

UNIVERSITY OF CALIFORNIA, BERKELEY

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO



SANTA BARBARA • SANTA CRUZ

Geotechnical Engineering
Department of Civil Engineering
440 Davis Hall
Berkeley, California 94720-1710

Phone: (510) 642-1262
FAX: (510) 642-7476

May 11, 1995

Mr. Brian McCloud
East Bay Municipal Utility District
P.O. Box 24055, MS 610
Oakland, CA 94623

RE: Mexican Gulch Slope Stability Study

Dear Mr. McCloud:

I have enclosed one copy of my Independent Study in Geotechnical Engineering at U.C. Berkeley, titled "Surface Displacement Rate of a Deep Seated Bedrock Topple at Mexican Gulch, Calaveras County, California". The subject rock topple does not appear to pose a threat to the existing dam facilities at this time; however, it is possible that future slope movements may partially block Mexican Gulch and constrict the spillway outflow.

I really appreciate your assistance in obtaining historical information regarding Mexican Gulch. This site offers great potential for further study of hillslope failure modes in highly discontinuous rock masses. We are currently modeling some of the landslides flanking Mexican Gulch with Discontinuous Deformation Analysis (DDA), and the initial results look promising. I plan to forward a summary of our numerical model studies to you as soon as they are complete.

Should you have any questions regarding this report, please do not hesitate to call.

Sincerely,


D. Scott Kieffer
Graduate Student Researcher
(510) 642-9005

Surface Displacement Rate of a Deep Seated Bedrock Topple at
Mexican Gulch
Calaveras County, California

D. Scott Kieffer
May 10, 1995

Submitted in partial satisfaction of 3 units of CE 299

Department of Civil Engineering
University of California at Berkeley

A handwritten signature in cursive script that reads "Richard E. Goodman". The signature is written in black ink and is positioned above a solid horizontal line.

Richard E. Goodman
(Supervisor)

TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction	1
2.0 Background	1
2.1 Dam Facilities	
2.2 Erosion of Mexican Gulch	
3.0 Regional Geologic Setting	2
4.0 Site Geology	3
4.1 Geologic Units	
4.2 Geologic Structure	
5.0 Rock Mass Structure	4
5.1 Discontinuities	
5.2 Joint Friction Characteristics	
6.0 Surface Displacement Rate of Rock Topple	6
6.1 Displacement Magnitude	
6.2 Displacement Interval	
7.0 Relation of Surface Displacements to Displacements in Underlying Bedrock	7
8.0 Limit Equilibrium Stability Analysis	8
9.0 Discussion and Conclusions	9
9.1 Average Surface Displacement Rate of Rock Topple	
9.2 Future Studies	

REFERENCES

TABLE OF CONTENTS (continued)

FIGURES	<u>Figure</u>
Regional Geologic Map	1
Site Geologic Map	2
Subsurface Cross Section AA' through FF'	3
Joint Orientation Survey Data	4A - 4H
Field Foliation Friction Measurements	5A - 5B
Subsurface Cross Section AA'	6
Estimated Fill Surface Displacement Vectors	7
Topographic Cross Section AA', Showing Estimated Surface Displacement Vectors	8
Base Friction Model Test Results - Comparison of Surface and Shallow Depth Displacements	9A - 9E
Limit Equilibrium Stability Analysis	10A - 10F
PHOTOGRAPHS	<u>Photo</u>
Aerial Site Overview	1
Geomorphic Development of Mexican Gulch	2 - 5
Deep Seated Rock Topple	6 - 11
Surface Displacements in Rock Topple	12 - 15
Representative Base Friction Model Test	16A - 16G

1.0 INTRODUCTION

Mexican Gulch is the outlet channel for the South Spillway of Pardee Dam, located on the Mokelumne River about 35 miles southeast of Sacramento, California (Figure 1). Pardee Reservoir is owned and operated by the East Bay Municipal Utility District (EBMUD), and it is a significant water source for industrial and municipal use in the east San Francisco Bay area. Since completion of the dam facilities in 1929, overflow spillway discharges have dramatically altered the morphology of Mexican Gulch. Recent downcutting and oversteepening of the channel banks has triggered several large scale landslides in strongly foliated, highly discontinuous crystalline metamorphic rocks.

