WESTERN ARCHEOLOGICAL CENTER
TUCSON, ARIZONA

Geologic Analysis of Rock Deterioration At Selected National Park Service Archeological Sites

ROCK MOTION HAZARD

Including:

Report A; Rock Motion Hazard
- El Morro
- Bandelier
- Chaco Canyon
- Wupatki National Monuments
- Mesa Verde National Park

Addendum to Report A; Return Trip to:
- El Morro
- Bandelier National Monuments
- Mesa Verde National Park

Report B; Rock Motion Hazard
- Tonto
- Canyon de Chelly
- Navajo
- Walnut Canyon
- Montezuma Castle National Monuments

And Summary Analysis of
Rock Fall Hazard, Section 3

By: Bruce G. Wachter, Ph.D.
Under Contract with National
Park Service, Western
Archeological Center, Tucson,
Arizona, 1978.

Report A; Rock Motion Hazard

ROCK DETERIORATION REPORT A

Rock Motion Hazard

Reconnaissance of:

El Morro
Bandelier
Chaco Canyon
Wupatki National Monuments
Mesa Verde National Park

By Bruce G. Wachter, Ph.D.
and Jay Lazarus

Under contract with National
Park Service Western Archeological
Center, Tucson, Arizona

June, 1978

Rock Deterioration Report A

Rock Motion Hazard

Reconnaissance of: El Morro
Bandelier
Chaco Canyon
Wupatki National Monuments
Mesa Verde National Park

1. Introduction

The purpose of this report is to provide some advance awareness of rock motion hazards (rock fall, slump, glide, and creep). A reconnaissance trip was made during the period May 8 to 16, 1978 under contract to the Western Archaeological Center, Tucson. The reconnaissance was to provide geologic perceptions of rock deterioration problems at the sites noted and to identify peripheral geologic problems that may threaten the sites or their safe operation.

The notable geologic problem is that of rock motion, which is threatening integrity of ruins and inscriptions as well as providing a safety hazard. Specific rock motion hazards will be mentioned by site. This definitely should not be understood to mean that each site has been examined in full and hazards identified and catalogued. This report is the first step in a process that could well include:

1. Reconnaissance of all sites considered likely to contain rock motion hazards.

2. Detailed site-by-site follow-up to identify, catalogue and rank by priority of damage and safety potential all rock hazards.

3. Note those hazard situations requiring immediate stabilization, elimination, or monitoring.

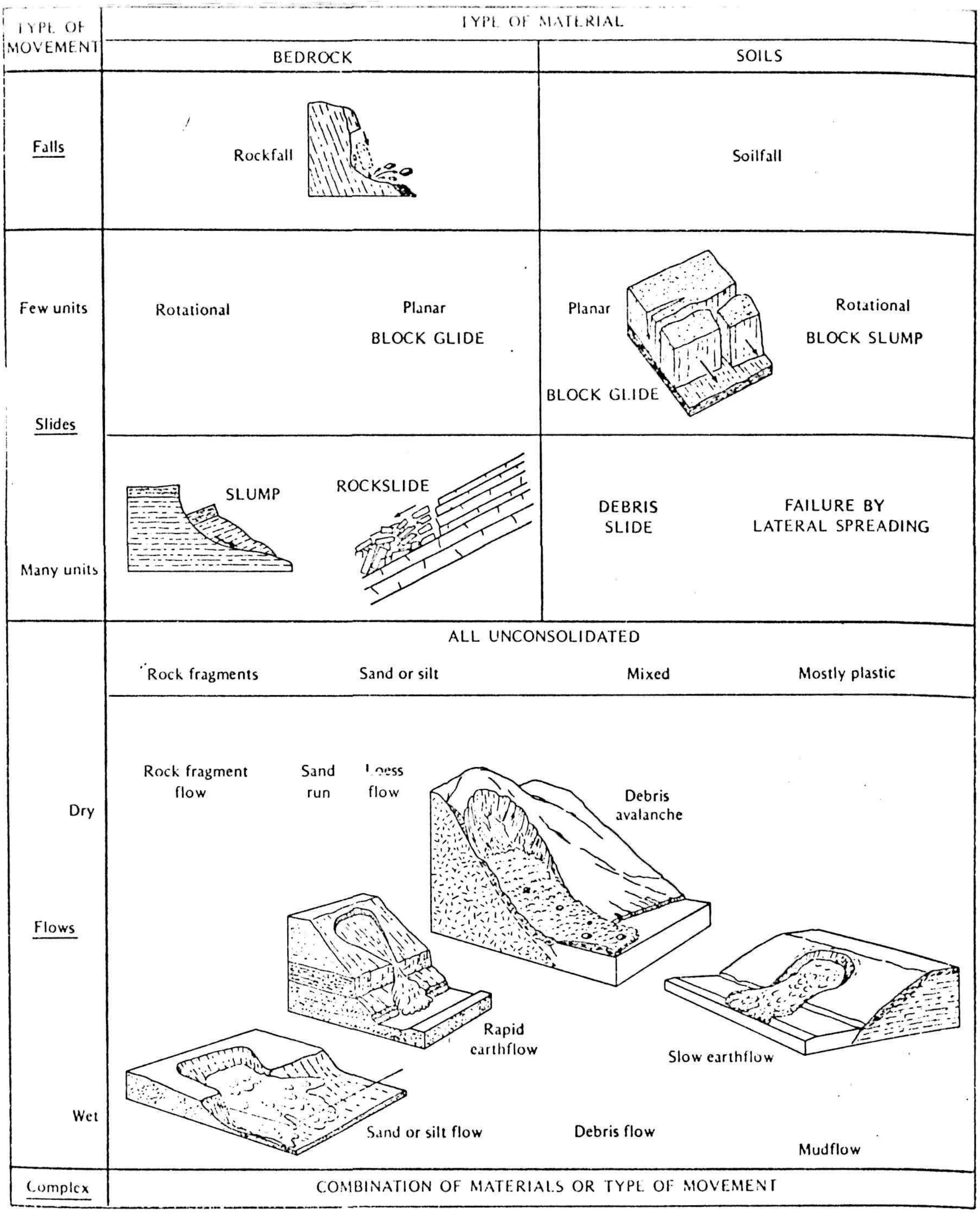
4. Decision and action by administration and geologists, engineers, or rock mechanics professionals as necessary by priority.

The advance nature of this report may provide some additional awareness of the nature of rock motion at any of the Park Service jurisdictions in the Southwest and immediate identification of many of the serious hazards. Immediate monitoring by site staff may be advisable.

2. Types of Rock Motion

Under the overall heading "Landslide" or "Mass Movement", the engineering and geological professions have established elaborate and inconsistent categorizations of rock (and soil) motion. Figure 1 is a simple but serviceable classification. Figure 2 illustrates slow slope motion of rock, soil, or talus, known collectively as "creep".

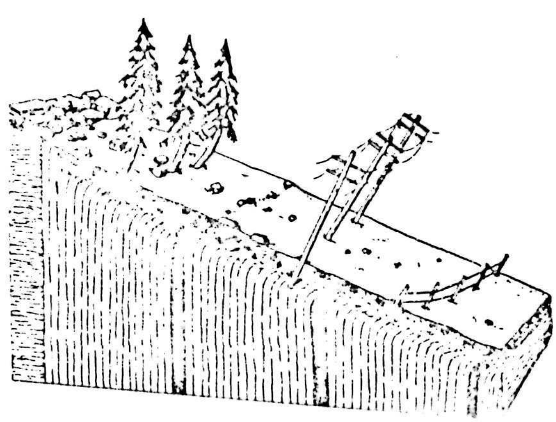
This report stresses small-scale local motions best categorized as rock fall, slump, block glide, talus creep, and complex forms in which rock fall combines to some degree with other forms of movement. Full-fledged slide avalanche and flow phenomena are possible at some of the sites, but these forms are not easily predicted by simple reconnaissance study. Particularly Mesa Verde could benefit from a broader hazard study dealing with larger phenomena by coordinating knowledge likely gained by



Classification of landslides according to the United States Highway Research Board.

Figure 1. Landslides.

Figure 2. Creep.



construction of the access highway with air-photo and ground study of potential slide-avalanche hazards.

Figure 3 better symbolizes the scale of motion considered here (adding complexities of origin and motion due to slump, glide, and creep) which includes rock masses of kilogram to 10,000 ton magnitude.

3. Example: The Fall of Threatening Rock*

This case is well enough known in geology and archaeology to be a cliche; it is, in addition, the best documented case of rock fall (plus creep and glide).

The 30,000 ton monolith formed by detachment from the cliff, which is composed of soft (low strength) sandstone (Cliffhouse member of Mesa Verde Formation), which is permeable (to water flow) and widely jointed (natural fractures divide the otherwise massive sandstone into large blocks, though the strength of the massive sandstone is low enough to allow spontaneous fracture with beginning motion). The sandstone rests on incompetent bentonitic (shrink-swell) clays and coal seams (subject to rapid deterioration).

The coal-clay unit erodes rapidly, undermining the sandstone cliff. Conditions of Figure 3 are nicely met so that rock fall is the inevitable and on-going geologic process of Chaco Canyon. Further, the clays flow plastically when moist and unconfined (as at the cliff exposure) and provide a medium for slump or glide.

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*Schumm, S. A. and Chorley, R. J., 1964, The fall of Threatening Rock: Am. Jour. Sci., v. 262, p. 1041-1054.

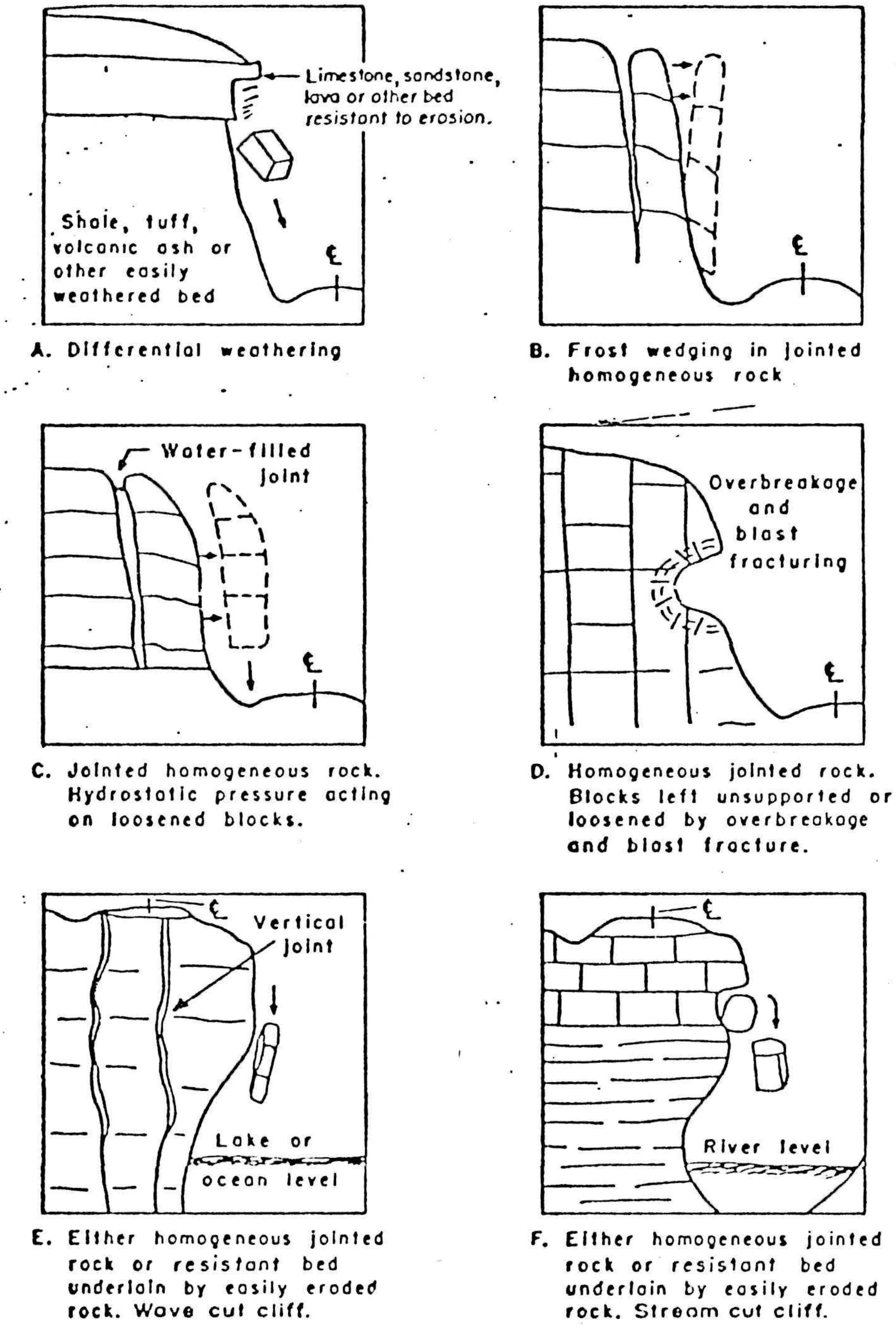


Figure 3. Rock fall.

Figures 4 and 5, reproduced from Schumm and Chorley, summarize the motion prior to the rock fall.

Comments:

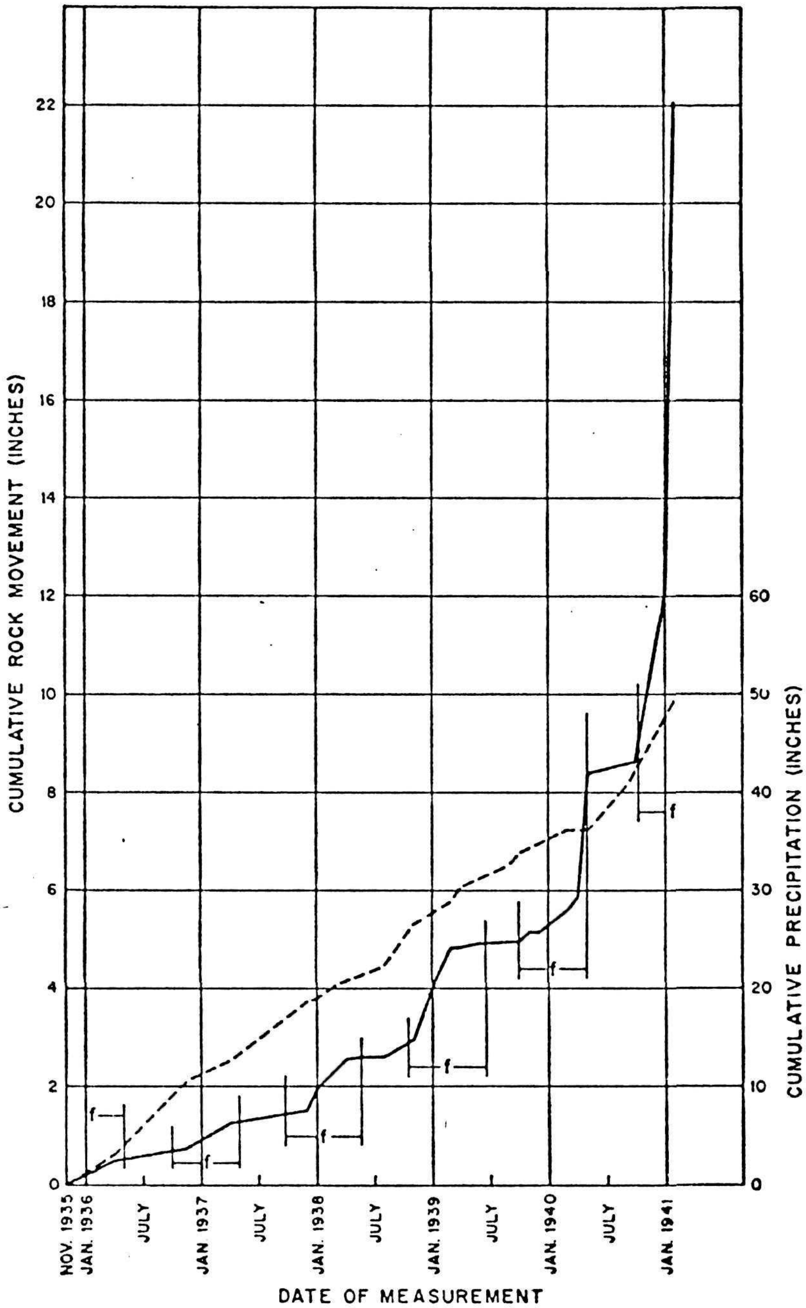
a. The actual rates and distances of motion preceding fall are applicable only to Threatening Rock itself (or to very similar monoliths on very similar underlayers). Though likely to be logarithmic in form, the time-distance curves for other rocks in motion may be greatly expanded or compressed in either time or distance; i.e., fall may occur before measurable motion or time and amount of measurable motion before fall may be extreme.

b. The suggested relationship of motion to precipitation is simplistic but it is significant that seasons of high precipitation should promote greater motion.

c. Seasonality of motion is notable, though for other rock falls seasonal motion may be shifted to springtime (higher elevations with freeze-thaw cycles concentrated in spring) or summer (precipitation more concentrated in summer) or simply random, following high-intensity weather or seismic events.

d. Rock fall, slump, glide, and minor to moderate slides are evidenced in the geological and archaeological past at Chaco Canyon and will continue with high geologic frequency.

e. Feasibility of identification and monitoring of rock motion is demonstrated by NPS activity re Threatening Rock.



. Cumulative movement of Threatening Rock (solid line) and cumulative precipitation (dashed line) plotted against date of measurement or time. Vertical lines, drawn at dates of first killing frost of the fall and the last killing frost of the spring for the years of record, indicate cumulative movement which occurred during periods of freeze and thaw. Freeze-thaw periods are designated f.

igure 4. Time-Distance Plot Threatening Rock, 1935-41.

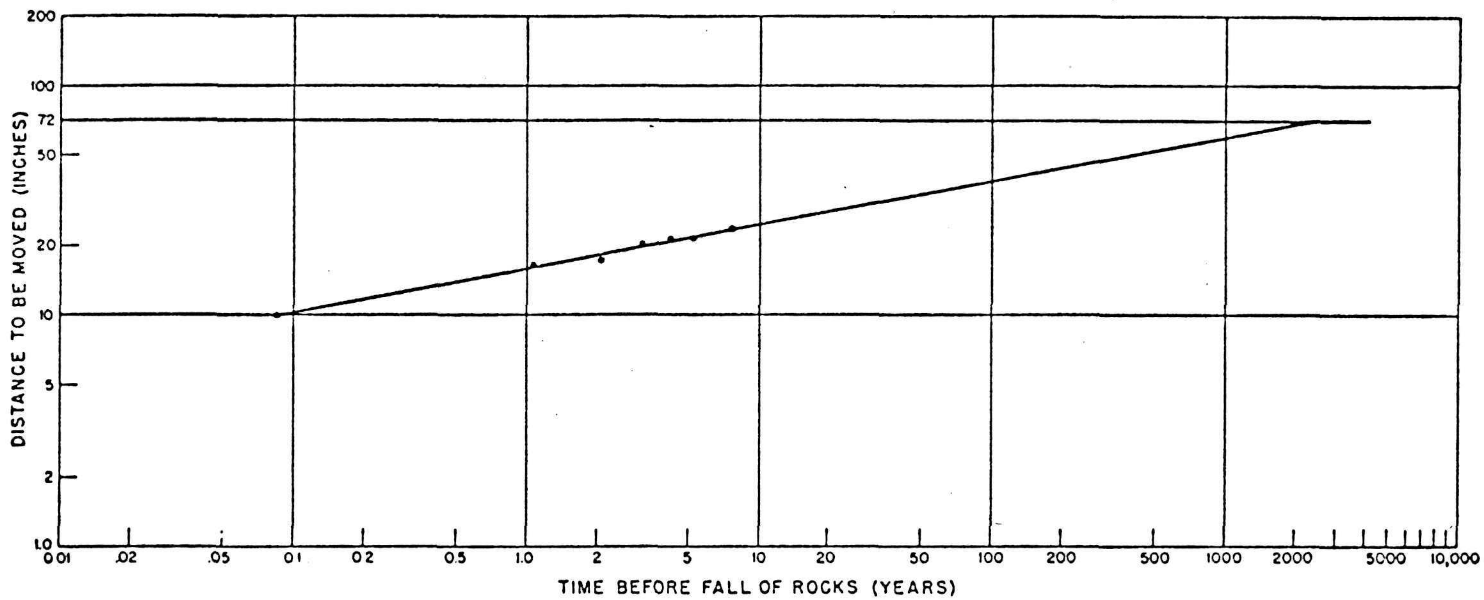


Fig. 4. Relation between distance to be moved and time before fall of Threatening Rock. For example, one year before the fall of the rock an additional 16 inches of movement was required. Extending the regression line until it intersects the horizontal line representing total rock movement before fall, 72 inches, yields an estimate for the time required for this movement (about 2500 years).

