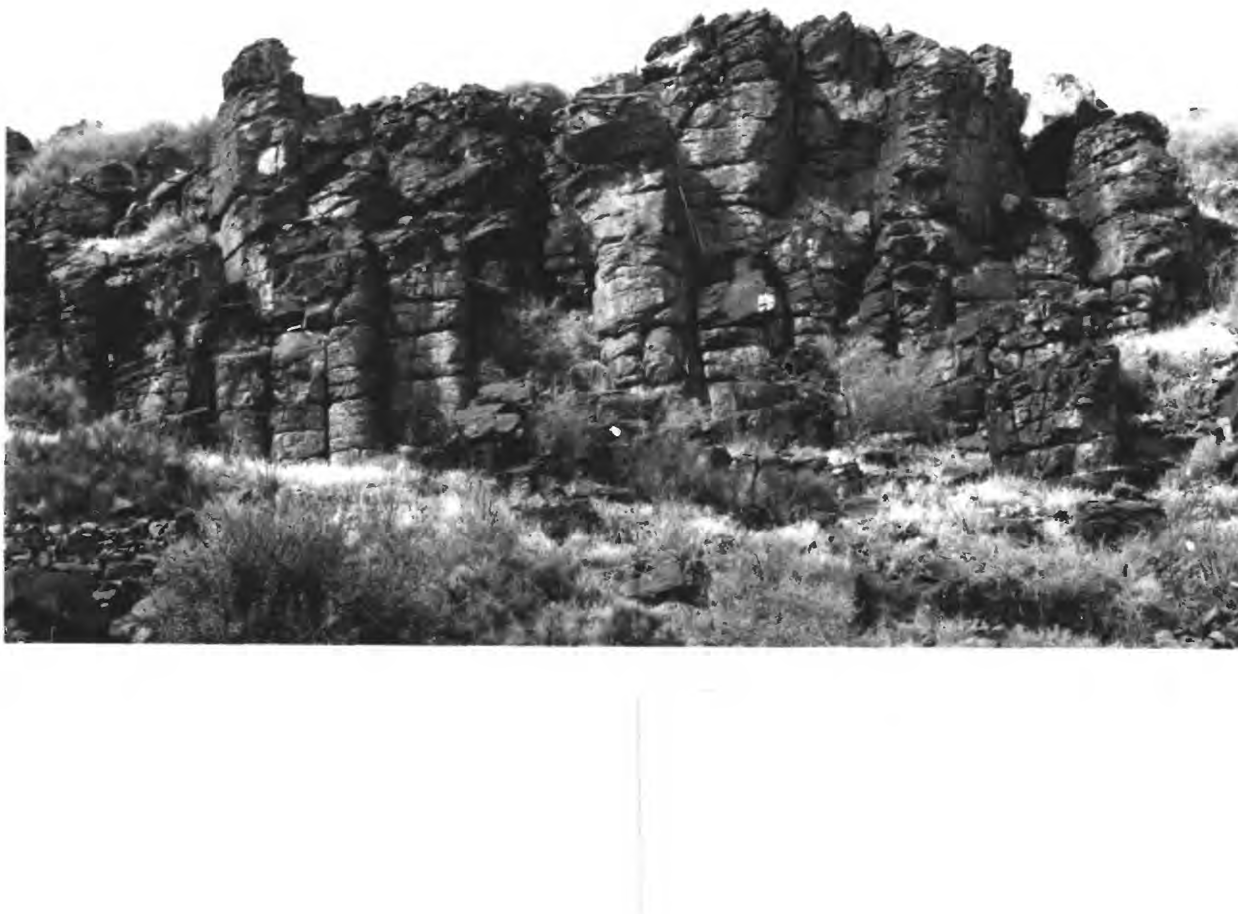

Figure 19 - Prominent northwest-striking fractures in Tertiary basalt northwest of station #27, Spencer Canyon quadrangle.

Table 1 -- Summary of average strikes and suggested correlations for fracture sets F1 through F7 for the Redwall Limestone, Surprise Canyon Formation, Supai Group, and Tertiary units.*

GEOLOGIC UNIT	FRACTURE SET						
	F1 (oldest	F2	F3	F4	F5	F6	F7 youngest)
Redwall Limestone (44)**	N48E	N51W	east	north	N25W	northeast	northwest
Surprise Canyon Fm (1)	northeast	northwest	east	north	N25W	northeast	northwest
Supai Group (12)	n.f.	n.f.	east	north	N25W	northeast	northwest
Collapse breccias (2)***	n.f.	n.f.	east	north	N25W	northeast	northwest
Tertiary units (3)	n.f.	n.f.	east	north	N25W	northeast	northwest

* The order of sets and their correlations between the Redwall Limestone, Surprise Canyon Formation, and the Supai Group are based on observed terminating relations among the joints at many localities. No information on relative ages of sets was gathered for the other units, and suggested correlations of sets to those in the Supai and Redwall is based only on orientation.

n.f. = not found

** Numbers in parentheses indicate number of stations examined.

*** one station in the Redwall; one station in the Supai.

the Redwall Limestone do, however, appear to correlate with fracture sets 3 through 7 of the Supai Group: the orientations agree and the relative ages are in identical sequence. Therefore, these suggested correlations are almost certainly correct.