The purpose of this study was to analyze the historical stability of an actively moving, approximately 150,000 cubic yard foliation-controlled bedrock topple along the northeastern slope of Mexican Gulch, and to estimate the average surface displacement rate of the topple. To accomplish this purpose, the following scope of work was performed:

- Review of pertinent published geologic data and unpublished consulting reports;
- Review of historical photographs of Mexican Gulch in EBMUD's files;
- Interpretation of stereo-paired aerial photographs;
- Geologic field mapping and collection of structural geologic data;
- Base friction model studies;
- Engineering and geologic analysis; and
- Preparation of this summary report.

2.0 BACKGROUND

2.1 Dam Facilities

The Pardee Dam facilities consist of a concrete gravity arch dam, an ogee crest spillway and an auxiliary siphon spillway above Jackson Creek that is no longer in use. Pardee Dam is 350 feet high, with a crest length of 1,340 feet and a maximum reservoir capacity of about 210,000 acre feet. The South Spillway is located above Mexican Gulch, a northwest-trending drainage about 800 feet south of the dam. The South Spillway is a tapered concrete lined chute structure that is about 850 feet wide at the crest and 425 feet wide at the toe, and it discharges onto highly discontinuous, weathered

metavolcanic and metasedimentary rocks. An overview of the Pardee Dam and South Spillway is shown on Photograph 1.

2.2 Erosion of Mexican Gulch

Mexican Gulch has a tributary drainage area of about 140 acres. Prior to any spillway overflows, active erosion along the drainage channel was insignificant (Photograph 2). Mexican Gulch has been subjected to many spillway outflows since 1929; however, the most dramatic alteration of the drainage morphology appears to have resulted from maximum flooding events in 1950, 1955 and 1986. Changes to the drainage morphology that have occurred since 1929 are shown on Photographs 3 through 5 (all photograph views are from the northern bank of the Mokelumne River, at the mouth of Mexican Gulch).

Peak historical discharges over the South Spillway were 23,130 cubic feet per second (c.f.s.), 13,780 c.f.s. and 21,340 c.f.s. in 1950, 1955 and 1986, respectively. Recent studies conducted by EBMUD estimated that the probable maximum flood (PMF) event in the Mokelumne River watershed would result in a reservoir outflow of 184,000 c.f.s.. As the dam facilities are presently configured, the PMF would overtop Pardee Dam by one foot and route approximately 180,000 c.f.s. through the South Spillway structure (Woodward-Clyde, 1994).

3.0 REGIONAL GEOLOGIC SETTING

The Pardee Dam facilities are located in the western structural block of the western Sierra Nevada metamorphic belt (Clark, 1964). The western structural block includes the region between the Bear Mountains fault zone, located 1-3/4 miles to the east, and the boundary between the Great Valley and Sierra Nevada geomorphic provinces, located about 12 miles to the west (Figure 1).

The Melones fault zone, located 6-1/2 miles to the east, and the Bear Mountains fault zone are part of the northwest-trending Foothills fault system, which is the dominant geologic structure in the region. The Foothills fault system is believed to have formed by the collision of a complex island arc at the Melones thrust boundary in the Jurassic period, with accompanied accretion of metavolcanic and metasedimentary rocks west of the Melones fault (Norris and Webb, 1990). Displacements along the Foothills

fault system primarily occurred through the Jurassic and Cretaceous periods, with some late Quaternary faulting along short fault segments (Jennings, 1992).

4.0 SITE GEOLOGY

4.1 Geologic Units

Geologic Units mapped in the study area include the Jurassic period Gopher Ridge Volcanics and Salt Springs Slate (Clark, 1964), and unconsolidated Quaternary deposits of alluvium, landslide debris and artificial fill. The distribution of these is shown on Figure 2, and they are briefly described below.

Gopher Ridge Volcanics (Jgo) The late-Jurassic Gopher Ridge Volcanics consist of metamorphosed ash-lapilli tuff and coarse volcanic breccia, chiefly of rhyolite and dacite composition. These rocks are typically moderately strong to strong where slightly weathered, and strong to very strong where fresh. The thickness of moderately to slightly weathered rock is generally about 45 feet in the study area vicinity (Woodward-Clyde, 1988).