Movement	Years required
1st foot	1600
2nd foot	650
3rd foot	200
4th foot	60
5th foot	8.0
6th foot	0.2

Figure 5. Logarithmic Plot Time-Distance, Threatening Rock.

4. Determination of Rock Motion

a. El Morro

Figure 6 shows a monolith of large size in motion on the southeast face of Inscription Rock. The obvious fracture is not of immediate concern, as its weather-rounded edges and mineral staining on the fracture surface suggest recent stability. The less obvious crack shows current motion by sharp edges, lack of patina, and delicate hair-line crack propagation downward (through a historic inscription) (Figure 7).

The abrupt "horsetailing" or dendritic propagation appears to indicate that this monolith has begun moving on the ultimate pivot point and the present phase of motion could be terminal. The nature of motion is not dependent on failure, plastic flow, or glide on incompetent underlayers. Failure is within the rock itself. Immediate monitoring is suggested.

Other instances of rock fall or slabbing are inevitable due to the undercutting of the cliff by the cove-like rock-weathering/erosion near present ground level. Slabbing poses a minor hazard to people and is presently threatening inscriptions and pictoglyphs above the undermined zone (Figure 8). At least one other joint block monolith along the southeast face shows potential for movement. Vertical cliffs such as that above and northeast of the pool should be examined periodically for small slabs that could detach and fall or bounce to the trail immediately below.

Figure 9 looks southwest from the walkway along the northwest side of Inscription Rock. The precarious looking monolith on the skyline does not show definite signs of current motion, but the large mass (100

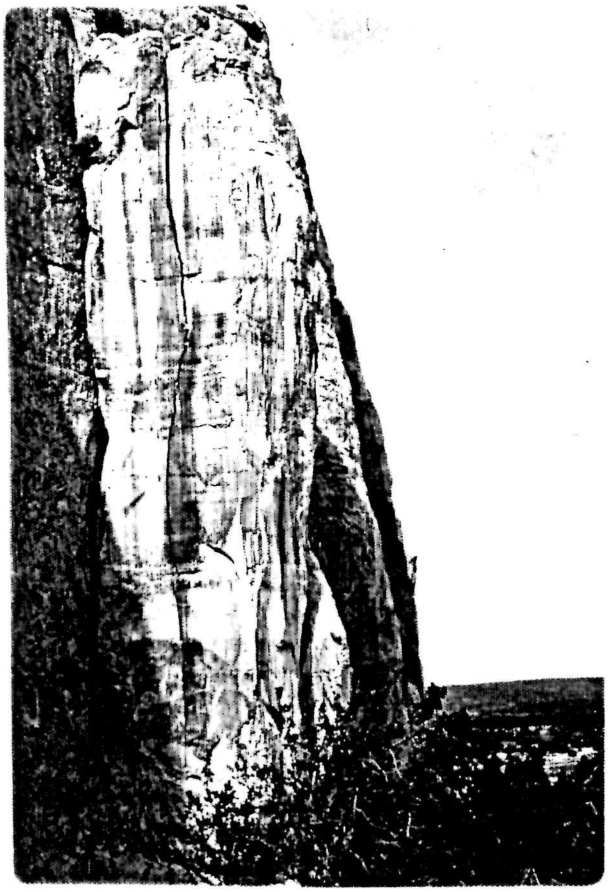


Figure 6. Monolith in motion, El Morro, southeast face of Inscription Rock. The well weathered joint (rounded edges) that separates the monolith from the cliff does not appear to be active. The vertical crack down the center of the monolith, though rounded by weathering near the top, is sharp-edged and unweathered in its lower portion.

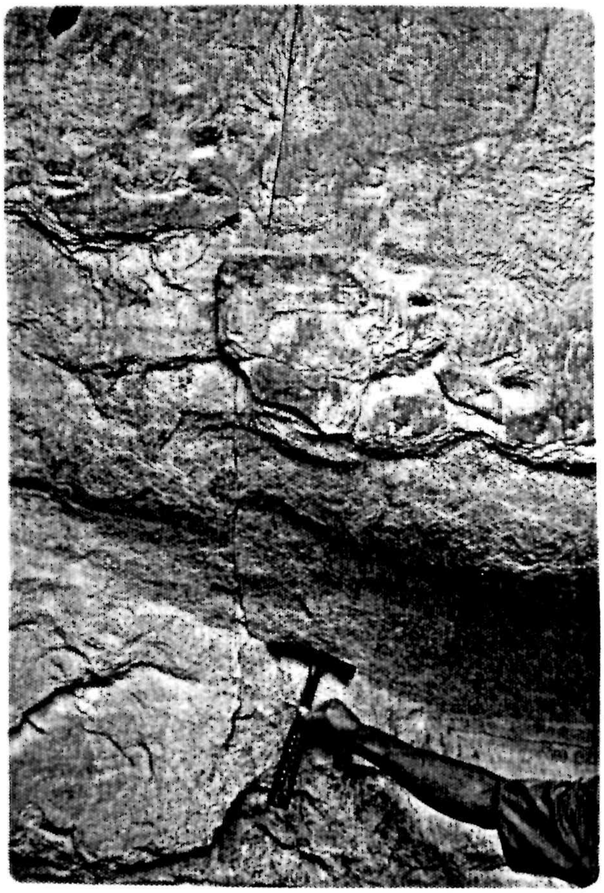


Figure 7. Lower portion of active crack shown in Figure 6. The crack "horsetails" at this point, i.e., becomes dendritic with multiple hairline traces extending 0.3 to 0.6 meters below the rock pick.

Figure 8. Intense deterioritation at ground level undermines cliff face making slabbing or collapse inevitable. (Southeast face of Inscription Rock, El Morro, below E. Pen Long inscription) Here no immediate threat exists to people but petroglyphs and historic inscriptions are slabbing away. Note petroglyphs on the original red-stained face.

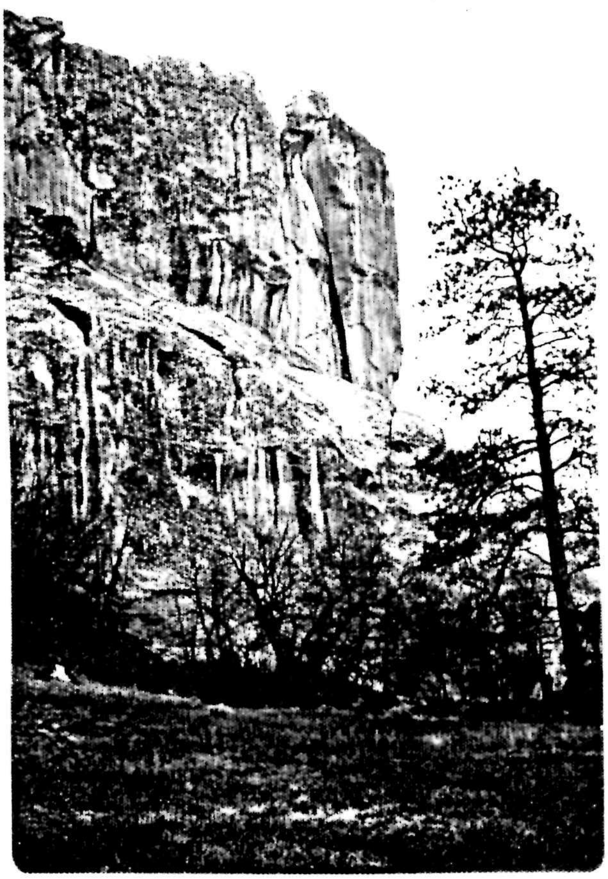


Figure 9. Large monolith entirely separated from northwest face of Inscription Rock (El Morro). Apparently not in motion presently, it rests on a small pedestal of deteriorated sandstone. Motion could be instantaneous. Triggering by seismic vibration is possible.

to 1000 ton range) rests on a small pedestal of deteriorated rock. The possibility exists of sudden fall with little previous motion. It is subject to seismic shock.

Alcove formation is underway at the two centers shown in Figure 10. Moisture is evident on most of the slab faces one week after a 10" spring snowfall and freeze-thaw no doubt contributes to periodic rock fall from the enlarging alcoves. Danger is slight as trails do not pass near.

b. Bandelier

Cove deterioration at the soil line causes overhang and exposure of soft crumbly tuff (volcanic fragments and ash in varying states of coherence) and ultimate slabbing of the cliff face. Normal erosion rate and rock fall frequency on the Bandelier cliffs is quite low, as the inherently weak tuff forms a mineral crust, a sort of case-hardening, after long exposure. The base-cove deterioration and the rooms, vents, and niches in the lower cliff break the stabilizing crust and also create structural inconsistencies from which failure can propagate. Rock motion is maturing and likely spreading from the cliff habitations. Two large historic falls are known: (1) a random fall of 1000 kg magnitude from the high cliff above the restored pueblo at Talus House, and (2) a slab of 10,000 kg magnitude at Longhouse which detached from the cliff at the base cove and fell a few meters in the late 1960's.

Figure 11 shows base coving at the cliff base and instability over an artificial opening. A small (10 kg) overhead block is loosened by crack propagation and is ready to fall. It should be removed or

Figure 10. Active alcove formation on northwest face of Inscription Rock (El Morro). Note moisture on slab faces (gray coloration). Rock falls must occur frequently.

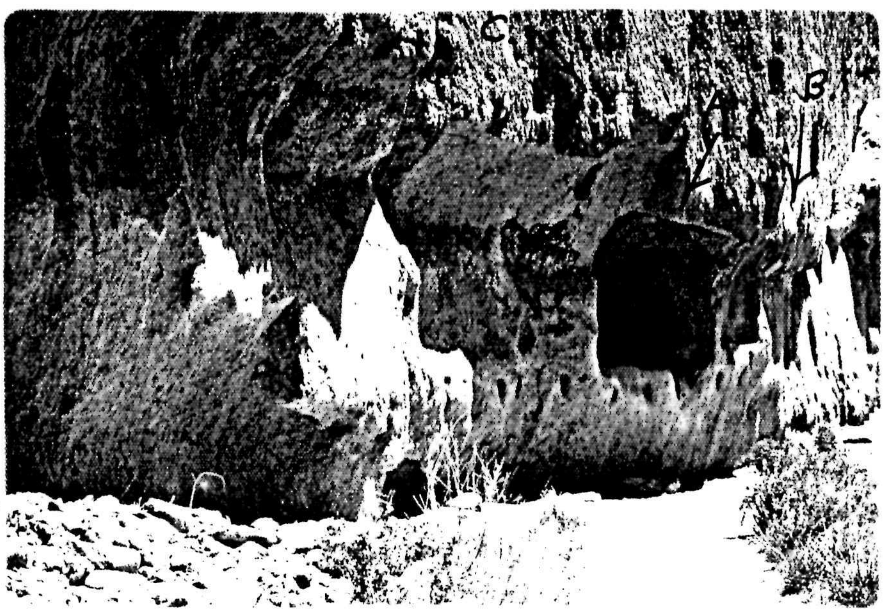


Figure 11. Western-most cliff room at Longhouse, Bandelier. Active motion around the artificial opening: A. 10 kg-scale block ready to fall on visitor path. B. 500 kg-scale block defined by freshly propagating cracks. C. 100 kg-scale block. Note fresh diagonal faces above-left of room indicating post-habitation rock fall. Base-coving is evident.

pinned immediately, considering heavy visitor traffic here. A one-half ton slab is in motion and cracks are propagating around it at the upper right of the opening (Figure 11); fall is probably not imminent, but monitoring would be advisable and interesting. A 100 kg-scale block is in motion 3 feet above and to the left of the room opening. This situation typifies small-scale instabilities in the Longhouse cliff.

Larger-scale hazards are forming in the central Longhouse area (Figure 12). Hairline cracks in plaster indicate significant motion of 1000 ton magnitude monoliths. Branching pattern of cracks may indicate a maturing of the motion to terminal phase. Figures 13 and 14 show similar motion of other large monoliths in the same area as Figure 12. The leaning slab in the background is the late 1960's fall. It would appear expedient to monitor several of these cracks beginning as soon as possible.

The Talus House area appears to be more stable--but examination was very brief. Bandelier will rate high priority for a complete rock motion study. Danger is extreme due to the extent of trails relative to unstable cliffs--including trails to outlying areas. Ground vibrations generated at nearby Los Alamos may promote rock motion or trigger fall in this region, as could the higher precipitation, colder winters, and heavy vegetation (root growth).

C. Chaco Canyon

As illustrated by the fall of Threatening Rock, rock motion and fall is endemic and of high geologic frequency at Chaco Canyon. Visitor

Figure 12. Hairline branching cracks in plaster, central Longhouse area, Bandelier. Cracked plaster indicates post-habitation motion of 1000 ton-scale monolith. Dendritic (branching) pattern suggests that monolith is pivoting on the area of instability, created by rooms, vents, and niches.

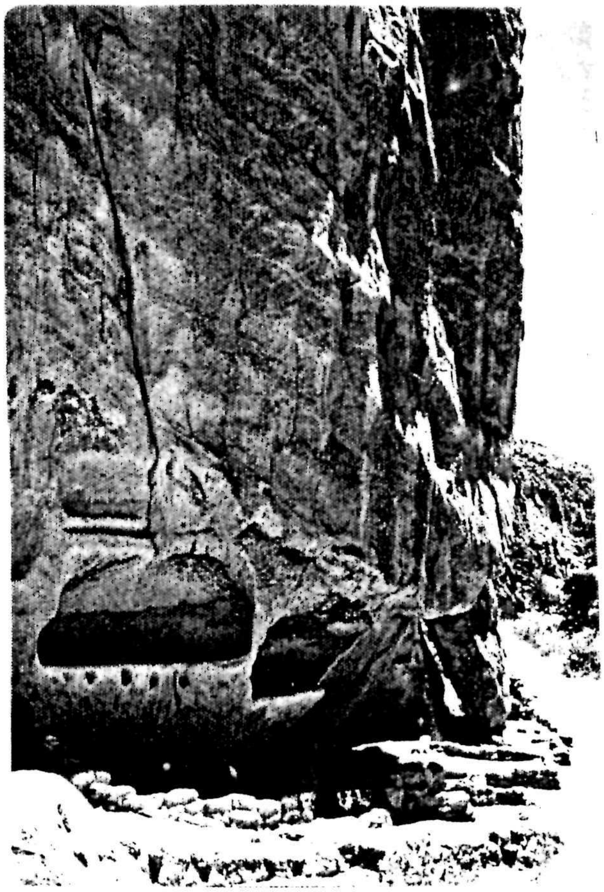


Figure 13. Central Longhouse area, Bandelier. Old crack left of center shows recent motion (cracked plaster). Many other fresh cracks indicate extreme instability and present motion in this area of closely-spaced rooms and deep undermining of cliff.

Figure 14. Overhang portion of Figure 13. Branching cracks on large and small scales. Area is travelled by visitors. Large leaning monolith in background in 1960's fall.

traffic is not concentrated at the cliff bases, as at El Morro and Bandelier, so small random fall events are not as significant individually. The greater extent and frequency of instability at Chaco Canyon calls for a careful study of broader scale to determine probable small-scale events in areas of random visitor access.

Large-scale events still threaten the road and ruins areas. No detailed reconnaissance was attempted, other than to define the problem. Determination of large-scale instabilities should be made soon and monitoring re-initiated.

d. Mesa Verde

Rock motion at Mesa Verde shows a combination of effects seen at El Morro and Chaco Canyon. The cliff-forming sandstones rest on erodable shales which are exposed to weathering throughout miles of cliffs and canyons. Slump, glide, and slide is expected as sandstone is undermined by erosion of shale and moves due to shale plasticity.

The alcoves of Spruce Tree House and Cliff Palace appear to be fairly stable overhead. Historic falls and the necessity to rock-bolt over Spruce Tree House reminds that apparently stable alcoves still are in fact actively forming by progressive spalling and slabbing. Efforts to direct water from above the alcoves should slow the rates of slabbing.

Cliff Palace itself has been in motion due to large-scale creep of the talus slope on which it is built. Figure 15 is of a crack extending through a talus block and masonry. This is but one of dozens of crack systems in talus and masonry that show instability throughout Cliff Palace. Stabilization attempts, including a successful drainage tunnel

Figure 15. Cliff Palace, Mesa Verde. Post-habitation crack in talus block and masonry due to creep of slope material. Motion may have been stopped or slowed by drainage and stabilization, but is likely to reoccur or accelerate.

below, seem to have stopped or slowed motion. Acceleration with time or increase in precipitation is likely. The situation here requires monitoring of changes in location or elevation of points in the ruin and on the slope. Periodic transit levelling as well as monitoring of certain cracks would be possible. Mass motion should be large prior to catastrophic failure (accelerated creep should precede slump or slide).

At Balcony House there is a serious problem overhead. A large slab (100 ton magnitude) one to three meters wide and approximately 35 meters long is detaching from the roof of the alcove (Figure 16). The bounding cracks are sharp and fresh, showing centimeters of movement of the sagging slab; much of the movement has occurred since habitation Where the slab arches near the floor, a small block has been recently dislodged by the movement (Figure 16). The ruin is open to visitors and pathways pass beneath the slab. A large part of the ruin is threatened by this developing fall. Sudden fall with little additional motion is a possibility--this is a case for immediate engineering attention, not just monitoring.

Warren Kuh, an archaeology student, has (in 1976) marked the slab and references the marks in a paper that is on file at Mesa Verde. James A. Lancaster (one time Maintenance Director(?) at Mesa Verde) had recorded many rock hazards in the Park. These reports provide a head start in a necessary rock hazard study for Mesa Verde.

(Spruce Tree House, Cliff Palace, and Balcony House were the only cliff sites visited on this trip.)

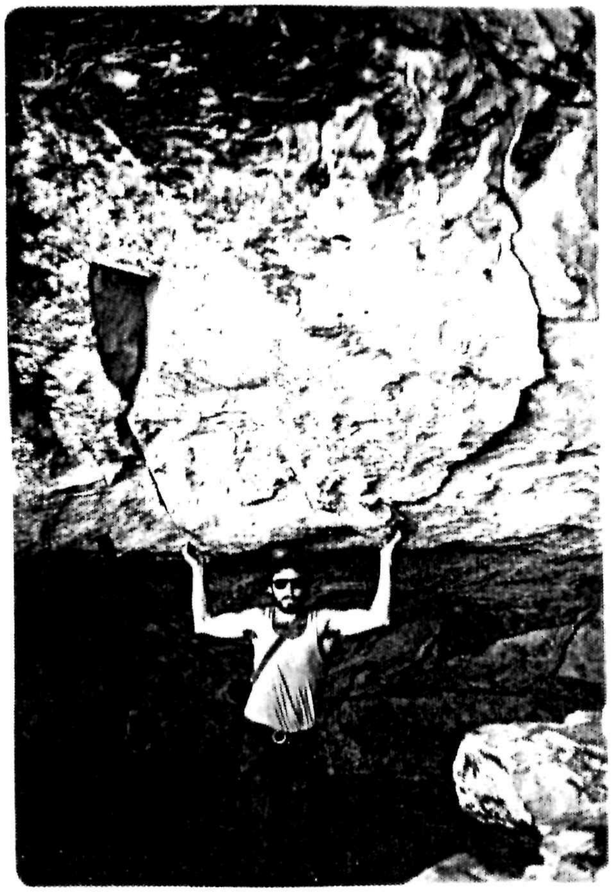


Figure 16. Lower portion of a long arched slab detaching from alcove roof above Balcony House, Mesa Verde. Recent movement is evidenced by offset, broken smoke crust and recent dislodgement of the small block (cavity above Jay's right hand).

e. Wupatki

Rock units prone to motion at Wupatki National Monument are the Moenkopi Sandstone and Kaibab Limestone.