All five 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 and Tertiary units, so the suggested correlations of sets and inferred similarities of fracture histories are based only on fracture orientations.

In this study, I do not attempt to determine the event responsible for each fracture set on the western Hualapai Plateau, although my data do indicate that the rocks of the Hualapai Plateau have experienced several episodes of deformation that initiated joint development. Rocks, especially limestones, are very weak under tensional stresses, so extension joints may develop from very low stress applications that do not give rise to faults and folds. It may be that the timing of some of the fractures does not correlate with deformation events that produced the monoclines and faults on the Hualapai Plateau. Nevertheless, it is possible that tectonic events that affected the Hualapai Plateau did influence development of some of the fracture systems.

This study has established that the early northeast- and northwest-trending fracture sets (F1 and F2) in the Redwall Limestone do not have correlatives in the Supai Group. This conclusion leads to at least two possible scenerios: 1) the Redwall Limestone was lithified, uplifted, and jointed prior to deposition of the Supai Group, or 2) the Redwall Limestone and the Supai Group were both in place, but the Redwall Limestone was fractured while the Supai Group was not. This is possible if the strains were not high enough to exceed the tensile strength of layers within the Supai Group. The one station studied in the Surprise Canyon Formation suggests the possibility that the Surprise Canyon Formation contains the early F1 and F2 sets of the Redwall Limestone. If this is the case, it would support the notion that the Redwall Limestone through the Supai Group were all present during jointing of the first two sets in the Redwall Limestone. More work on the Surprise Canyon Formation fracture history is required before any definitive regional correlations between fracture sets can be made.

In support of the first possibility, residual stress from the Antler Orogeny caused uplift and erosion from crustal instability at the end of Mississippian time (Skipp, 1979). The Antler Orogeny was most intense in late Devonian to early Mississippian time. Gentle upwarping during regional uplift in late Mississippian time may have induced the early fractures in the Redwall Limestone. Withdrawal of the seas that deposited the Redwall Limestone in northwestern Arizona occurred about 330 my ago (Billingsley and Beus, 1985). River valleys as deep as 400 ft (120 m) were then cut into the Redwall, and into them were deposited continental sediments of the lower Surprise Canyon Formation. Widespread karst development formed sinkholes, caverns, and solution breccia (McKee, 1979; Billingsley, 1986). The large northeast (F1) and northwest (F2) fracture sets in the Redwall Limestone may have formed during the interval between withdrawal of the Redwall seas and subaerial erosion during Surprise Canyon time, and may have localized karst features. More work is necessary to determine when the F1 and F2 fracture systems developed.

Compressional deformation during the Late Cretaceous-to-Eocene Laramide Orogeny caused large monoclinal folding in part due to reverse offset along reactivated Proterozoic faults. This was also a time of major uplift and erosion on the Hualapai Plateau (Huntoon, 1974; Young, 1979). Deformation from monoclinal folding was fairly localized, but the regional state of stress resulting from Laramide compression may have been sufficient to cause jointing of the rocks over a wide area.

Huntoon (1974) observed that Cenozoic movement along normal faults with northerly orientations is older (Eocene - Miocene?) than normal faults with northeast trends (Miocene - Eocene); he concluded that both fault systems were reactivated along Proterozoic faults and were active during early Basin-and-Range extensional deformation. McGill and others (in press) propose that normal faults in the Grand Canyon area influence stress fields regionally, which fracture rocks over wide regions that are not faulted, while the faults cause densely spaced jointing close to the fault traces. The young northeast set (F6) in the Supai Group may have formed during middle Tertiary normal faulting. The stress field presumably also affected the Redwall Limestone, which might account for the younger northeast set (F6) of the Redwall Limestone. The only evidence for reactivation in the Redwall Limestone that I observed was calcite cement along northwesterly trends that was brecciated.

POSSIBLE CONTROLS OF BRECCIA PIPE LOCATIONS BY FRACTURES

This study, although preliminary, has shown that the northeast (F1) and northwest (F2) fracture sets were imposed upon the Redwall Limestone prior to fracturing within the Supai Group. Thus, these features could have localized fluid flow, promoting solution and cavern development within the Redwall Limestone and collapse features by stoping of the overlying rock. This may have occurred either prior to Supai deposition or after the deposition of the Supai Group but while the Supai was still unfractured.