Salt Springs Slate (Jss) The late Jurassic Salt Springs Slate consists of dark gray strongly foliated quartz-sericite phyllite that weathers light brown to gray. The phyllite is typically composed of 60 to 90% quartz, up to 40% sericite and tremolite, with trace pyrite, epidote and carbonate minerals (Clark, 1964). These rocks are moderately weak to moderately strong where fresh, and weak to very weak where highly weathered. The thickness of highly weathered rock ranges from about 25 to over 60 feet where exposed at the site. The Salt Springs Slate conformably overlies and interfingers with the Gopher Ridge Volcanics.

Rock Topple (Qt) The subject rock topple, as shown on Figure 2 and Photographs 6 through 11, is exposed along the northeastern slope of Mexican Gulch, entirely within the highly weathered Salt Springs Slate. The rock topple exhibits a block flexure failure mode, characterized by pseudo-continuous flexure of long columns through accumulated motions along cross joints (Goodman and Bray, 1976). The topple mass is approximately 1,000 feet long, with an average width of 150 feet and an approximate volume of 150,000 cubic yards. The topple consists of loose blocks of highly weathered Salt Springs Slate with little to no

natural soil cover. The topple is locally overlain by artificial fill, and active displacement of the underlying bedrock has produced a series of reverse-facing scarps and gaping tension cracks in the fill.

Alluvium (Oa) Alluvial deposits in the study area consist of unconsolidated recent stream deposits in the channels of Mexican Gulch and the Mokelumne River. The alluvium in Mexican Gulch, not mapped on Figure 2, consists of relatively thin, localized deposits of large, angular cobbles and boulders.

Artificial Fill (Of) Artificial fill in the study area was placed in conjunction with the dam construction in the late 1920's. As shown of Figure 2, fill overlies a portion of the rock topple near the confluence of Mexican Gulch and the Mokelumne River.

4.2 Geologic Structure

The study area is structurally situated on a steep, northeastern-dipping fold limb. Relict bedding is not apparent in most exposures but generally appears to parallel foliation. As shown on Figure 2, a foliation-parallel bedrock fault occurs within the Salt Springs Slate, adjacent to the conformable contact with the Gopher Ridge Volcanics. An interpretation of subsurface geologic conditions in the study area is presented on Subsurface Cross Sections AA' through FF' (Figure 3).

5.0 ROCK MASS STRUCTURE

5.1 Discontinuities

Approximately 100 structural measurements were statistically analyzed to characterize the in-place rock mass fabric in the study area. As shown on the joint orientation survey data (Figure 4A through 4H), the rock mass is highly discontinuous, with pronounced foliation and four recognizable joint sets. The foliation-parallel fault zone is continuous through the study area.

Foliation is the most persistent discontinuity, controlling many of the observed slope failures in Mexican Gulch. The spacing of open fractures along foliation is typically less than one foot in the highly weathered phyllite bedrock. The joint set spacings are highly variable, but generally range from about 2 to 15 feet. The persistence of all joint sets generally exceeds several tens of feet, and discontinuity surfaces are

typically planar, relatively smooth to slightly rough, and range from slightly to highly weathered. Discontinuity orientation data collected at the site is summarized in Table 1, below.

TABLE 1 - DISCONTINUITY SURVEY DATA

DISCONTINUITY	MEAN STRIKE AND DIP	SPACING (feet)
Foliation	N36W/72NE	< 1
Joint Set 1 (J1)	N55E/87SE	2 - 6
J2	N63W/35NE	6 - 12
J3	N39E/54NW	2 - 6
J4	N73E/13S	2 - 6
Fault	N36W/70NE	2 - 6

5.2 Joint Friction Characteristics

Over 200 field tilt tests were conducted to estimate the frictional properties of the Salt Springs Slate foliation surfaces. Field tests were conducted on paired and unpaired foliation surfaces in both highly weathered and moderately weathered bedrock. The minimum friction angles, ϕ_{\min} , as shown on Figures 5A and 5B, correspond to the angle at which motion initiated in the field test. Motion arrested for many of the test samples after a relatively small initial displacement, followed by continual sliding at a maximum angle that estimates the peak friction angle of the foliation surface, ϕ_{peak} . The difference between ϕ_{peak} and ϕ_{\min} is an approximation of the foliation surface dilation angle. A statistical summary of the field friction tests is presented below.