The Moenkopi Sandstone is harder and of greater strength than the Mesa Verde units at El Morro, Chaco Canyon, and Mesa Verde. The Moenkopi often has a pronounced layering that promotes slabbing (Figures 17 and 18).

Many of the ruins are built on outcrop pedestal or small bluffs such as Wukoki Ruin (Figure 17). There alternating soft massive sandstone and harder layered sandstone alternate with some softer shale beds included. The soft sandstones or shales cove moderately to severely at the base leaving slabs of the hard layered rock suspended and unstable. Some movement is evident in a 1000 kg scale slab and smaller crack-bounded layer segments. The fall area is accessible to visitors.

Ruin NA635 is not accessible to visitors but there small-scale slabbing threatens a portion of the ruin--typifying important but non-urgent decisions to be made relative to ruins preservation (Figure 18).

Kaibab Limestone shows tendency for falls due to vertical jointing of beds and hard to soft layering (Figure 19). This ruin is near the road to the Lomaki area and so attracts visitor traffic.

Figure 20 shows deep undermining of Kaibab Limestone in the gorge below Lomaki. The lower (horizontal slab) appears to be in motion, as do the two vertical sections. The vertical cracks do not obviously affect the masonry above, however, so motion may not exist. Areas below and above the possible fall are accessible to visitors. The lower slab is

Figure 17. Wukoki Ruin, Wupatki, built on outcrop pedestal of Moenkopi Sandstone. Rock motion is evident on the opposite side of the pedestal (180° from photo view) in overhanging slabs.

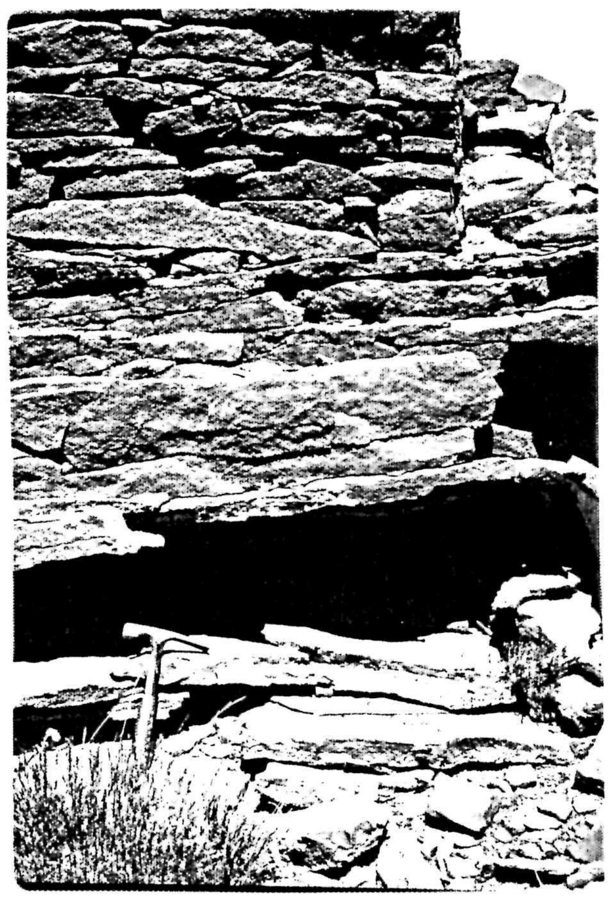


Figure 18. Ruin NA635, Wupatki. Small-scale slabbing of hard, layered Moenkopi Sandstone threatens section of ruin.

Figure 19. Blocky character of Kaibab Limestone in Lomaki area, Wupatki. Tendency to fall is accentuated by bedding, vertical jointing, and soft erodable interlayers.

Figure 20. Horizontal slab apparently in motion below Lomaki Ruin, Wupatki. Vertical segments threaten visitor area and ruin above, but are not definitely in motion. Kaibab Limestone.

is likely to fall suddenly, but long-term motion with visual indication is expected for the vertical segments.

5. Delineation, Monitoring, and Prevention of Rock Motion

The delineation of rock motion hazards requires first a site-by-site study within each critical Park or Monument. "Critical" refers to any Park or Monument within which sites are located on, in, or below cliffs or ledges where rock motion may threaten safety of visitors or personnel or threaten the ruin itself.

For this phase of the study, geologic perceptions seem to be most important. Either a geologist or geological engineer with strong geologic sensitivity would be suitable. An important part of this study involves communication with site staffs regarding their knowledge of specific cases of potential and past rock falls. Priorities should be established on a basis of imminence and size of falls determined by the geologic work and degree of threat to: (1) people, (2) ruins and historic sites, (3) facilities as determined by the appropriate NPS administration in consultation with the geologist or geologic engineer. The priorities should specify: (1) immediate engineering action (stabilization or elimination of moving mass), (2) immediate monitoring, (3) monitoring advisable in the near future.

Monitoring:

Todd Rutenbeck of NPS Western Archaeological Center, Tucson, has anticipated the monitoring problem. He has developed simple but accurate reference devices that can be placed on rocks or ruins that may be in motion. Periodic measurements can be taken by site staff and then reported to WAC for interpretation. Where broad motion, such as that possible for Cliff Palace, Mesa Verde, is not detectable by monitoring of crack separation, accurate survey references should be set and periodic transit or electronic checks made on lateral and vertical motion. Todd Rutenbeck and WAC are developing this capability also. A central coordinating agency is necessary so that experience in interpreting various types and rates of motion relative to final fall can be developed and applied over the long term.

Prevention:

Obviously, the cure varies case by case. Initial decisions may be easy in unimportant areas where intentional elimination by mechanical means is appropriate, either by mechanical means (prying off of slabs or blocks) or by blasting. Administration may need advice from outside engineers (civil or mining or rock mechanics) to clarify options in touchy locations as to means available:

1) Stabilization (pinning, bolting, grouting, supporting, drainage, unloading, retaining walls, etc.)
2) Elimination (prying, blasting, jacking, etc.)
3) Isolation (fencing, posting, etc.).

In summary, the rock fall problem requires recognition, cataloging, classification as to priority (which is likely to require monitoring), evaluation as to threat, and decision regarding prevention of catastrophic falls.

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Addendum to Report A

ADDENDUM TO REPORT A

Rock Motion Hazard

Return trip to:

El Morro and
Bandelier National Monuments
Mesa Verde National Park

By: Bruce G. Wachter, Ph.D.

Under contract with National
Park Service, Western
Archeological Center,
Tucson, Arizona

September-October, 1978

ADDENDUM--Report A

Rock Motion
Return trip to: El Morro
Bandelier
Mesa Verde

1. Purpose of Addendum
2. El Morro
3. Bandelier
4. Mesa Verde

1. A second trip to several Park Service jurisdictions was made in September-October, 1978. The main purpose of this trip was to begin marking of simple rock motion sites and to familiarize Todd Rutenbeck of WAC with various rock fall types and locations for installation of instruments. Also the trip provided opportunity for some additions to and re-evaluations of initial impressions recorded in Report A.

2. El Morro. A recent rock fall, happening this last summer after the first visit, demonstrates the slow rate continuity of slabbing processes (Figure 1A). This slabbing zone had been active prior to 1600 A.D., exposing by then a smooth face for inscription by Onate. Though this small fall (200 kg-scale) provided no great hazard, similar larger scale instabilities exist on the north face of Inscription Rock.

   Figure 2A symbolizes the instabilities apparent on the north face. It is a recent fall scar 20 m beyond trail guide point 21. No motion is identifiable at present, but this type of arched unstable zone, here and at other monuments, seems particularly unpredictable.

   Also on the north face:

   -an active slabbing zone with several largely detached masses exists one-third to two-thirds of the way up the cliff face between trail points 18 and 19.

   -above point 20, at the peak of the cliff prominence, a 5 ton-scale mass is separated from the main cliff by cracks and is unsupported from below.

   -above point 21 is an unsupported slabbing zone. No particular blocks can be identified as "in motion" at present except for numerous small flakes of weathering crust of possible 10 kg-scale fall potential.

Figure 1A. Area of recent rock fall (summer, 1978).
a. Fall scar.
b. Onate inscription on face below scar.
El Morro.

Figure 2A. Major instabilities exist along the north face of Inscription Rock on large scale as shown here and as random detaching flakes and blocks of 5 kg to 5 ton scale. El Morro.

The monolith of Figure 6, Report A, actually showed a closing of the dendritic crack system (Figure 7, Report A) since the first visit. This can hardly mean that the monolith is moving back into place. Though indication is that some minor secondary effect (thermal expansion cumulative over summer??) is equal to or excessive of any gross movement. A 50 year-old photo shows the vertical crack clearly--though the critical lower portion was not visible in that photo for comparison with present status. Apparently fall is not imminent; rates of motion may still be very slow. Monitoring is planned by WAC.

A climb to the base of Woodpecker Rock proved conditions to be as precarious as suggested by earlier distant view. The small base pedestal is weather-deteriorating and old diagonal fractures provide further weakness (Figure 3A). Surprisingly, no actual motion (new cracks or strain slabbing) can be seen.

Recommendations: The situation is far more threatening above the north face trail than along the south face. The section between trail guide points 17 and 20 is quite unstable, as is the area above and west of point 21.

Woodpecker Rock must be considered an immediate threat to the present trail alignment below. The situation does not lend itself to instrumental monitoring--failure could be total and without warning.

The monolith on the south face is now considered less a threat than originally thought. Monitoring hardware will be installed, though complex shattering of the midsection of this mass adds some unpredictability.

A few loose float blocks and retaining-wall stones should be removed from the switchback section of trail up the south face. A few wall-stones should be mortared in this area also.

3. Bandelier. In the Longhouse area Todd Rutenbeck noted an impending fall area more threatening than the others discussed in Report A. A massive sheet 30 m long by 10 m high is almost entirely detached from the cliff face (Figure 4A). Basal moisture deterioration has broken the durable weathering crust that protects most of the Bandelier cliffs. The resultant base-coving is progressively removing support. The sheet leans 0.5 m from the cliff at top center and complex shattering (vertical and diagonal cracks mainly along the base) may indicate near-terminal status. Again, prediction is not yet possible. Partial monitoring is possible with present hardware, but monitoring of the central-peak section will require a remote reading device.

   Other observations of Bandelier:

   a. Rates of rock motion are quite low in the <u>Longhouse area</u>. Though rates are likely accelerating since disruption by habitation, fall hazards are likely less imminent than assumed after the first trip (Report A).

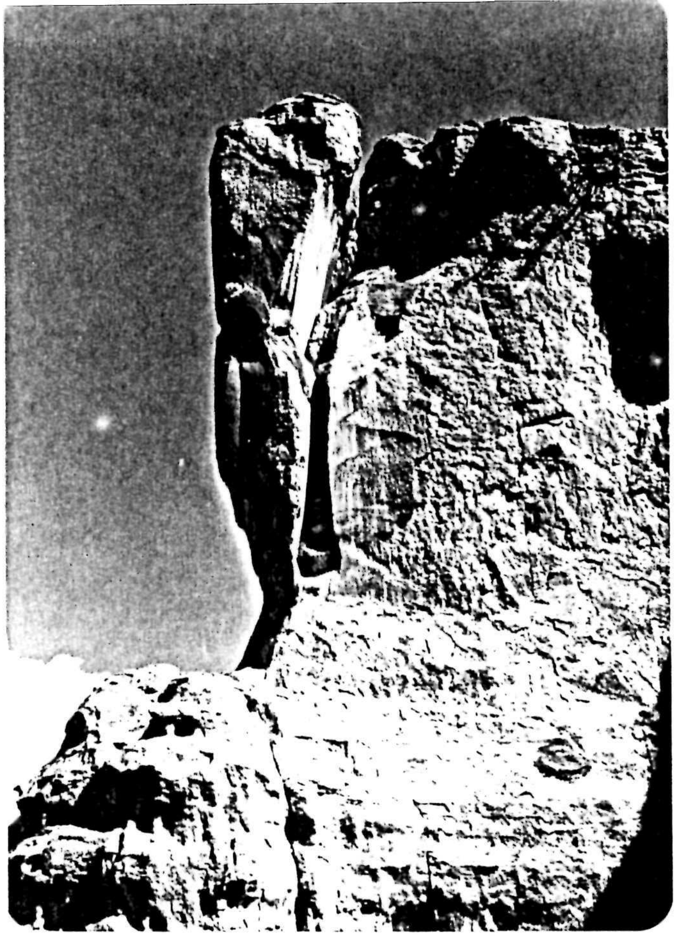

Figure 3A. Base of Woodpecker rock is softened by weathering. Fall is "geologically imminent" but no actual motion is apparent with which to predict timing. El Morro.

Figure 4A. Bandelier, Longhouse area. 30 m by 10 m massive sheet separating from face. Base coving and complex shattering add to a sense of imminent fall. The ranger walks on the visitor trail.

b. Several of the cave-like rooms show active instability (e.g., second-story cave above room 110, second-story cave above room 130, and second-story cave above room 156). Each of those caves exhibits active cracks and detaching segments that deserve monitoring. Access should be controlled.

c. More random cliff-fall hazard exists than implied in Report A. For example:

(1) Several large detached blocks near the top, and miscellaneous unstable material lower on the cliff-point above the trail just before reaching Longhouse (Figure 5A).

d. Similar instabilities exist on the cliff above Frey Trail, west of Talus House.

e. Below Frey Trail, above Longhouse trail between Talus House and Longhouse, float boulders are perched precariously on eroding soil and threaten the trail below.

f. Two 5 to 10 ton-scale boulders rest on 45^{o} inclines just above the narrow rock passageways along the trail west of Talus House. Despite precarious appearance, the rocks show no recent motion.

g. Four cave-like rooms accessible to visitors by ladder, upper portion of Talus House, are very unstable. Active crack systems show post-habitation motion in excess of any seen in Longhouse.

h. A massive monolith is separating from the cliff beside the water course along the low point in the trail just east of Talus House. No immediate threat exists. The situation is ideal for a monitoring installation.

Correction: The slab fall of Figure 14, Report A, occurred in 1975.

Recommendations: Some crack systems have been marked for observation in Longhouse and Talus House--instrumental monitoring is planned for several locations by WAC. More reconnaissance work is necessary in the Talus House area and the cliffs generally need analyzing for imminent hazards. Time was too short for thorough study during the trips reported here.

Monitoring and careful examination of the high cliffs may generate immediate concern for several areas but as of now only the area of Figure 4A is considered an imminent fall hazard. Rolling and sliding rock is a hazard. Slopes should be policed carefully for loose blocks above trails, particularly in the area below Frey Trail between Talus House and Longhouse.

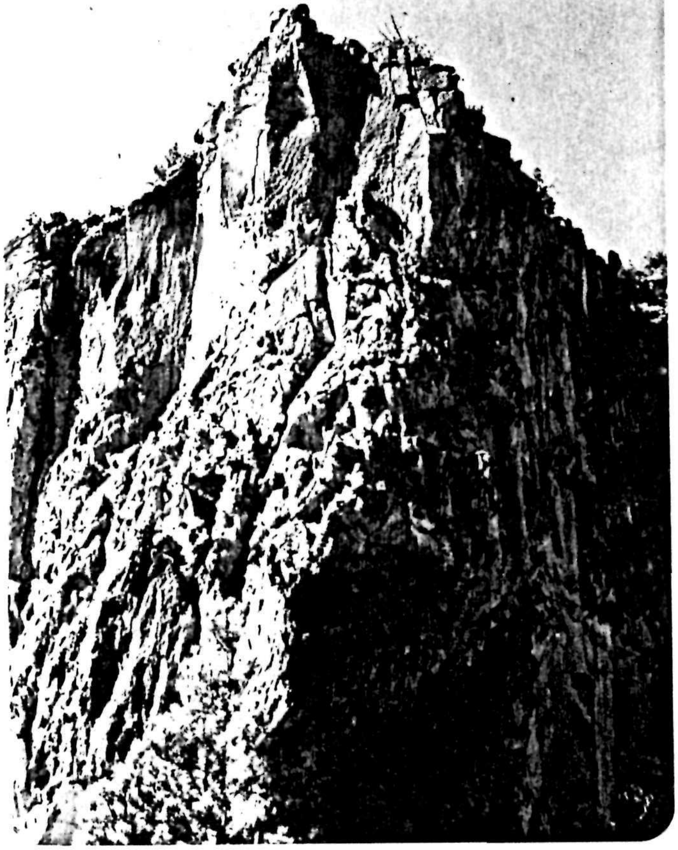

Figure 5A. Detached, perched blocks exist right and left of the peak. Cliff-point above east end of Long-house, Bandelier.

Figure 6A. Balcony House, Mesa Verde. Ceiling of alcove, taken from floor of central kiva. Crack systems of the arched ceiling slab are propagating in the direction of the arrows. Fragments have fallen from "a" and "b". In area "c" strain is shown by surface flaking. Photo documents present status of cracks.

4. Mesa Verde. Only Balcony House and Cliff Palace were revisited. No significant new or imminent-appearing fall hazards were noted within the ruins; in fact, Cliff Palace appears, after the perspective provided by visits to a dozen similar situations in the National Monuments, to be quite stable.

   At Balcony House, the overhead "arched slab" of Figure 16, Report A, is considered serious and very unpredictable. Horizontal overhead slabs may fall with little warning from pre-motion or crumbling (as shown by the most recent ceiling fall in Keet Seel, Report B). The "arched slab" is, in fact, a complex network of slabs and cracks that are "working" at several places. Figure 6A shows that the high end above the center of the ruin is in motion that is comparable to the lower portions shown in Figure 16, Report A.

   The trail to Cliff Palace deserves some attention, as a balanced float boulder threatens the trail 100 feet beyond the locked gate. Overhanging and perched slabs above the first switchback should be tested with a pry bar. The same applies to miscellaneous blocks and slabs above the trail segment between the switchback and the entry ladder. The cliff face about 100 feet before reaching the ladder has several very precarious slabs.

   The trail passes beside an overhanging mass of 1000 ton-scale that is undercut at trail level about 3 m back to a vertical fracture that may provide a detachment plane. An adjacent block of several 100 ton-scale has completed this process and has dropped. No motion is evident, surprisingly, on the 1000 ton-scale mass. Monitoring is planned by WAC. Stabilization of the low overhanging mass can be easily accomplished by base supports.

   Some instability is apparent in the dark-stained, most-projecting portion of Cliff Palace alcove overhead, right end.

   Huge masses are detached above the Cliff House exit trail. The entire cliff segment, the top of which extends to the top of the exit trail ladders, rests ultimately on a smaller block below (at the level of the trail as it exists at the ruin). This keystone block is showing strain slabbing and/or moisture deterioration. No immediate hazard exists. Monitoring is being discussed.

   The Balcony House trail has several questionable slabs and boulders above that should be tested with a pry bar.

   The cliff section about 25-35 m back from the 32 ft ladders is very unstable 20 m up the face. The base section is coving intensely under salt and moisture attack. Active slabbing seems to indicate current strain. Monitoring is planned.