It is presumptuous at this time, however, to delinate only northeast and northwest trends from the map (fig. 20) that shows locations of collapse features on the Hualapai Plateau. With the large number of collapse features mapped, it is possible to connect the points in many different orientations that do not necessarily reflect the underlying fracture pattern. This procedure appears to have been effective, however, on the Marble Plateau where numerous pipes line up along northeast and northwest trends (Sutphin and Wenrich, 1983). Previously undiscovered collapse features were located by extrapolating along these trends (Sutphin and Wenrich, 1983).

This study shows that the Redwall Limestone contains early northeast and northwest fractures and fracture zones, which possibly localized the cave passages and caverns that later formed breccia-pipes, as hypothesized by Sutphin and others (1983). Therefore one might project from known pipes in the northeast and northwest directions for possible areas to explore.

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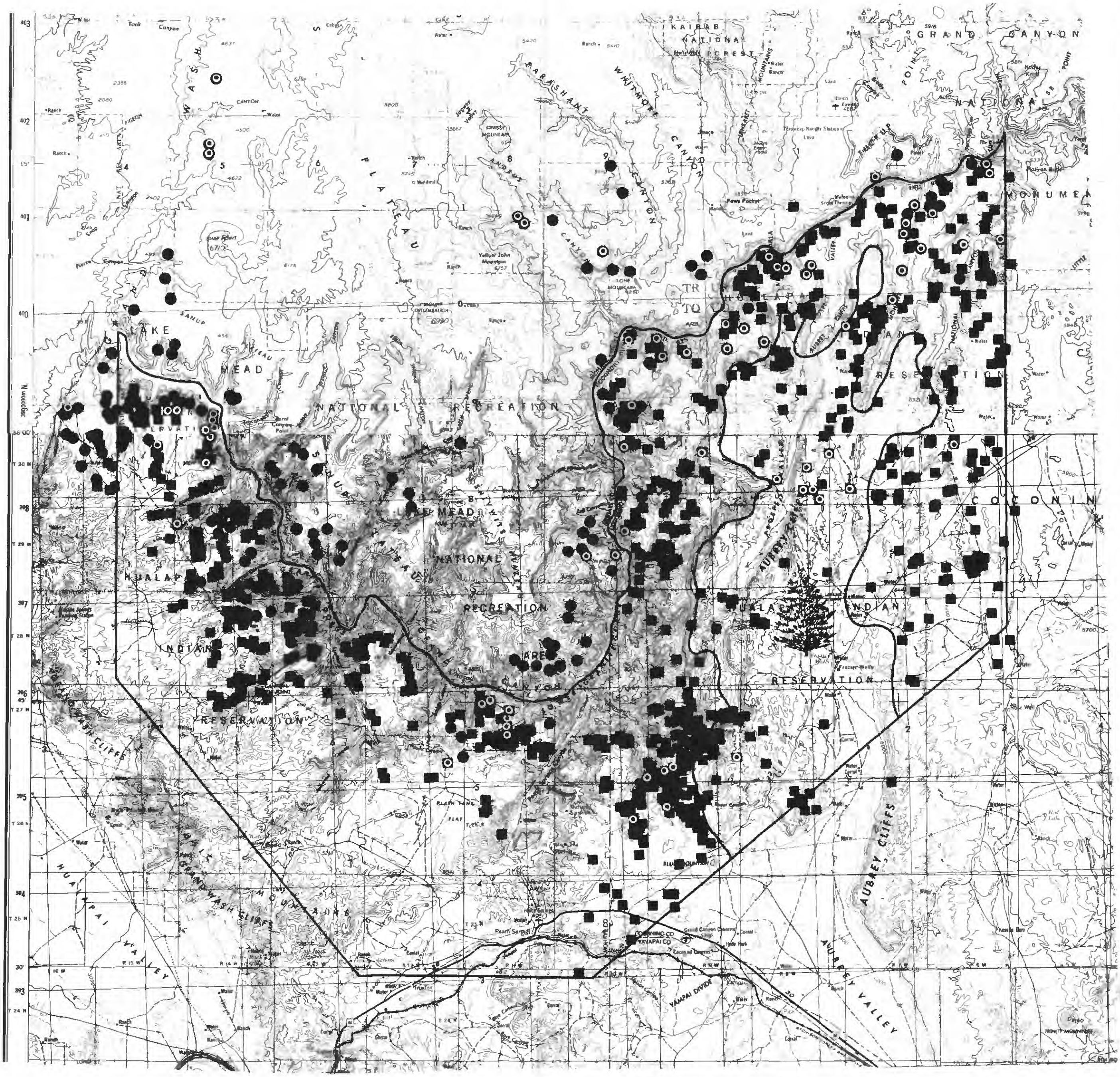

Figure 20 - Map of collapse features, including sink holes, on the Hualapai Reservation. Squares with circles superimposed are mineralized pipes. The tree on the eastern side of the reservation represents heavily forested area. Taken from Wenrich and others, 1986. Scale is 1:250,000.

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