TABLE 2 - SUMMARY OF FIELD FRICTION TEST DATA

TEST SURFACE	ϕ_{peak} , average degrees (Std. Dev.)	ϕ_{\min} , average degrees (Std. Dev.)
Paired Foliation Surfaces		
Highly Weathered Phyllite	37 (10.2)	32 (9.0)
Mod. Weathered Phyllite	45 (15.4)	45 (15.8)
Unpaired Foliation Surfaces		
Highly Weathered Phyllite	27 (2.7)	24 (4.1)
Mod. Weathered Phyllite	34 (8.9)	30 (4.8)

Considerable scatter in test results for paired surfaces is attributable to a notable affect of sample size and dimension on measured friction angles. Friction angles exceeding 50 to 55 degrees were generally measured for relatively small, slabby samples with the height of the top block generally less than about one inch. Since the relief of

asperities was fairly constant for all test samples, the measured friction angles appear to increase with the ratio of asperity relief to sample height.

The test results for unpaired foliation surfaces present relatively minor scatter, and sample size and dimension did not appear to exert an appreciable affect on the test results. Since asperities are not mated across the test surface, these tests approximate the friction angle for smooth surfaces.

6.0 SURFACE DISPLACEMENT RATE OF ROCK TOPPLE

Active surface displacement of the rock topple has produced numerous reverse facing scarps and gapping tension cracks in the crest area of the toppling mass (Photographs 13 and 15). In the vicinity of Cross Section AA', surface displacement has produced a series of subparallel tension cracks in a cap of fill material along the northeastern side of Mexican Gulch (Photographs 12 and 14). The fill and underlying highly weathered Salt Springs Slate in this area appear to have toppled in response to the recent erosion of Mexican Gulch. The flood event that modified channel morphology and permitted toppling to initiate in this area can be identified from historical photographs. It is thereby possible to estimate the maximum average fill surface displacement rate along Cross Section AA' (Figure 6) by dividing the estimated resultant displacement by the time interval over which toppling has been a kinematically-permissible failure mode.

6.1 Displacement Magnitude

A topographic profile of the existing fill surface along Subsurface Cross Section AA', normal to the direction of maximum tensile separation, is shown on Figure 6. The position of the original fill surface can be estimated by constructing a balanced cross section of the existing fill material, assuming that the original grade and existing grade are coincident beyond (east of) the zone of active tensile separation. The balanced cross section estimate also assumes that no fill material has failed into the channel of Mexican Gulch subsequent to the flood event that permitted toppling to initiate.

As shown on Figure 7, maximum horizontal and vertical displacements of 15 and 9.5 feet, respectively, are estimated. The displacement vectors of several points along the assumed original fill surface, as shown on Figure 8, indicate that vertical displacement

components, resultant displacement magnitudes and angular rotations of fill blocks increase in a direction toward the free slope face.

6.2 Displacement Interval

The original drainage path of Mexican Gulch, as shown on Figure 2, took an approximately 35 degree westward bend where Subsurface Cross Section BB' crosses the gulch. Based on historical photographs of Mexican Gulch, the 23,000 c.f.s. flood of 1950 appears to have excavated an approximately 40,000 cubic yard block of Salt Springs Slate at the drainage bend, between Subsurface Cross Section BB' and the Mokelumne River. The existing grade, along with the estimated original and post-flood excavation grades along Cross Section AA' are shown on Figure 8. The block of excavated Salt Springs Slate is bounded by the original and existing grade lines, and it can be seen by comparing Photographs 3 and 5. As discussed in later sections, excavation of the Salt Springs Slate in 1950 likely permitted toppling to initiate in the area of Cross Section AA'.

7.0 RELATION OF SURFACE DISPLACEMENTS TO DISPLACEMENTS IN UNDERLYING BEDROCK

In order to determine whether displacements at the fill surface can be related to displacements of the underlying bedrock surface, base friction model tests (Goodman, 1976) were conducted to simulate the kinematics of the observed field failure. The fill and bedrock model materials consisted of a mixture of flour, sand and cooking oil. Thinly spaced discontinuities were impressed into the Salt Springs Slate model material to simulate foliation, and the fill model material consisted of a notably weaker, continuous mixture. The initial configuration of a typical base friction test is shown on Photograph 16A, followed by excavation and progressive failure in Photographs 16B through 16G.