Loose masonry is perched over the entry ladders in the extreme left end of Balcony House ruin. That area should be roped off and loose masonry stabilized. Minor active slabbing exists on the alcove above the entry ladders.

Recommendations: Immediate policing and testing of accessible loose rock above trails should be organized. Presumably trails other than those to Balcony House and Cliff Palace could benefit from such attention. Loose masonry over trails, steps, and ladders should be stabilized--this applies to trailworks and retaining walls as well as ruins. (No unstable retaining walls or trailworks were seen along Balcony House or Cliff Palace, however.)

Thorough geologic reconnaissance of all accessible cliffs, ruins, and trails is recommended.

Monitoring is planned and will be documented by Todd Rutenbeck of WAC.

Report B; Rock Motion Hazard

ROCK DETERIORATION REPORT B

Rock Motion Hazard

Reconnaissance of:

Tonto
Canyon de Chelly
Navajo
Walnut Canyon and
Montezuma Castle National Monuments

By: Bruce G. Wachter, Ph.D.

Under contract with National Park Service, Western Archeological Center, Tucson, Arizona

August, 1978

Rock Deterioration Report B

Rock Motion Hazard

1. Introduction
   Refer to Sections 1-3 of Report A.

2. Determination of Rock Motion
   a. Tonto
      (1) Upper Ruin
      (2) Lower Ruin
   b. Canyon de Chelly
      (1) Sliding Rock
      (2) White House
      (3) Antelope House
   c. Navajo
      (1) Keet Seel
      (2) Inscription House
      (3) Snake House
      (4) Betatakin Trail
      (5) Betatakin
   d. Walnut Canyon
   e. Montezuma Castle
      (1) Main Castle
      (2) Castle "A"
      (3) Montezuma Well

3. Delineation, Monitoring, and Prevention of Rock Motion
   a. Refer to Section 5, Report A.
   b. Second trip to El Morro, Bandelier, Mesa Verde, Navajo
      Montezuma Castle.
   c. Amplifying Comments (Important, Administration especially note)
   d. Initial monitoring program underway at present time, Western
      Archeological Center, Tucson.

1. Introduction

Report "B" is a continuation of work outlined in Report "A" and should be attached to that first report (identical distribution is assumed). The fullest understanding of rock motion hazard, even by individuals concerned with the specifics at one ruin, Park or Monument, is possible by reference to both reports. See, particularly, the introductory and explanatory Sections 1-3 and summarizing Section 5 of Report "A".

This Report "B" is somewhat more specific in the identification of hazards at the ruins (and along trails) visited. The purpose was more advanced than simple "reconnaissance" but is less than a complete analysis of rock fall hazards. It is apparent that highly detailed studies would be necessary to approach completeness; 100% confidence in monitoring, prediction, and prevention of rock fall is not likely at even the most simple and concise cliff sites.

2. Determination of Rock Motion

a. Tonto

(1) Upper Ruin. The trail approach to the upper ruin traverses a soil-covered slope along the base of a shattered quartzite (Dripping Springs Quartzite) cliff as shown in Figure 1.

The quartzite is intensely fractured, tending to form loose blocks of 10 to 100 kg scale that threaten the trail below. Within 100 m of the ruin, the texture of fracture becomes finer and the smaller more irregular fragments are cemented by a carbonate (calcite, dolomite plus silica) material such that the fragmental rock (breccia) behaves more like a strong, massive limestone. There is some tendency to vertical slabbing but active rock motion is not obvious.

In the alcove 50 m south of the ruin active slabbing of three types is evident; two do not appear to be generating high-frequency rock fall due to the tenacious nature of the cemented formation (Figure 2).

1. vertical slabbing, parallel to cliff.
2. irregular slabs on massive inclined faces.
3. horizontal slabbing (not well shown--above and right of packsack) along undercut bedding planes and at north end of alcove.

These alcove-slabs of 10-1000 kg size are just above the trail and the alcove is easily accessible to visitors. Type 1 and 2 are slow to detach but the small, blocky bedding plane slabbing is progressing quite rapidly.

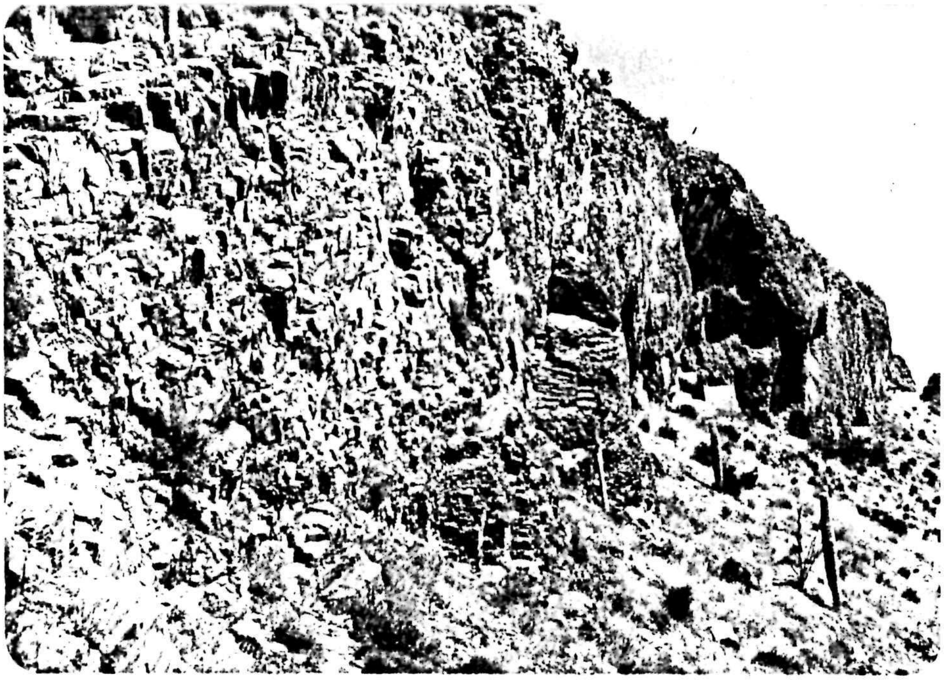

Figure 1. Tonto. Fractured quartzite above trail (seen in right foreground) grades to massive, carbonate-cemented phase (right midground). Trail to Upper Ruin.

Figure 2. Tonto. Distinct slabbing processes in alcove 50 m south of Upper Ruin. Despite the threatening appearance, fall is not common from the cemented quartzite breccia.

The distinct slab over the ruin (Figure 3) has generated some concern, partly due to the presence of an active solution channel visible at the slab boundary (Figure 4). Solution process may well promote long-term motion but at the Upper Ruin solution-deposition of carbonates more often appears to be recementing and stabilizing older slabs. This particular slab appears also to be otherwise attached along one side.

A near-vertical crack defines a large monolith at the south end of the Upper Ruin alcove (Figure 5). Note the rounded edges of the crack indicating long-term existence of the system. The crack extends entirely through the south buttress of the alcove but fades into solid rock above ground at the gate (Figure 6). It appears to be inactive, but it may deserve monitoring as reactivation or slow motion will effect stability of much of the alcove.

Recommendations: The blocky-fractured cliff section above the trail (Figure 1) could be easily examined for precarious blocks and columns. Those that fall under pressure of a short pry-bar could be eliminated, otherwise long-term stability may be assumed.

Similar slabbing could be done in the alcove south of the ruin. The bedding-plane slabbing zones should be checked every few years for new detachments. The larger slabs will be considered for monitoring by WAC.

The monolith at the south end of the Upper Ruin will also be considered for monitoring by gauge points set across the main crack or by marks to watch for propagation of the present south-lower extremity of the crack.

Note similar recommendations of recent study by Dames & Moore (Bukovansky, 1978)*.

(2) Lower Ruin. Most of the alcove appears to be stable but at the north end buttress zone a large, old crack system is apparently reactivating. Fresh hairline cracks appear as branching propagations of the old crack, breaking previously "healed" zones (Figure 7). Just below the pictured area, tension is indicated by freshly-formed short en echelon or "slash" fractures. The quartzite in this area is less cemented, presumably more brittle than the Upper Ruin rock and rests on shaley horizons. Further, the north end buttress is foundationed into a silty zone softened by alteration.

A network of interlocking slabs begins over the southwest corner of room 7 and extends above room 10 (rear center of

*"Report of Roof Stability Conditions, Tonto National Monument, Arizona," Dames and Moore Job No. 02050-052-14, August 1978.

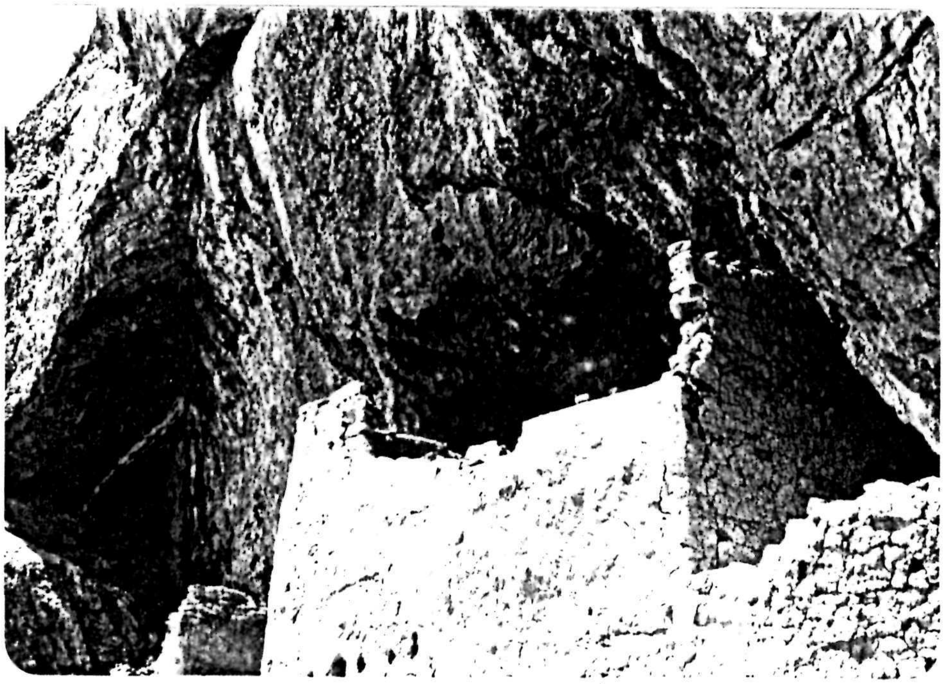

Figure 3. Tonto. Distinct slab above the Upper Ruin. Does not appear to be in motion presently.

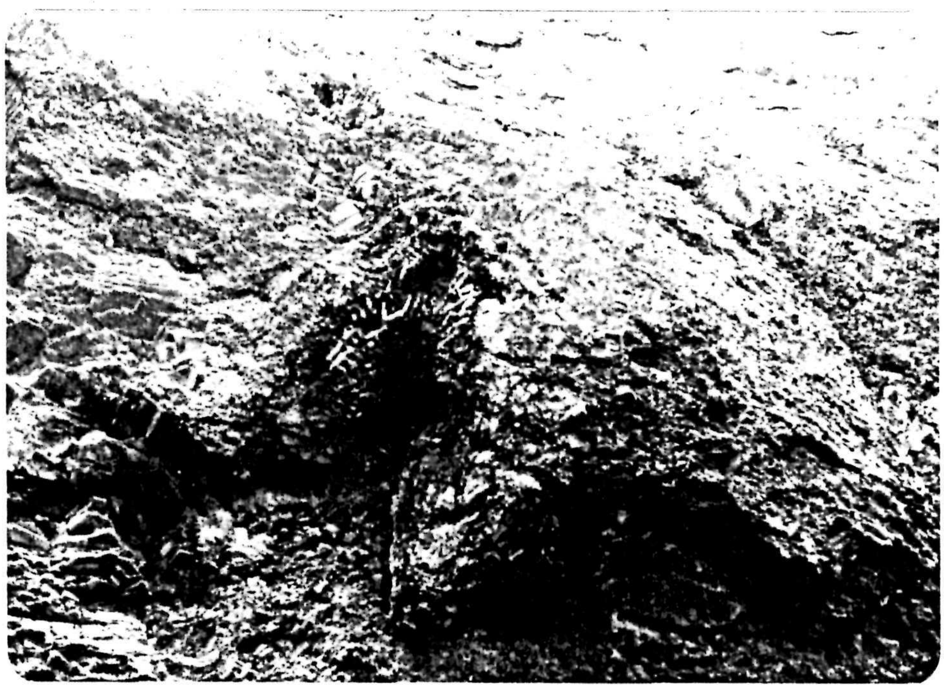

Figure 4. Tonto. Solution channel along the boundary of the slab above Upper Ruin.

Figure 5. Tonto. Near-vertical crack defines a large monolith at the south end of Upper Ruin alcove. (Looking south from south rooms of ruin.)

Figure 6. Tonto. The crack (south end of Upper Ruin) extends through the alcove buttress but fades into rock at the gate. No signs of recent motion exist.

Figure 7. Lower Ruin, Tonto. Reactivating crack systems at north end buttress of Lower Ruin. Large old crack (center, vertical) branches into new hairline cracks above, right, and left of notebook. Other fresh hairline cracks have opened several feet below and to the right out of view. (Looking north from room 7.)

Lower Ruin). A large slab above room 8 has moved but apparently not since habitation.

Recommendation: Immediate monitoring is necessary and is planned by WAC to determine the degree of threat to trails below, the visitor's center, and the ruin from the north end motion.

b. Canyon de Chelly

(1) Sliding Rock Ruin. The ruin is pointedly named for the fact that most of the masonry has slid entirely out of the alcove. Natural talus blocks rest on the steep slope of the alcove base in a precarious manner. In Figure 8 note the two large slabs, mid-ground beyond the masonry wall. They cannot be stable in any geologic sense, yet they support small masonry remnants, apparently in original position. A second talus accumulation at the southwest end of the ruin appears equally unstable but again supports masonry (Figure 9).

The alcove sandstone is remarkably stable in the walls and overhead. Though the alcove appears to be actively forming by progressive slabbing, no major slabbing since habitation is obvious. Canyon de Chelly overall is surprisingly stable. Rock motion, even random fall, appears to be rare in the areas visited--with the exception of Antelope House.

Recommendations: In spite of the lack of motion in the individual talus blocks noted, the history of Sliding Rock and the geologic instability of talus of steep slopes demands the lowest possible visitation in the ruin and along the cliff base below the alcove.

(2) White House Ruin. Also generally stable. A very large slab under the upper level ruins shows obvious offset along a vertical crack (a) in Figure 10. Motion is indicated by cracking of the masonry above (b).

Recommendations: The situation should be inspected from above and gauge points installed or a remote system devised for motion monitoring.

(3) Antelope House. Post-habitation rock fall is evident along the rear alcove wall above a zone of active base slabbing (moisture deterioration). Slabbing propagates upwards in some areas into thicker slabs, in others the propagation dies as slabs thin upwards (Figure 11). The progressions are clearly marked by remnant smoke crusts. Acceleration may occur as softer rock is exposed by slabbing-off of the weather-rind.

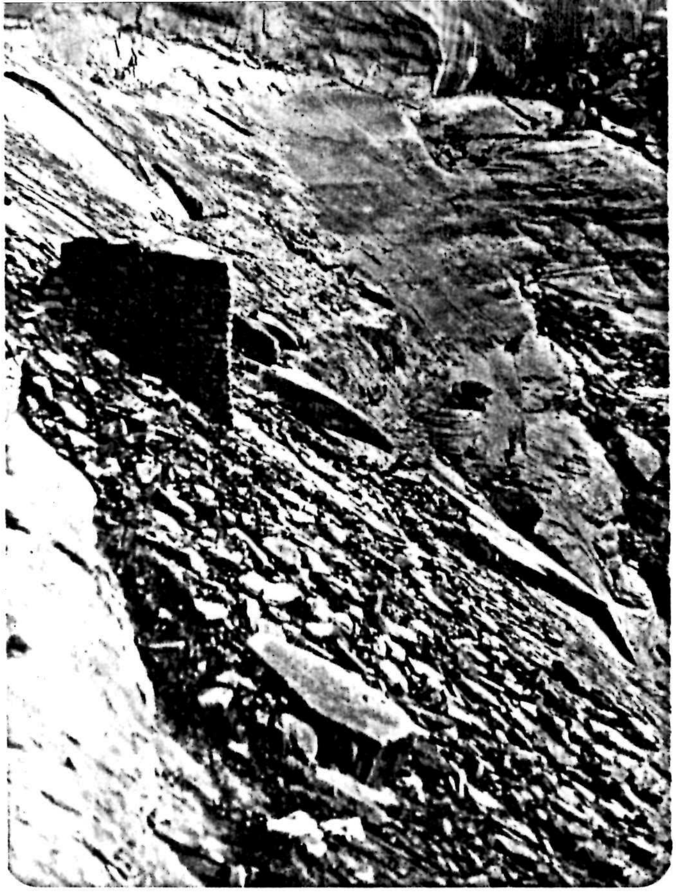

Figure 8. Precarious-looking talus blocks, northeast end of Sliding Rock Ruin, Canyon de Chelly, support small segments of masonry.

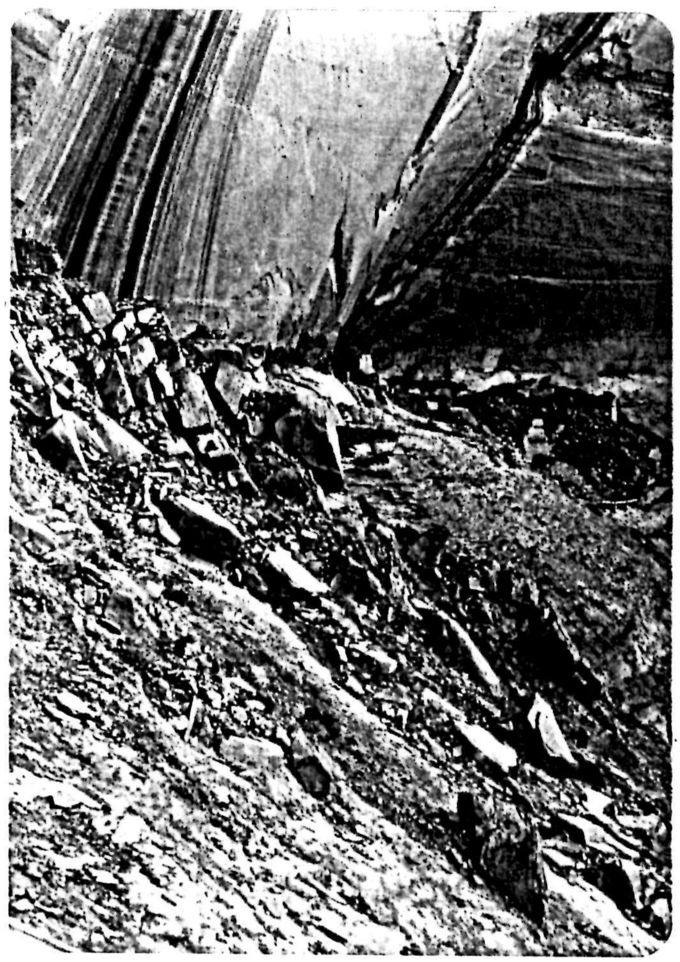

Figure 9. Southwest end of Sliding Rock Ruin. Another "unstable" talus mass again supporting masonry in original position.

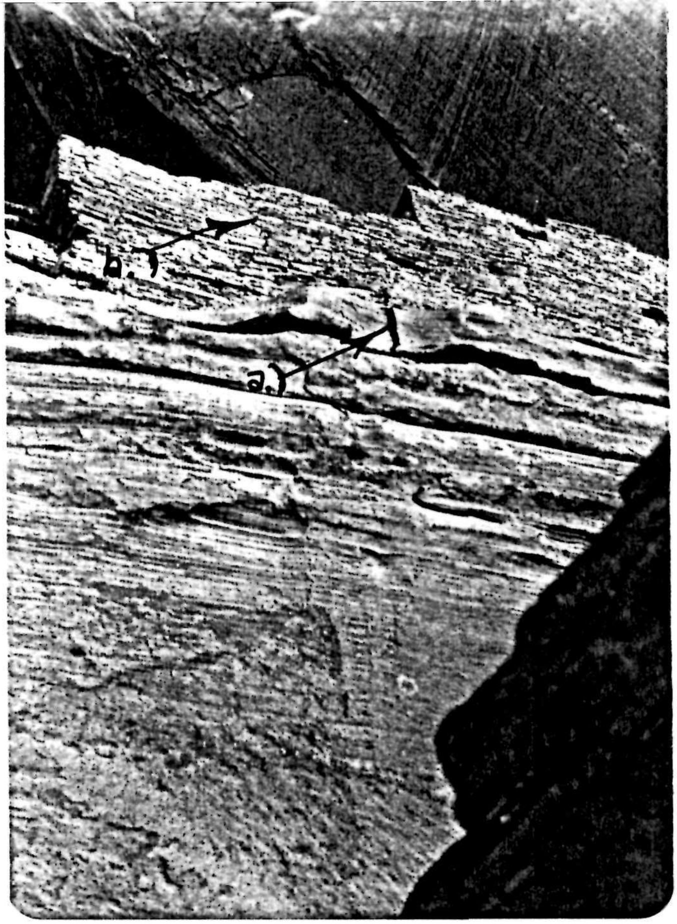

Figure 10. White House Ruin, Canyon de Chelly. Offset at crack (a) shows past motion that may be continuing since habitation. Masonry is cracking above (b).

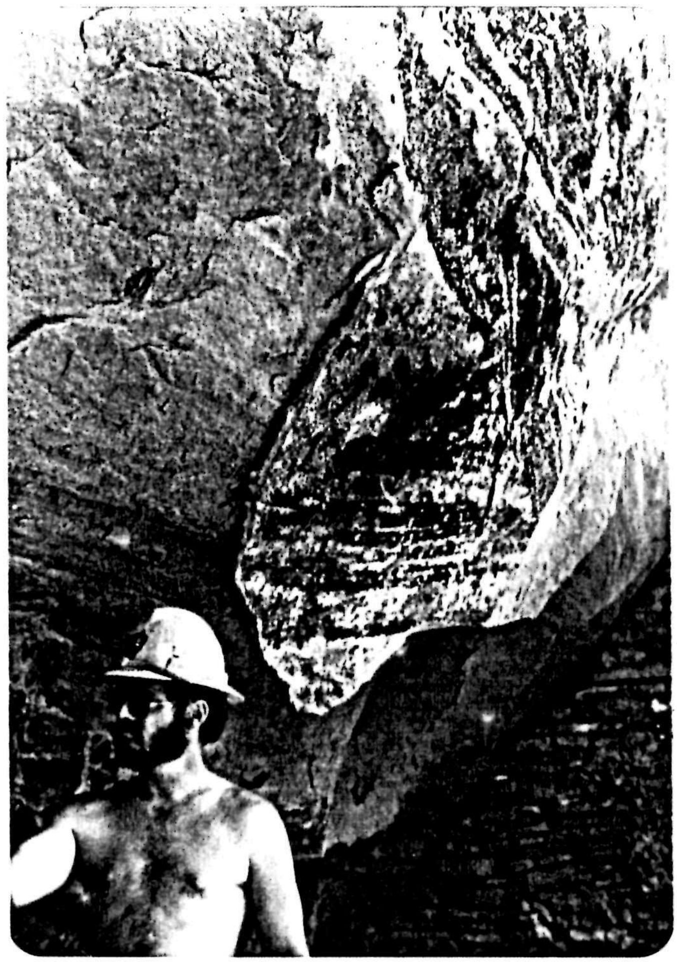

Figure 11. Post-habitation flaking and slabbing upward from alcove base. The slabbing may accelerate as the hardened weather-surface is undermined and soft rock exposed. Antelope House, Canyon de Chelly.

A major rock fall occurred in the grotto northeast and adjacent to Antelope House. The fall, 10-100 ton scale dropping a few meters from the horizontal root overhang, was witnessed in the 1920's.

Recommendations: Antelope House is visited regularly, so pry-bar slabbing of the alcove rear wall is suggested where the unstable section extends above pathways. The adjacent grotto (rock fall area) is fenced off from the visited area, but is easily accessible by determined visitors and is used for shelter and machinery storage by a Canyon resident. Monitoring of overhanging slabs is advisable--this would provide interesting data regarding the continuing instability vs. possible temporary stability following a major known fall event (Park Service jurisdiction?).

c. Navajo

(1) Keet Seel. The Keet Seel alcove shows significant post-habitation slabbing, complicated by the steep (near-horizontal) angle of the overhang. A large percentage of smoke crust has slabbed off.

A recent fall (100 kg scale) is known in the actively slabbing rear-west end of the ruin. Several small partially loosened slabs exist on the near-horizontal section of overhang but presently offer no great hazard to visitors. Note that the minor support provided by masonry walls has temporarily stopped one progressive zone ceiling slabbing in this area (Figure 12). Individual zones will accelerate or decelerate, depending whether thickness of slabs increases or decreases, respectively, with progressive slabbing. Two rock falls reported since this visit apparently originated in or near this zone and that of Figure 13.

An arched area of post-habitation slabbing is obvious at the east end of the ruin and monitoring of the separating left leg is necessary due to presence of visitor paths below (Figure 13).

A large sheet of rock is in motion immediately above the access ladder. Active flaking is evident in both ends of this sheet. The rock-sheet is bowed away from the ceiling at its center. Water that recently drained over the surface is now passing behind the slab. Moisture plus freeze-thaw will hasten fall. One small (50 kg scale) portion is quite precarious now and is cause for immediate concern (Figure 14).

The fatal rock fall (1978) near the Keet Seel campground points out the difficulties in determining rock fall hazards. Figure 15 illustrates the source area of the fall from an

Figure 12. Keet Seel. Recently active ceiling slabbing has temporarily ceased at point of support over the masonry wall. (A large slab-fall has been reported in this area a few weeks after this photo, causing considerable damage to a wall.)

Figure 13. Arch-like zone of progressive slabbing shows clearly the amount of fall since habitation. Keet Seel. (A second rock fall reported by Monument staff may be from this zone.)

Figure 14. Sheet of rock in motion. Location is inopportune, directly above the visitor access ladder. Note water coursing behind the sheet as indicated by stains. Keet Seel.

Figure 15. Area of fatal rock fall of 1978. Near Keet Seel campground.

apparently otherwise stable cliff face. (The source area was not visited nor were the other projections on the upper cliff checked for stability during this visit.) It is not likely that even careful inspection and monitoring can meaningfully predict or control random falls such as this one.

Recommendations: Manual slabbing may be used to eliminate small detaching rock masses low on the sides and ceiling, particularly at the west end of Keet Seel.

Close attention should be paid to the large sheet over the visitor access ladder and thought should be given to the monitoring problem, here very difficult due to physical inaccessibility of the cracks. The small precarious slab must be removed as it is likely an immediate threat to visitors. If that is impossible, the location of the access ladder and visitor congregation points should be changed.[1]

(2) Inscription House. Moderate to serious instabilities exist.

In Figure 16 (alcove above central portion of ruin) (a) precarious-appearing boulders probably will stay in place (excepting earthquake) in spite of apparent instability (see again, Figure 8). Note weather staining, or patina, suggesting long-term stability of the boulders.

(b) Completely detached blocks are wedged into the diagonal fracture plane so posing no immediate threat.

(c) The diagonal fractures section the cliff into zones that may become progressively more unstable. The zone below (c) has fallen recently after losing support from below due to sapping of the alcove base.

Figure 17 shows severe base sapping progressing upward. Likely this is the natural process by which alcoves form and enlarge though here the process could be accelerated by construction and presence of the ruins. In any case slabbing may now increase upward from the sapped zone.

[1] Manual slabbing is reported underway since the two rock falls of autumn, 1978. It appears that instrumental monitoring of slab separations may be unrewarding at Keet Seel if these two falls, not preceded by obvious separations, are typical.

Figure 16. Apparent and real instabilities, Inscription House alcove.

a. Loose boulders probably stable for a long-term period (note patinization).
b. Detached block wedged securely in fracture.
c. Zone of recent and progressing fall.

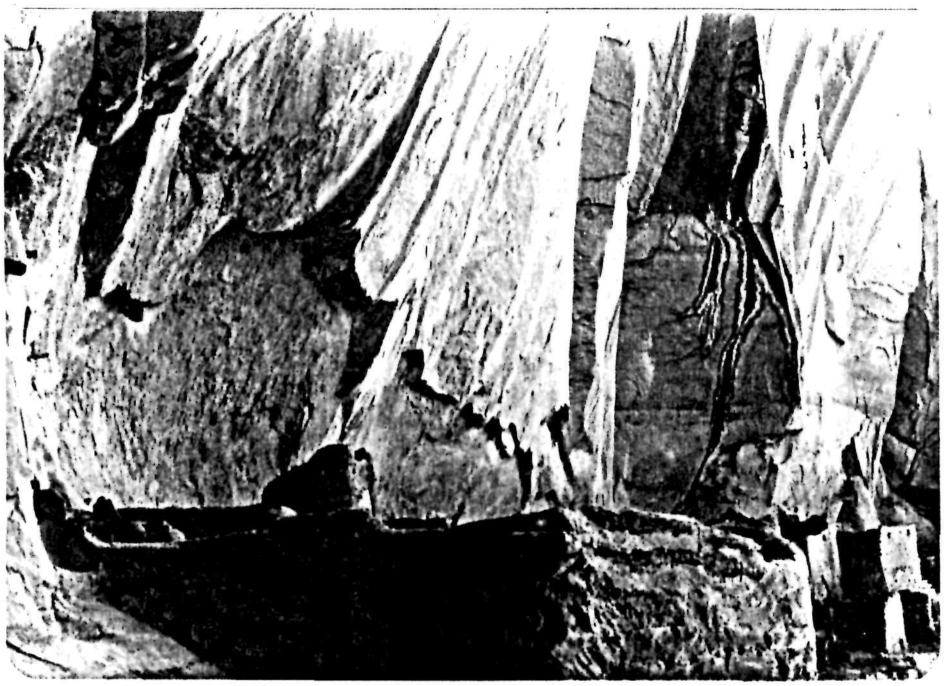

Figure 17. Base sapping across central portion of alcove has contributed to progressive post-habitation instability and rock fall including that of zone (c) in Figure 16.

The deep grotto at the left end of the ruin has been very active since habitation. The ceiling is flaking off generally as light slabs and small sheets. Some presently in motion are up to 4" thick and constitute a hazard to people.

At the opening of the grotto complex instability exists. Figure 18 shows an arched slab that is detached behind and "working" at top and bottom. Figure 19, adjacent, shows the active sapping zone (a) which has propagated caving upward removing material from beside the arched slab. The arch overhead is quite unstable and a block of 500 kg scale is ready for fall (b).

Recommendations: The grotto can be slabbed manually with a long-handled tool. The overhead block (Figure 19b) should be removed before Inscription House ruin is re-emphasized for visitation. The arched slab (Figure 18) should be monitored instrumentally.

Another problem exists in the Inscription House--Snake House area, that being the rapid arroyo cutting and piping erosion. The trails skirt and cross actively eroding areas subject to caving or collapse of arches and pipes in the underlying silts. The Inscription House access trail traverses isolated erosion-remnant masses of silt that are somewhat doubtfully attached to the bedrock cliff face (just below and right of the ruin). The trail should be visually monitored by rangers and reference pins set along the erosional-remnant sections to warn of slump motion of the silt masses.

(3) Snake House. The cliff above the west half of the ruin shows instability on all scales (Figure 20). Base sapping is likely to promulgate and accelerate fall hazards. Major and minor recent falls are evident in this area (Figure 21).

It appears that little can be done to control the fall hazards here short of bolting the base-sapped area to slow upward progression of instability. Random fall from above will continue. Visitor traffic should not be encouraged.

(4) Betatakin Trail. Though something of a small-scale engineering wonder in itself, construction of the trail has created some immediate and long-term rock fall hazards.

The retaining walls along the outside portion of the path are built of stacked unmortared stone, apparently not tied laterally into the slope or into the fill beneath the path. Three types of failure are effecting rock fall hazard:

(a) Loose cap rock at trail level which can fall or be kicked over the edge.

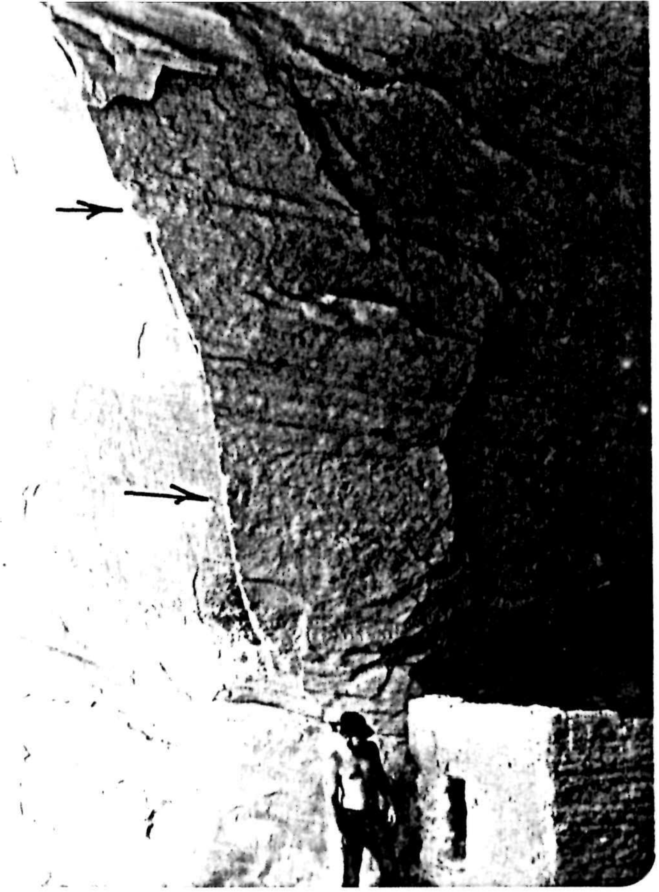

Figure 18. Opening into grotto at end of Inscription House ruin. Arched sidewall has a detached slab that is in motion.

Figure 19. Adjacent to Figure 18. Base sapping (a) has promulgated upward. Overhead is now very unstable, the block at (b) hangs over the present visitor trail.

Figure 20. Snake House, Navajo.

(a) Random instability on cliff face above ruin.
(b) Active base sapping will accelerate instability.

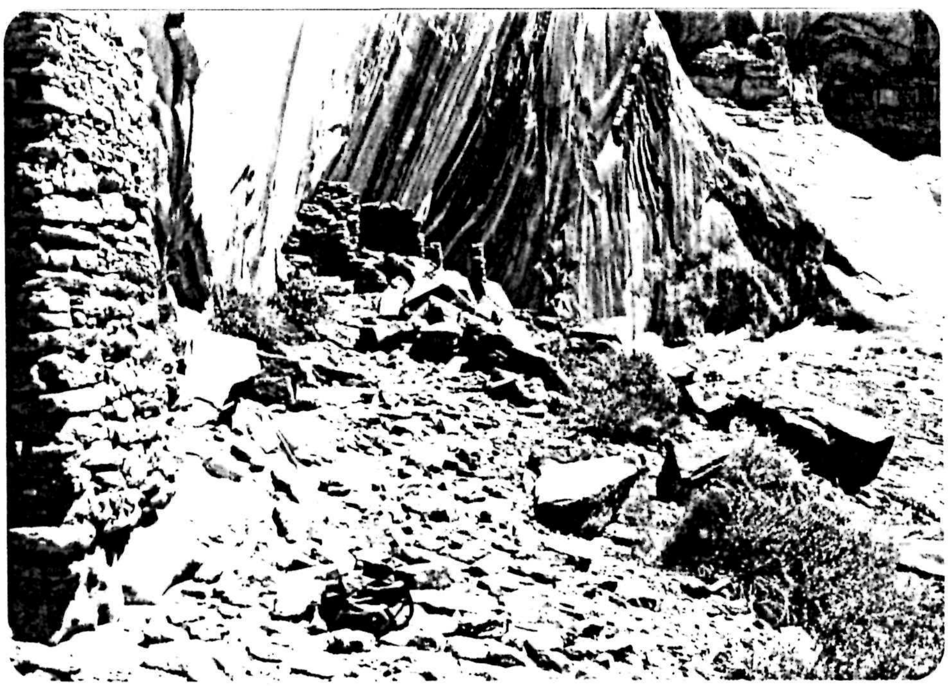

Figure 21. One of several recent falls at Snake House (below (a) of Figure 20).

(b) Rocks working out of the mass of the wall or lower portions of the wall caving out in sections as slope soil erodes beneath.

(c) Spreading, working or over toppling of walls as fill beneath the trail compacts, settles, or works due to moisture and shrink-swell. (The last (c) is not an immediate hazard). See Figure 22.

Each of the retaining wall failures becomes a serious hazard only along switchbacks where people pass beneath. Small rocks could become significant hazards along the head of the box canyon where the trail switches back beneath itself six times. High missile velocities are possible.

The cliff above the gate-barrier is naturally unstable. Note in Figure 23 the fracture systems parallel to the face that promote natural slabbing. Bedding planes provide the horizontal weakness along which the slabs break and release.

Blasting of the trail passageway has aggravated the already poor situation by:

(a) Shattering and disrupting overhanging rock masses.

(b) Removing support, thus accelerating rock motion and detachment.

Present rock motion in this section is indicated near the gate-barrier by (Figure 24):

(a) Horizontal cracks in the outer block; motion is at the up-trail end; hinged at the barrier.

(b) Apparently active crack systems on horizontal and vertical faces.

(c) Absence of large companion block probably dropped during construction.

(d) Cracks in plaster at barrier, patched and cracked again, indicate rapid motion outer section of overhanging block, upper arrow (b).

Below (down trail) from the barrier at the last switchback before reaching Saucer Cave a 2 m overhanging ledge appears stable enough to warrant low priority for monitoring installations in spite of a natural fracture that partially separates the outer and inner masses. Some small block separation is evident on the lip and deserves testing with a scaling bar.

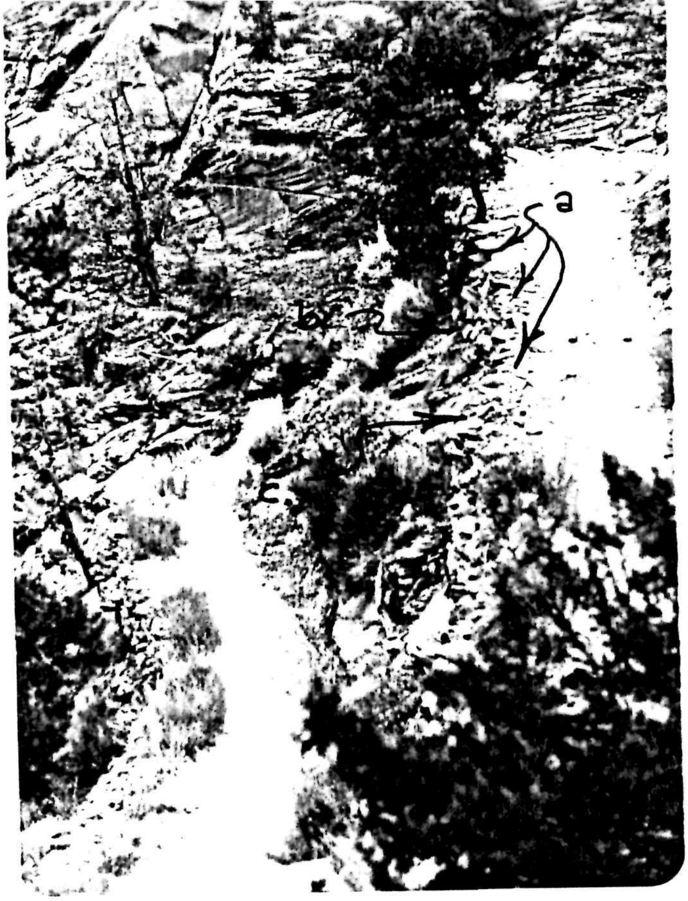

Figure 22. Rock fall hazards related to trail retaining wall. Betatakin Trail, Navajo.

a. Loose cap rock.
b. Rocks work loose from wall or cave on loose soil.
c. Wall spreads as trail fill "works".