Displacements of points along the fill surface and corresponding points along the top of the modeled bedrock surface were measured throughout four model tests. In each test, the slope angle and height, discontinuity orientation and fill thickness were slightly varied. The results of displacement measurements for individual tests are shown on Figures 9A through 9D, and the combined results from all model tests are shown on Figure 9E.

In all tests, surface displacements and shallow depth displacements (at the top of the modeled bedrock surface) were essentially equivalent for small to moderate deformations. At high deformations; however, the vertical components of bedrock displacements were consistently up to 30% greater than the vertical components of corresponding fill surface displacements, and the horizontal components of bedrock displacements were consistently up to 10% less than the horizontal components of corresponding surface displacements. The combined results of the physical model tests, as shown on Figure 9E, suggest that the surface displacements may be a good approximation of underlying bedrock displacements for varying slope configurations at low to moderate deformations.

8.0 LIMIT EQUILIBRIUM STABILITY ANALYSIS

Limit equilibrium analyses were conducted to evaluate the historical stability of the existing rock topple along Cross Section AA'. The stability analysis was conducted with respect to the in-place rock mass structure for the estimated slope configurations before and after the 1950 flood, and for the existing slope configuration.

The factors of safety in the stability analysis were computed by the relation $F.S. = \tan \phi_j / \tan \phi_{j,\text{required}}$, where $\phi_{j,\text{required}}$ represents the discontinuity friction angle required for limiting equilibrium with respect to interlayer flexural slip. Analyses were conducted with foliation friction angles (ϕ_j) ranging from 24 and 32 degrees to bracket the probable factor of safety. Friction angles of 24 and 32 degrees were determined for unpaired and paired foliation surfaces, respectively, in the highly weathered Salt Springs Slate. Results of the stability analysis are presented on Figures 10A through 10F and are summarized in Table 3. Interlayer flexural slip is kinematically permissible when the normal to a discontinuity set plots within the ruled regions of the stereonet (Goodman, 1989). The ruled regions are bounded by the horizontal great circle and a great circle ϕ_j degrees below the slope of the hillside, and small circles oriented 30 degrees from the hillside dip vector. Interlayer flexural slip is a prerequisite for large flexural deformations associated with toppling.

TABLE 3 - SUMMARY OF SLOPE STABILITY ANALYSIS

SLOPE CONDITION	SLOPE ANGLE (degrees)	ϕ_j (degrees)	ϕ_j, required (degrees)	Factor of Safety (with respect to interlayer slip)
Pre-1950 flood	20	24 - 32	2	13 - 18
Post-1950 flood	75	24 - 32	55	0.32 - 0.44
Existing Slope	90	24 - 32	70	0.16 - 0.23

The stability analysis indicates that interlayer slip along foliation in the area of Cross Section AA' was not kinematically possible under the original slope configuration. This conclusion is supported by existing in-place foliation near the southwestern end of Cross Section AA' (deformation should be apparent in this outcrop if toppling had occurred prior to the 1950 flood). Excavation of the Salt Springs Slate during the 1950 flood oversteepened the hillside and permitted interlayer flexural slip to develop.

9.0 DISCUSSION AND CONCLUSIONS

9.1 Average Surface Displacement Rate of Rock Topple

Historically, few conclusions have been made regarding the speed at which large scale toppling failures occur. In model studies, toppling gradually develops over an initial rotation of a few degrees, followed by rapid downslope movement at a critical combination of angles and displacements (de Freitas and Watters, 1973).

As summarized in Table 4, a maximum resultant surface displacement of 18 feet is estimated from a balanced cross section of the fill, and surface displacements are empirically correlated to underlying bedrock displacements through base friction model studies. Historical site photographs and limit equilibrium stability analyses indicate that the 1950 flood event excavated an approximately 40,000 cubic yard block of Salt Springs Slate that oversteepened the hillside and permitted flexural slip to occur along foliation. The stability analysis used in this study can not predict whether large scale toppling displacements will develop subsequent to initial interlayer slip. However, given the regular, close spacing of open fractures along foliation and the highly discontinuous nature of the rock mass, it is likely that relatively large displacements initiated shortly after oversteepening of the hillside. Dividing the maximum estimated surface displacement by the 45 year time interval over which interlayer flexural slip has been permissible yields an average bedrock surface displacement rate of 0.4 ft/yr.