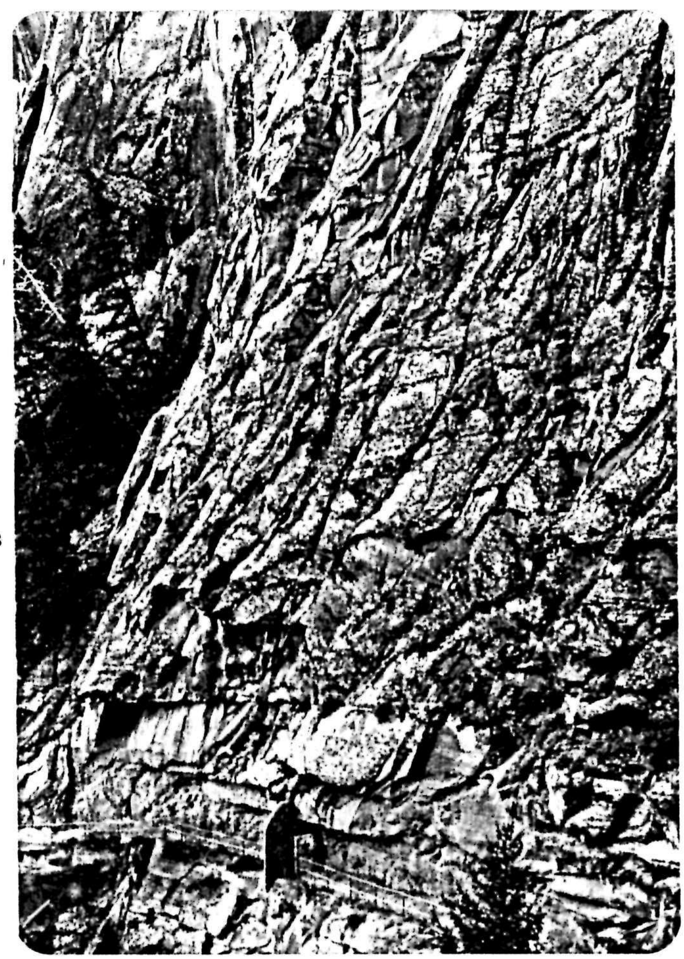

Figure 23. Natural slabbing promoted by vertical fractures crossed by bedding plane fractures. Note many "fresh" scars on the cliff face. The trail further undermines this unstable area. Betatakin Trail, Navajo.

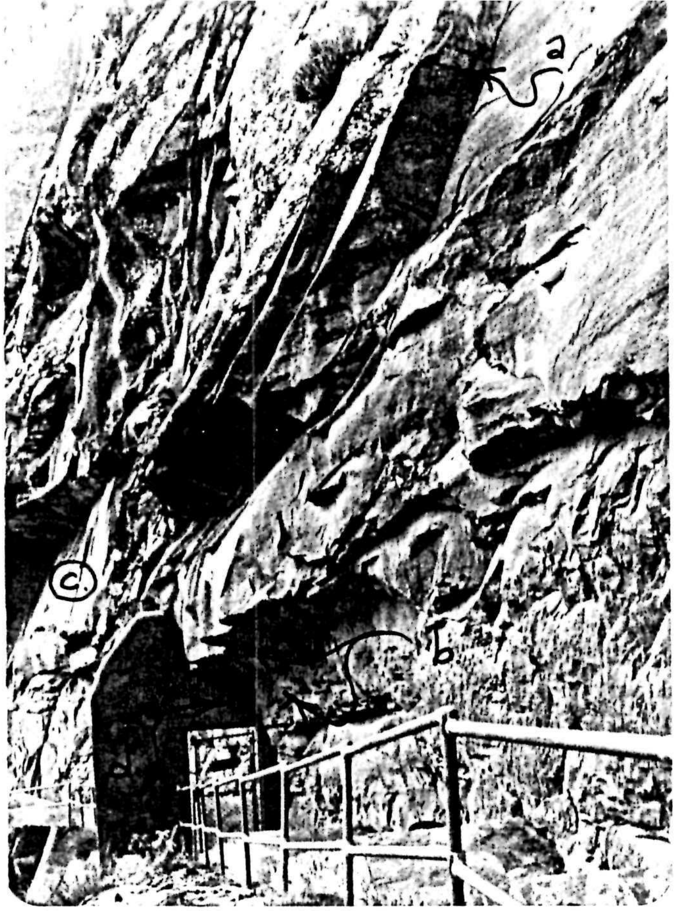

Figure 24. Betatakin Trail, Navajo. See text for explanation of points a-d.

Figure 25. Betatakin Trail, Navajo. Overhang appears to be stable in spite of diagonal fracture (no motion is apparent). Minor block separation has occurred on the lip.

Saucer Cave is actively enlarging, geologically, by scaling and slabbing of the walls and ceiling. No immediate fall is obvious and slabs tend to be thin and light in weight. The active zone directly above the visitor benches should be scaled now and periodically in the future, however.

Recommendations: Very soon, loose cap rocks should be removed from the trail edge and from retaining walls. Accessible portions of cliffs, slopes, and ledges above the trail should be scouted for hanging, balancing, or potential rolling natural rock.

Soon stabilization of retaining walls should be budgeted and accomplished in minimum to include mortaring of top courses and unstable zones. Hopefully to provide for complete mortaring, reinforcement, and lateral tie into slopes beneath trail fill.

Monitoring devices will be installed in the gate-barrier zone. The ends of several crack systems have been marked and documented by Western Archeological Center, documentation will be sent to Navajo so that periodic checks on rock motion are possible. Monument staff should watch continuously the cracks in the gate plaster. Do not repair cracked plaster. Heavy engineering or re-routing of the trail may be necessary.

Manual scaling of Saucer Cave should be done periodically, once every few years.

(5) Betatakin. Problem areas are more apparent here than at any other ruin so far visited (though rates of motion and frequency of fall may prove to be less).

The west end of the alcove below and left of the westernmost rooms is showing compound motion. The needle-like monolith (Figure 26, a) has moved over a meter from its parent rock face. The centerline of the monolith tilts about 2° away from the face and base rock is highly deteriorated from salt and moisture action. The monolith rests on a soft shale formation. A section of its base "a'" is acting separately.

A fairly young vertical crack extends from "b" down into the ruin, suggesting strain in this buttressing section of the alcove.

In section "c" (Figure 26) several detaching monoliths are moving independently as attested by <u>recent</u> rock fall debris below and shattering of the standing masses. The left hand monolith of section "c" narrows toward its base of rotten sandstone, again supported by shale.

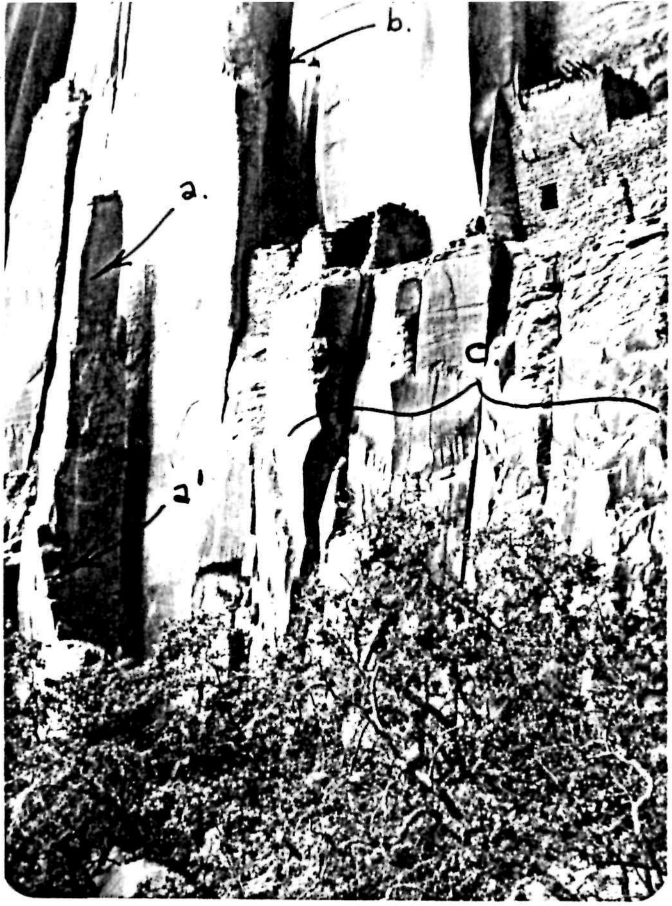

Figure 26. Visitor exit trail passes beneath unstable section at west end of Betatakin (Navajo). See text for explanation.

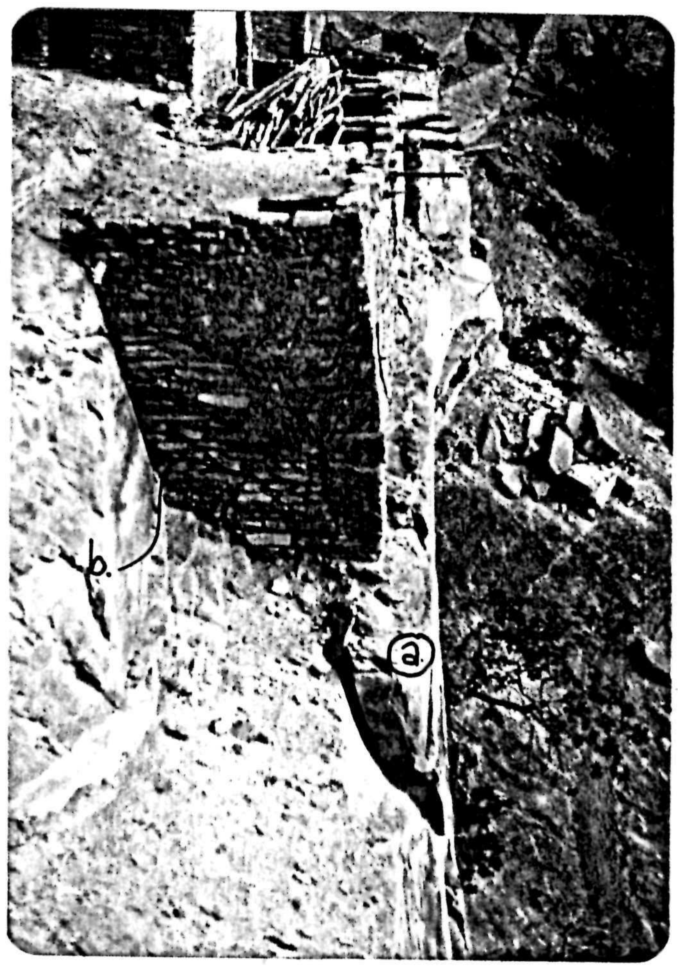

Figure 27. Motion of slab "a" detaching from the rock face causes cracking "b" in the masonry above. Betatakin. Note recent fall debris in background (right) which relates to instability shown in Figure 28.

Just to the right of view in Figure 26 a detaching slab shows its motion in the cracking masonry above (see Figure 27).

Just west of the central (access trail) portion of the ruin more cracked masonry has resulted from complex motion of supporting slabs. In Figure 28 the cracks at "a" relate to motion of block "b" as it loses support from blocks "c" which have completely separated from the cliff and are settling in the shale. Recent fall debris crosses the present trail area below.

The vertical slab east of center above the access trail is a curiosity. Of several ton scale, it is perched on a shattered pedestal and has been separated from its source by a crack now over a half-meter wide. (This may be the result of impact from recent fall from the rear of the alcove above, but the slab should be tested for current stability with a long pry-bar.) Figure 29.

Two other masses in this area deserve monitoring (see Figure 29).

The large arched mass in the center of the ruins, below the highest rooms known as "the flake" appears to be attached at both ends. The upper end (Figure 30) is "working" under strain and post-habitation fall has removed part of the overlying masonry. Immediate fall hazard is not apparent from this "working" end, but perspective is poor so the various working blocks in section "a", Figure 30, should be checked from above.

Below and right of the flake, active slabbing is progressing upward from the moisture-vegetation line (section c, Figure 30). Moderate slabs (b) and several small slabs should be tested with a bar and removed as necessary. Similar moisture slabbing is progressing at the rear of the alcove as shown in Figure 31.

The upper right (east) end of the ruin has been damaged by recent falls. The arched area of Figure 32 is unstable. Slab "a" is approaching fall and should be removed immediately. Slab "b" is attached at the upper and rear edges to some degree, but due to unpredictable behavior of horizontal detachments it should be removed, as visitors congregate in this area. The unstable arch terminates to the right in an area of face-slabbing shown in Figure 33.

From the "Rock Art" area at the east end buttress zone of the alcove, one can look east (Figure 34) or west (Figure 35) to see all degree of complex instability. The buttress masses of the cliff are working as shown by separated monoliths, fresh vertical cracks, shattering, and recent fall.

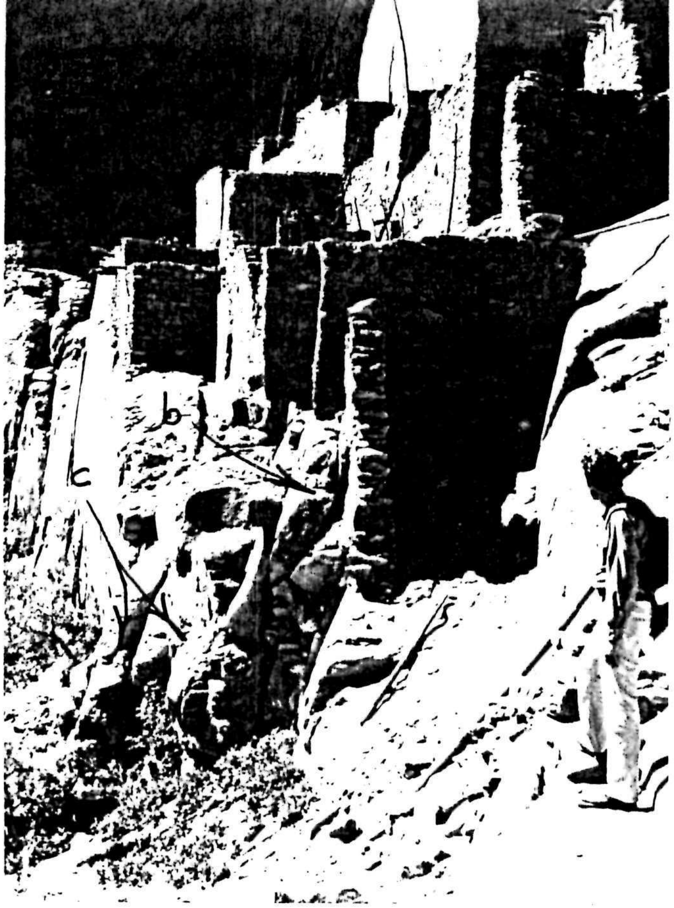

Figure 28. Cracks at "a" due to motion of block "b". Section "c" is settling in the shale. Recent fall debris lies beyond and below. Betatakin.

Figure 29. Apparently precarious 10 ton slab has half-meter wide crack out of view, behind. Blocks below the masonry (center) show motion and a fallen block behind the tree is cracking to threaten the trail.

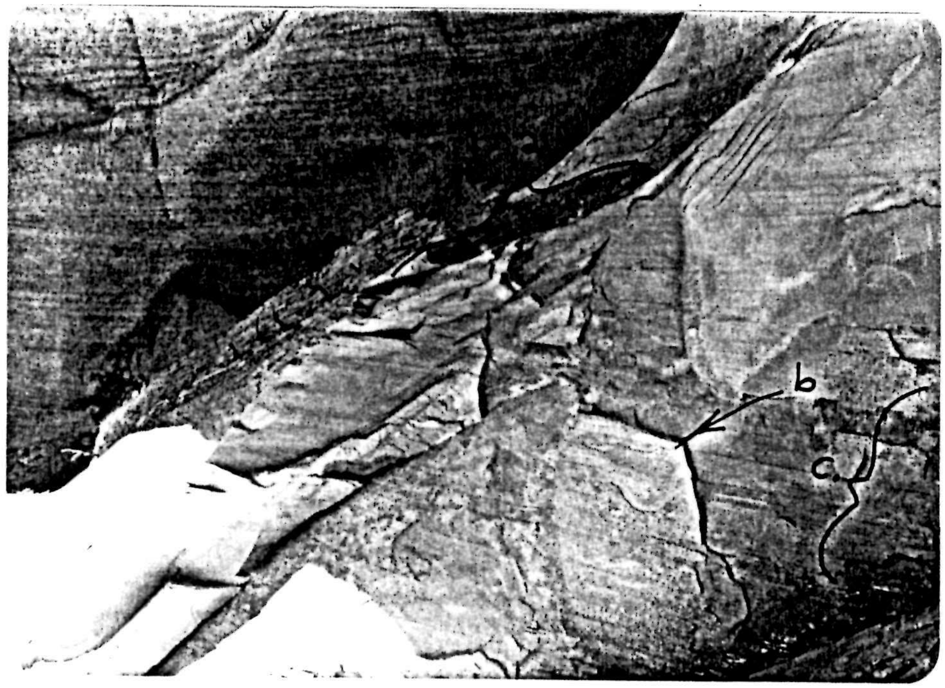

Figure 30. Upper end of "the flake" is working and has caused post-habitation fall (section "a"). Slab "b" is detaching due to moisture deterioration which extends beyond view through section "c".

Figure 31. Classic slabbing upward from moist zone, rear of alcove, Betatakin.

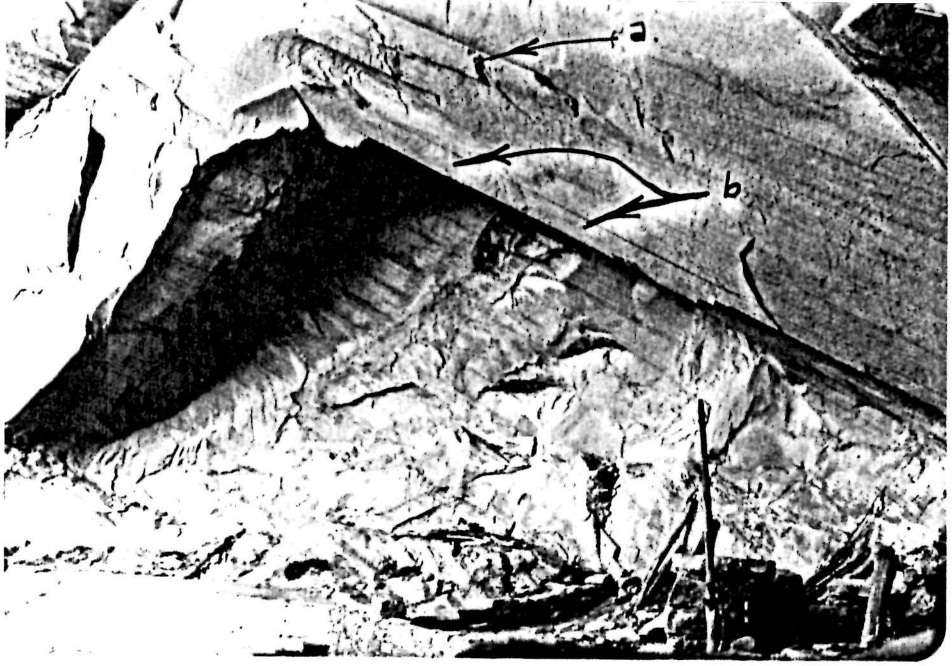

Figure 32. Upper east extremity of Betatakin. Prism-like slab "a" is ready to fall. Sheet "b" is detaching but is unpredictable.

Figure 33. Active slabbing above room adjacent to and right of Figure 32.

Figure 34. Looking east from Rock Art area, Betatakin. Monolith is in motion with balanced blocks on tip. Instability in recess has caused recent fall onto small ruins.

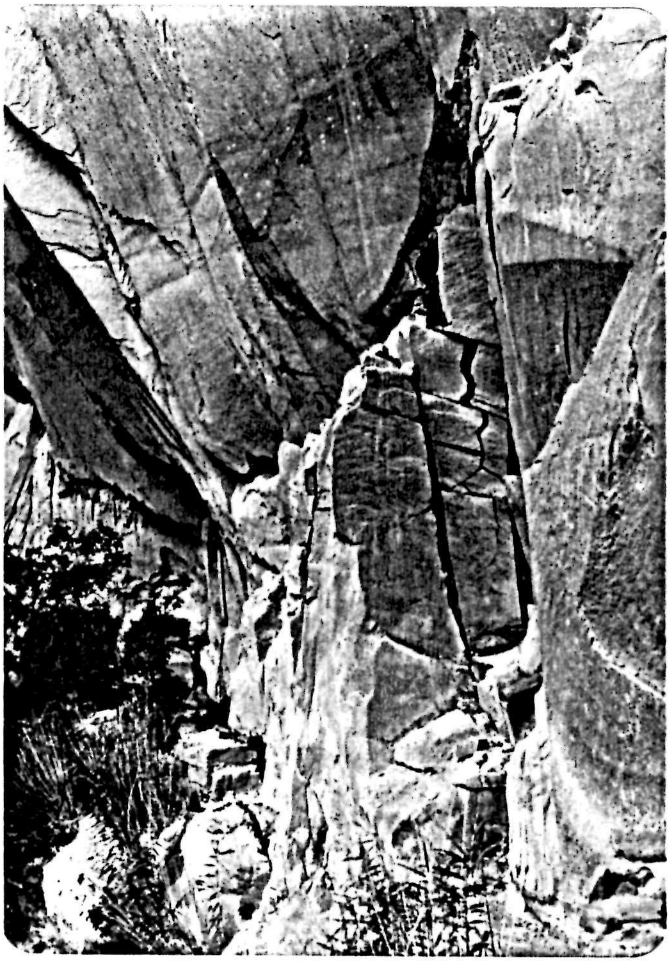

Figure 35. Shattered zone, looking west from Rock Art area. Also vertical cracks above show motion in this section of the cliff which buttresses the east end of Betatakin alcove.

The inner cliff sections may move downward relative to outer detached monoliths such as in Figure 34. This suggests that the underlying shale may be behaving plastically under load of the massive buttress sections. Detachments settle less rapidly or actually rise if shale wells up under flow.

Recommendations: Monitoring devices will be installed in most of the areas noted. Ends of cracks have been marked and documented in a few locations. This documentation will be sent to Navajo so crack propagation may be observed.

Several slabs should be removed immediately and manual slabbing initiated as noted in the text. Decisions are in order relative to removal, trail re-routing, or monitoring regarding:

a. The monoliths of Figure 26
b. The vertical slab of Figure 29
c. Slab "b" of Figure 32 (remove slab "a")
d. Miscellaneous slabs and monoliths in the Rock Art area.

d. Walnut Canyon

Several distinct types of rock fall hazard exist:

(1) Massive ledges overhanging the trails with motion apparent on propagating cracks (Figures 36, 37).

(2) Massive ledges overhanging the trail with minor motion indicated by strain slabbing at pivot points (Figures 38, 39).

(3) Massive, precariously balanced float blocks beside the trail (Figures 40, 41).

(4) Unstable cliff faces (Figure 42).

(5) Random falling, rolling rocks (Figure 43).

Several of the large limestone ledges that overhang the Island Trail are apparently in motion. Those most obviously marked by propagating crack systems are the first two encountered at ruins 735 and 736. The crack systems within the ledge at ruins 736 A-D are particularly active. Rock masses of 10-1000 ton scale are involved (Figures 36, 37).

Motion is evident presumably to a lesser scale in large, overhanging masses at trail guide number 6 (Figure 38) and trail guide number 13 (Figure 39).

A 500 ton scale float block at the far southeast end of the Island Trail seems to overbalance its center of gravity, hanging over a

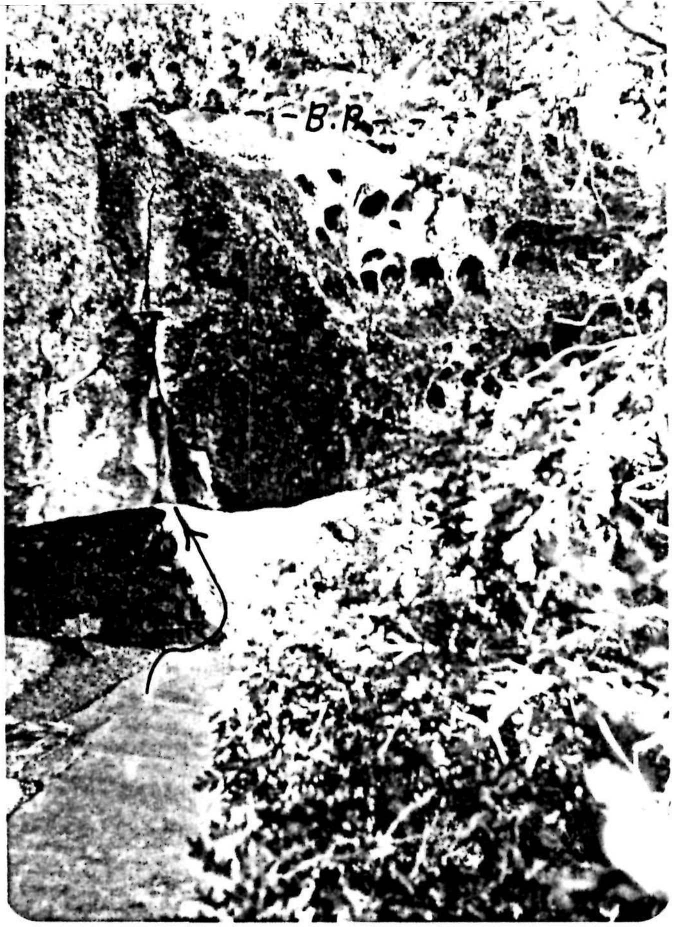

Figure 36. Walnut Canyon massive ledge overhangs trail at first ruin on the Island Trail (ruin 735). Old crack at arrow appears to be re-activating, extending upward to the bedding plane (B.P.) and out of view across the horizontal surface.

Figure 37. Ledge over trail at ruin 736. Old smoke-filled cracks are reactivating. Fresh cracks (not visible in photo) extend tens of feet over ruins 736 A-D. Walnut Canyon.

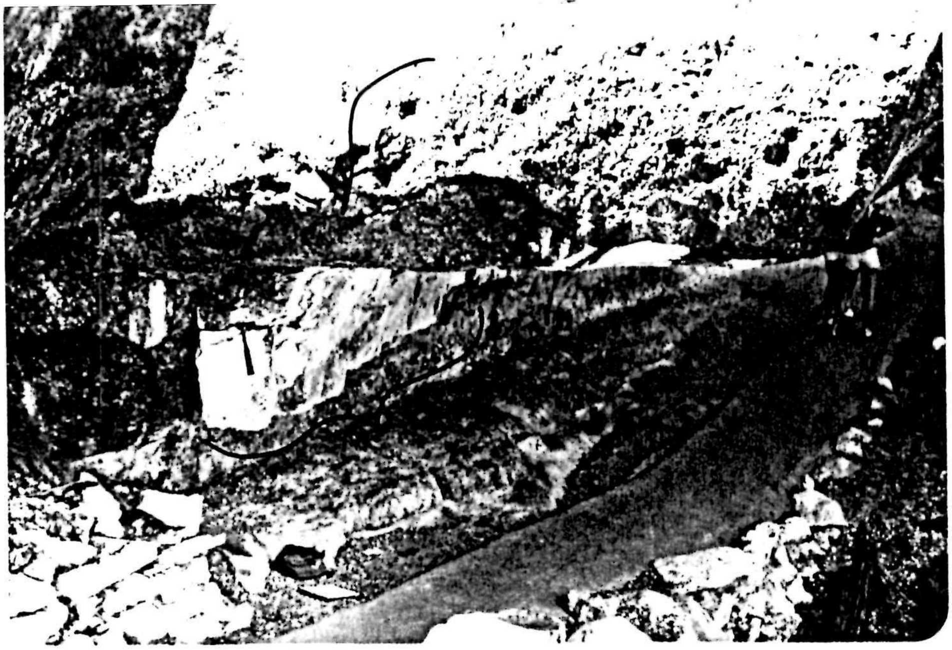

Figure 38. At trail guide point number 6. Overhanging ledge shows strain along hinge point by flaking, slabbing, and discontinuous cracks. Walnut Canyon.

Figure 39. At trail guide number 13 a smaller ledge has less obvious indication of strain; minor buckling and spalling of surface crust (a). Note diagonal crack (b) above, apparently not active. Walnut Canyon.

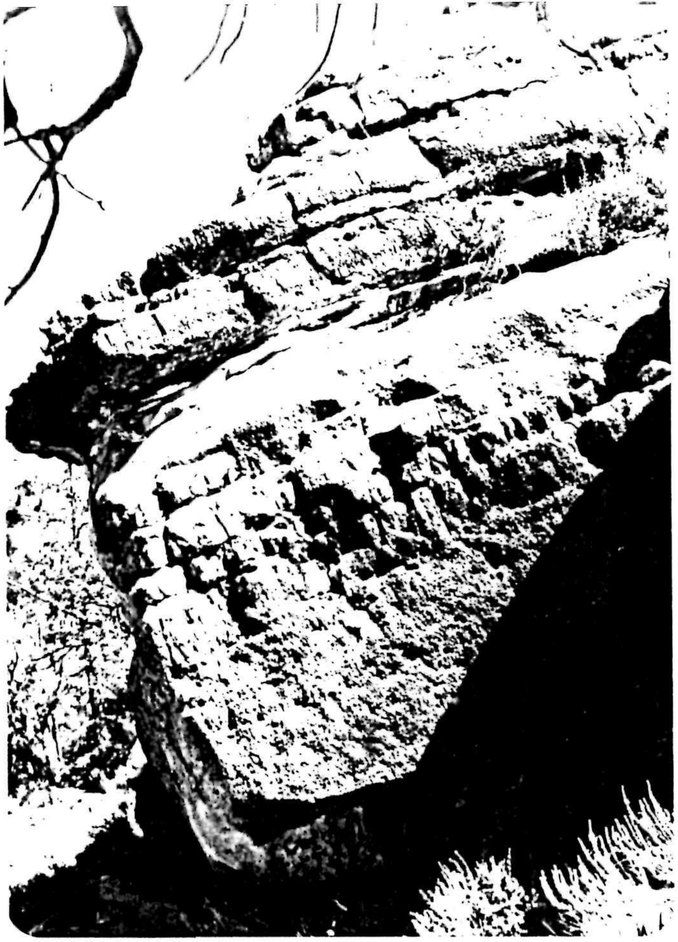

Figure 40. 500-ton scale float block seems to overbalance its support point adjacent to the Island Trail (far S.E. end). Other large blocks of landslide origin rest against the rear of this block. Walnut Canyon.

Figure 41. Smaller balanced block, rests on a deteriorating ledge. Trail and a rest-stop bench are under the lower end of this block. Another float block rests on soil right of the camera. This second block is cracking and may be near partial fall. Walnut Canyon.

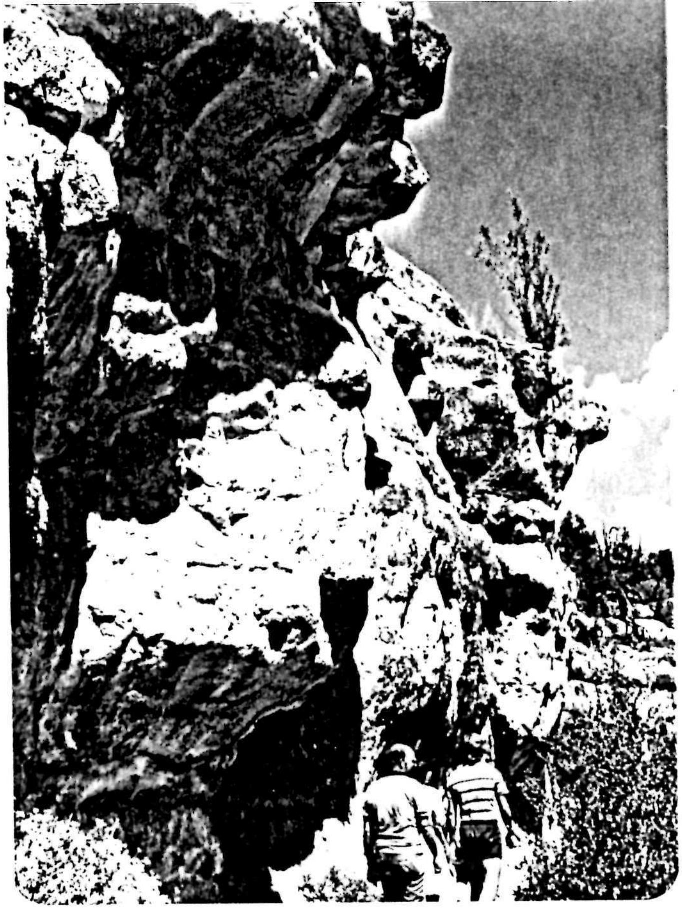

Figure 42. Unstable cliff segment is "working". Shattered soft faces have retreated due to fall exposing the harder rock above, which has also begun to crack. Near trail marker number 17. Island Trail, Walnut Canyon.

Figure 43. Random fall from otherwise stable faces and ledges. Walnut Canyon.

½-1 meter gap adjacent to the trail (Figure 40). No motion has been observed by Monument staff, but preventative reinforcement is desirable. Whatever geometry holds this block in place also keys other rubble behind that rest on the large block.

Similar but smaller and probably less precarious blocks threaten the trail immediately below the visitor's center above the lowest rest-stop bench (Figure 41).

An unstable cliff face threatens the trail near trail guide point number 17. This area is "working" with complex cracks and slabbing of soft lower rock and an unstable overhang of harder rock (Figure 42).

Random fall from otherwise stable faces and ledges and remobilization of old float blocks by frost action, soil erosion, vegetation and people may well be the most severe hazard at Walnut Canyon (Figure 43). The limestone breaks in chunky pieces that are more likely to roll than the sandstones of other Monuments. An example is the 1 ton-scale rock pointed out by two staff members that has recently moved over .3 meter and will roll onto the trail between markers 3 and 4.

Recommendations: Most of the slopes and faces above the trail area at Walnut Canyon are accessible. They should be carefully and methodically policed for loose rock. Remove rock that is loose to touch or to light prying with a bar.

Western Archeological Center will install reference points at the sites mentioned above, where feasible, and will coordinate monitoring.

Some engineering thought should be given immediately to stabilizing the worst overhangs (Figures 36, 37) and the large float block (Figure 40).

e. Montezuma Castle

(1) Main Castle. In spite of appearance, the cliffs and alcove at the Castle are quite stable. Careful and close examination was not possible due to poor access and perspective, but generally fractures in the irregular limestones appear to be inactive. Often they are "healed" with recently deposited mineral material.

These limey, silty rock layers do not break regularly nor do they necessarily show fracture before fall--prediction is difficult. Yet it appears that attention can be focused on stability of the ruin itself. Another engineering reconnaissance trip is planned by WAC to consider instrumentation of the masonry and of the deeply undermined ledges below the ruin. No obvious rock motion exists, though a large block just right of the ruin may be in motion and should be monitored (Figures 44, 45).

The grotto at ground level below the Castle shows fresh cracking and has shed several tons of rock since 1890 (possibly a single fall) (Figure 46).

Figure 47, the close-up mosaic, is included for record purposes. Crack extensions may appear on later comparative photos. This area is closed to visitors and offers no hazard but instrumentation is desirable for general information and calibration of fall rates in this limestone.

Recommendations: Monitor as noted in text above. Todd Rutenbeck, WAC, is considering instrumentation and leveling procedures.

(2) Castle "A" Area. Extreme instabilities exist in and above Castle "A". Much of the cliff section below line "a" in Figure 48 shows either geologically recent fall or is "working" at present.

Fall may be impending from zone "b" (Figure 49). Much shattering and apparent movement, including 100 kg-scale blocks that are now loose to the touch, threaten the trails and stairs below zone "c". Several tons fell from the face in zone "d" in 1947 and instability continues.

Some monitoring stations may be possible on specific crack systems. The central zones ("c" and "d" of Figure 48) are difficult to deal with due to complex motion, shattering, and discontinuous crack systems (Figures 50, 51). To the right and left (Figures 52, 53) old crack systems which may or may not be active can be instrumented. Fall does not appear as imminent in the areas of Figures 52 and 53 as elsewhere.

Recommendations: Monitoring will be installed wherever possible, but the severe instabilities above walkways, stairs, and gathering points deserve immediate attention. The tallest (right hand) stairway to upper rooms is less threatened than lower walkways and stairs, though some danger exists there from the high cliff (section b, Figure 48). Of all sites visited this year, the central Castle "A" area most deserves detour of visitor traffic.

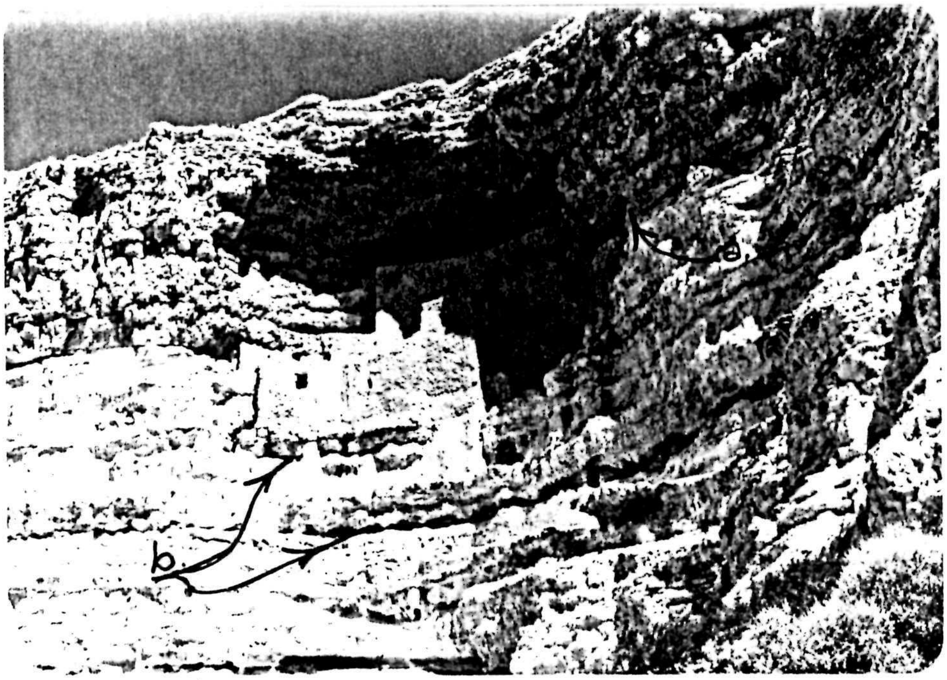

Figure 44. No obvious rock motion exists above or below the ruin. One block ("a") may be in motion. Walls showing old cracks and undermined ledges "b" below will be monitored.