TABLE 4 - ESTIMATED MAXIMUM AVERAGE SURFACE DISPLACEMENT RATES

MAXIMUM DISPLACEMENT (feet)	TIME INTERVAL (years)	AVERAGE SURFACE DISPLACEMENT RATE (ft./yr.)
15 (horizontal)	45	0.33
9.5 (vertical)	45	0.21
17.8 (resultant)	45	0.40

The estimated displacement rates are only applicable to a relatively small portion of the rock topple, near the confluence of Mexican Gulch and the Mokelumne River. Unfortunately, geologic relations required to estimate displacement rates in other portions of the rock topple are not evident in the field. The computed displacement rates equally distribute the deformations over a 45 year period, and do not account for discrete, transient displacements that may have occurred in the toppling mass.

9.2 Future Studies

The displacement estimates developed in this study are currently being compared to displacement solutions predicted by existing discrete element codes to evaluate parameter sensitivity and the compatibility of observed and predicted failure modes in highly discontinuous rock masses.

REFERENCES

- Clark, L.D., 1964, Stratigraphy and Structure of the Western Sierra Nevada Metamorphic Belt, California: United States Geological Survey Professional Paper 410.
- de Freitas, M.H., and Watters, R.J., 1973, Some Field Examples of Toppling Failure: *Geotechnique*, Volume 23, No. 4 (December, 1973), p. 495-514.
- Goodman, R.E., 1976, Methods of Geological Engineering, West Publishing Company, St. Paul, Minnesota, 472 p.
- Goodman, R.E., 1989, Introduction to Rock Mechanics, 2nd Edition, John Wiley and Sons, New York, NY, 478 p.
- Jennings, C.W., 1977, Geologic Map of California: California Department of Conservation, Division of Mines and Geology: Geologic Map No. 2, scale 1:750,000 (fourth printing).
- Jennings, C.W., 1992, Preliminary Fault Activity Map of California: California Department of Conservation, Division of Mines and Geology: DMG Open File Report 92-03, scale 1:750,000.
- Norris, R.M., and Webb, R.W., 1990, Geology of California, John Wiley and Sons.
- Woodward-Clyde Consultants, 1988, Final Report, Pardee Dam South Spillway Geological Investigation; Project No. 8710086A.
- Woodward-Clyde Consultants, 1994, Pardee Dam and South Spillway Modifications, Preliminary Design Study, Project No. 92C0389A.

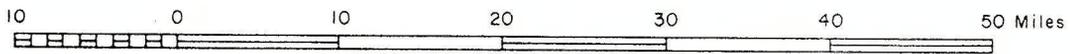
FIGURES

FIGURE 1
Regional Geologic Map



SCALE 1:750,000

(1 INCH EQUALS APPROXIMATELY 12 MILES)



TOPOGRAPHIC CONTOUR INTERVAL: 500 FEET (DOTTED LINE REPRESENTS 100-FOOT CONTOUR).