Figure 45. Block to right of ruin may be in motion (same as "a" in Figure 44). Accessible from the ruin.

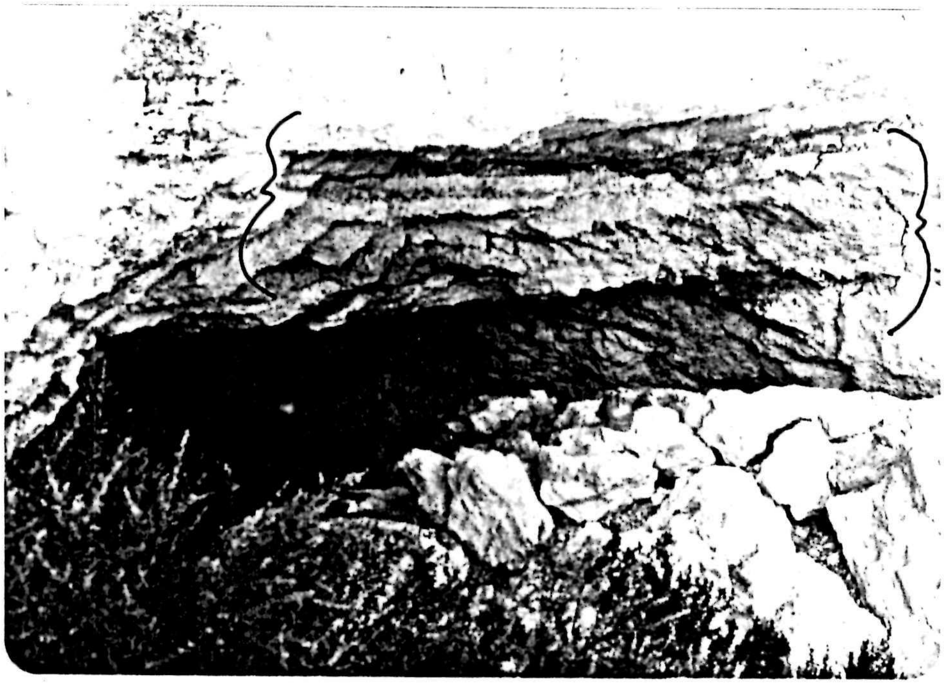

Figure 46. Grotto at ground level below Montezuma Castle. Fall has happened since 1890. Brackets show area of photo mosaic in Figure 47.

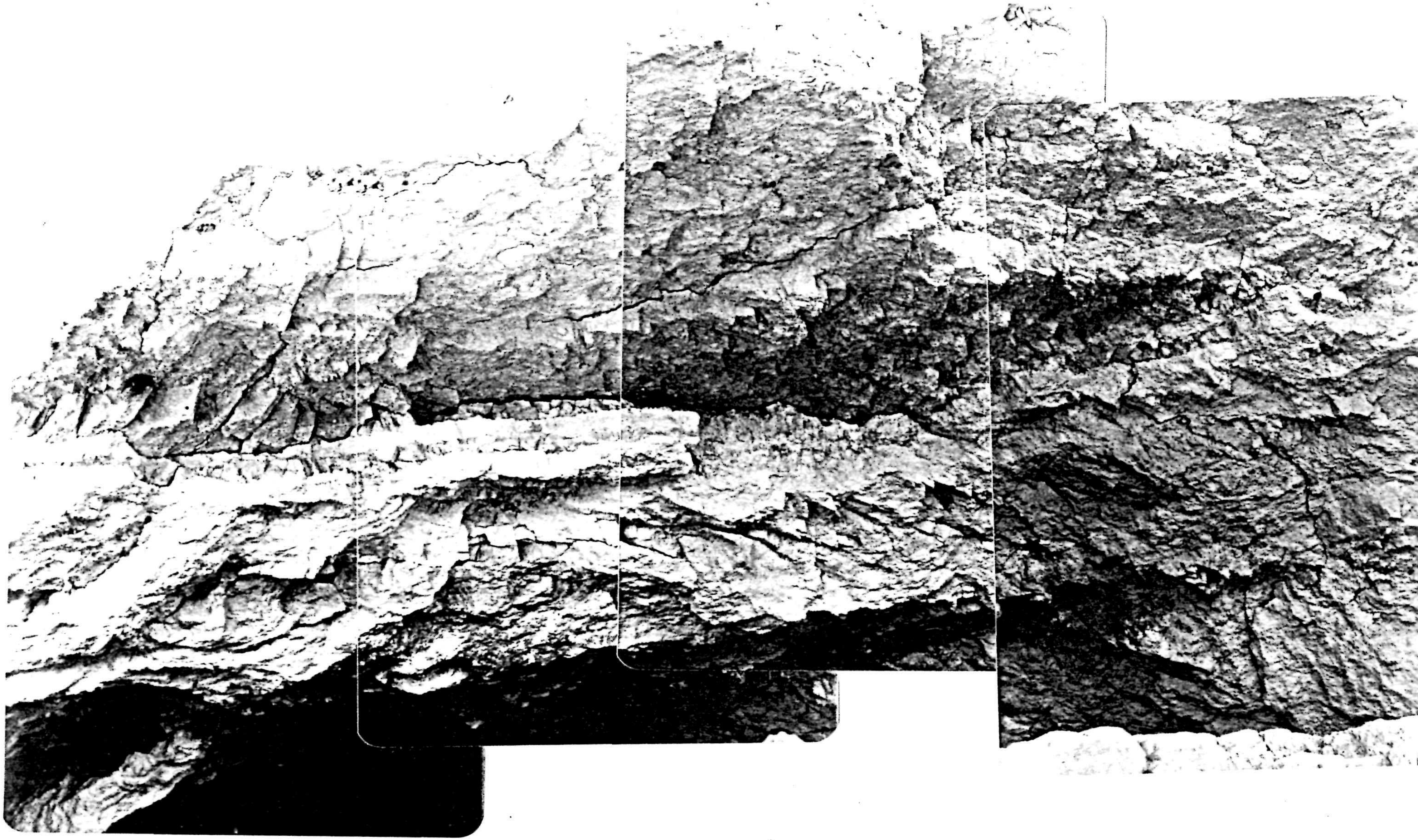

Figure 47. Crack system in grotto below Montezuma Castle. Photo time approximately 10 a.m., October 1, 1978. Kodacolor 400.

Figure 48. Unstable cliff in and above Castle "A", Montezuma Castle (see text for explanation).

Figure 49. Zone "b" from Figure 48, showing loose slabs. All swallow's nests have fallen from the upper crack (motion?).

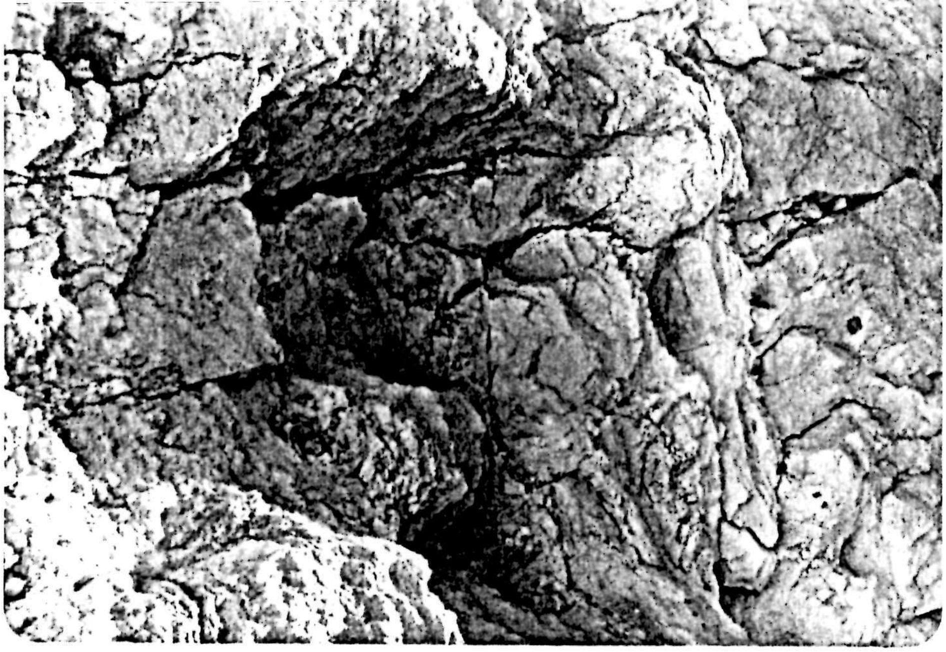

Figure 50. Shattering, zone "c" (Figure 48), Montezuma Castle.

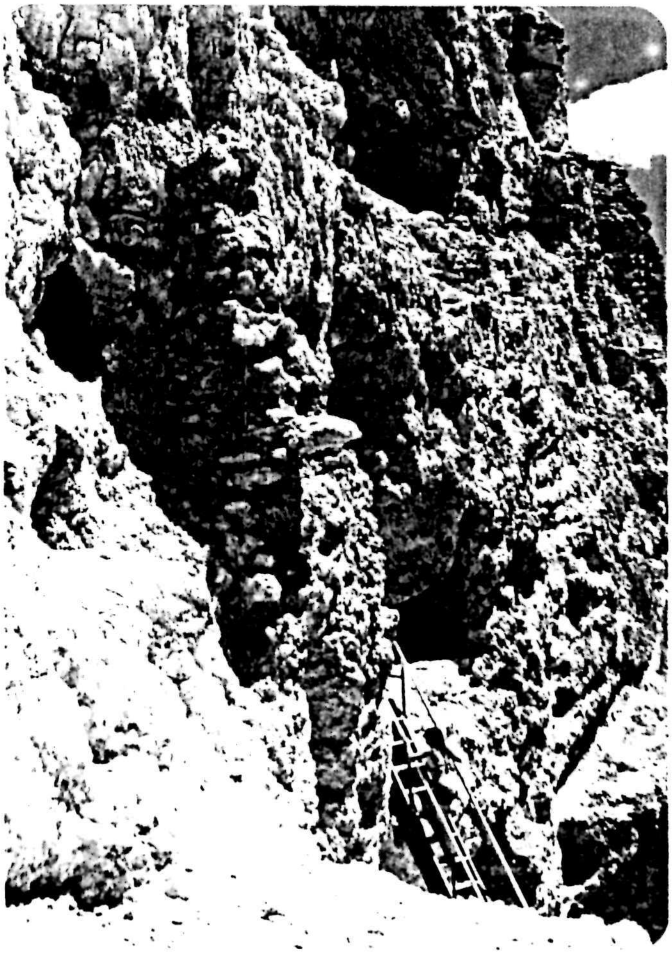

Figure 51. Precarious boulders in masonry remnant have been watched closely by Monument staff and remain firm. Much shattering is evident behind and above (including the mass to which the masonry is attached). Montezuma Castle.

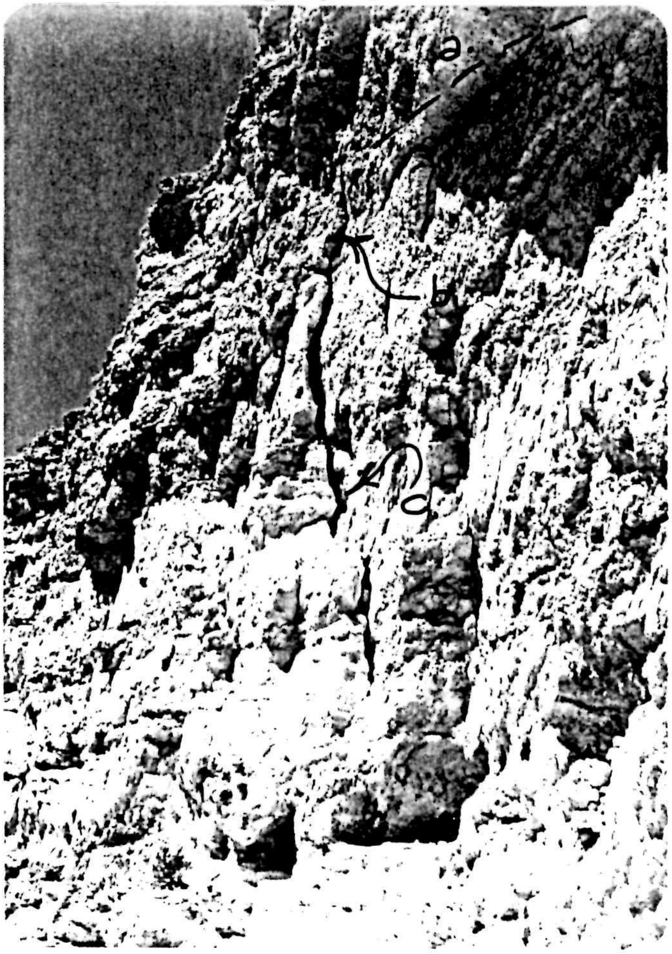

Figure 52. Slab to left of Figure 38 is not highly unstable, except possibly block "b" ("a" is continuation of line "a" of Figure 48--note fresh fall scars). Fracture C may be expanding slowly and could be monitored. Castle "A" Area.

Figure 53. Old cracks in section above the tallest stairway, Castle "A" appear to have "healed" and then more recently reactivated.

(3) Montezuma Well

There is minor immediate hazard in a few small detached blocks on the cliff point above the trail into the well (Figure 54). Further down-trail toward Swallet Cave, random fall or rolling rock is possible from the slopes and ledges above the trail.

The trail to the outlet also passes beneath a low cliff that shows some miscellaneous block detachments through there appears to be no great or immediate threat.

Recommendations: Immediately remove with a long scaling bar the blocks hanging above the trail into Montezuma Well. Soon, police carefully the slopes, ledges, and low cliffs above the Swallet Cave trail and the outlet trail. Remove rock that is loose to the touch or that moves easily under pressure from a small pry bar.

3. Delineation, Monitoring, and Prevention of Rock Motion

a. See Section 5, Report A, Rock Motion Hazard, June, 1978, Wachter.

b. Second trip to El Morro, Bandelier, Mesa Verde, Navajo, Montezuma Castle.

A trip by Wachter and Rutenbeck (WAC) in Sept.-Oct., 1978, allowed a second look at sites discussed in Report A and in this report. This allowed additional reconnaissance identification of hazards and some re-evaluation of rates and degrees of motion. Additions and re-evaluations will be recorded for El Morro, Bandelier, and Mesa Verde as a formal "Addendum to Report A". New observations on Navajo and Montezuma Castle are incorporated into this report.

c. Amplifying Comments. I'm not aware of any existing literature on hazard due to rock fall. In fact, the status of the National Park Service is quite unique in sponsoring public foot traffic into rock fall prone areas.

Some preliminary thought on the actual nature of rock fall hazard is in order. Consider carefully the following:

(1) Target Time. Maybe the most important factor of rock fall hazard. For how long, (for example, what percentage of a year) is something of priority exposed to a specific rock-fall site.

A person passing a given rock-fall site on foot may be exposed to hazard for 3 seconds. In a vehicle traveling 20 km/h, target time may be only .03 seconds for the same potential fall.

-- Hazard is in a sense 100 times more severe for foot traffic than for vehicle traffic, relative to people.

Figure 54. Very loose hanging rocks above first portion of trail into Montezuma Well.

The number of passing targets per year will increase target time.

-- If 50 vehicles averaging 2 passengers each pass the rock-fall site for every 1 pedestrian, then target time will be similar for each.

Ruins, buildings, technical installations, etc., may be exposed 100% of any year.

IMPLICATION OF TARGET TIME: Avoid placing high priority, unprotected targets within the threat area of probable falls for any longer than necessity dictates.

Example: A 10 minute (600 second) lecture below a small hanging rock will increase target time by a factor of 1000 over the 0.6 seconds required to walk past the threat area.

Note the other factors introduced:

(2) Priority of target. This implies at least a subjective assessment of value placed on and degree of effort expendable to protect (in hierarchy):

people
ruins, historic resources
animals
modern buildings, facilities
vehicles
roads, paths, utilities
vegetation

(Possibly but not necessarily in that order.)

(3) Protection. This will apply mainly to people who can be considered more protected, physically, if:

in a vehicle
in a building
in a cave (if no fall hazards exist within)
wearing a hard hat

(4) Threat Area. Refers to the area passed by or receiving falling, bouncing, or rolling rock from a fall. High falls attain velocities sufficient to shatter the rock mass when it bounces on cliff projections. Fragments are broadly scattered also at high velocities. A rock rolling down an irregular slope has a "choice" of several paths accounting for a large area of probable-possible threat. A one cubic meter rock falling from a few meters above a trail has a threat area of only about 1 square meter.

(5) Necessity involves decisions on the part of administration regarding the importance of visitor or staff access to threat areas; the need for vehicles or placement of facilities in a threat area; the value of a given interpretive stop or of long-duration access as opposed to short-duration access; impossibility of moving threatened facility.

(6) Probability of Fall during some meaningful time span. This is the crux of the geologic and monitoring problems. How can we predict approximate probability of fall within culturally important time spans (1 day to perhaps 1000 years)? Monitoring may relate rates of motion to possible impending fall. Geologic observations and classifications must extrapolate the rate inputs to many types of fall in different environments and rock types.

Table 1. Tentative Classification of Rock Fall Situations.

- Horizontal (Ceiling Slabs)
- Overhanging Ledges Attached at Rear
- Monoliths
  - Hinged Above Ground in Brittle Formation
  - Hinged Below Ground in Soil or Shale
  - Moving Outward at Bottom
  - Moving Downward in Soil or Shale
  - Moving Upward Due to Flow or Swell of Shale
  - Leaning Outward from Cliff, at Top
  - Leaning Inward to Cliff, at Top
- Diagonal Wall Slabs, Outward at Top
- Vertical Wall Slabs, Blocks
  - Supported from Above or Sides
  - Supported from Below
- Diagonal Wall Slabs Top into Wall
- Float Blocks, Debris Trains, Piles
  - On Soil, Shale Slopes
  - On Rock Slopes
  - On Ledges
- Flaking, Scaling, Salt Crusting

Table 2. For Each Fall Situation, the Following May Apply.

- Behavior of Particular Rock Type (Strength, Brittleness)
- Degree of Detachment
  - New Cracks
  - Pre-existing Fractures
  - Natural Weakness (Bedding Planes)

Continuing Support
- Friction Laterally
- Wedging
- Pinned by Vegetation
- Soluble Material Healing Cracks

Motion Promoted
- Frost Action
- Moisture Deterioration of Supports
- Tree Root Growth
- Salt Crystal Growth
- Traffic, Vibrations, Load
- Progressive Undercutting

(7) Warning Time may emerge as a usable concept from geologic and monitoring work. For now, it must be highly generalized or ignored.

Description of the terms 1-7 above implies possibility of assessing hazards by refining a general formula such as:

$$\text{Hazard} = \frac{\text{Target Time} \times \text{Target Priority} \times \text{Probability} \times \text{Threat Area}}{\text{Protection} \times \text{Warning Time}}$$

Specific decisions should be made as a trade-off between Hazard vs. Necessity.

Obviously, the terms are not well enough defined for quantification but the concepts involved are clear, and can be applied semiquantitatively or qualitatively to hazard decision process.

d. Initial monitoring program is now underway. The recent trip to El Morro, Bandelier, Mesa Verde, Navajo, and Montezuma Castle started actual marking of propagation crack systems. Reconnaissance of possible rock motion sites suitable for instrumental observations was also accomplished.

A similar trip will deal with Wupatki, Tonto, and Walnut Canyon.

Soon afterwards, deployment of instrumental monitoring systems will begin.

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