Source: Jennings, 1977

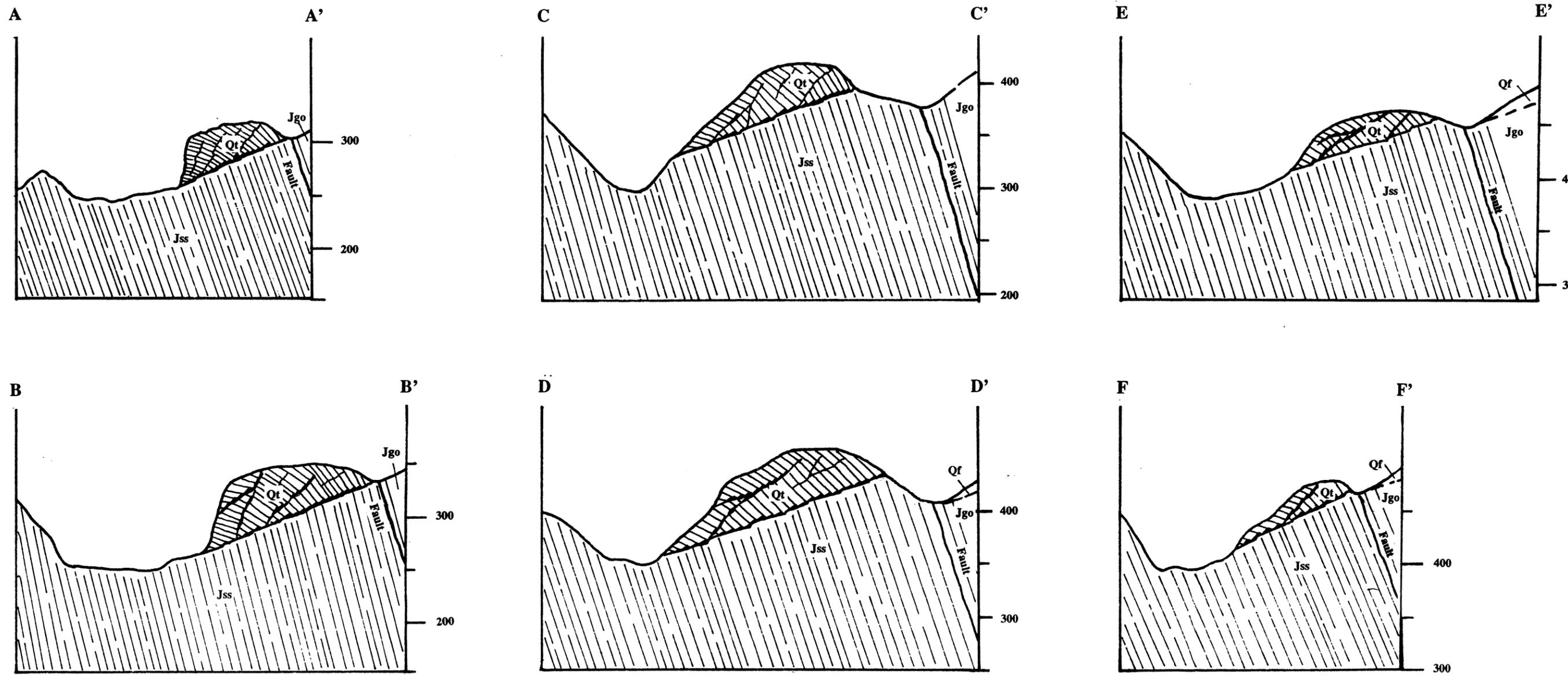


FIGURE 3
Subsurface Cross Sections AA' through FF'

Scale: 1 inch = 100 feet (horizontal = vertical)

*Elevations in feet, MSL datum.

Geologic Units

- | | | | | |
|------------|---|-----|---|--|
| Quaternary | [| Qf | - | Artificial Fill |
| | | Qt | - | Rock Topple |
| Jurassic | [| Jss | - | Salt Springs Phyllite |
| | | Jgo | - | Meta-tuff and volcanic breccia of the Gopher Ridge Volcanics |

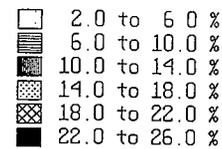
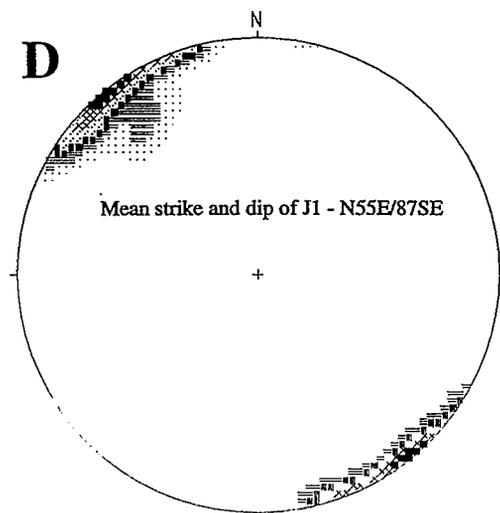
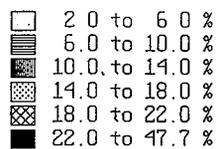
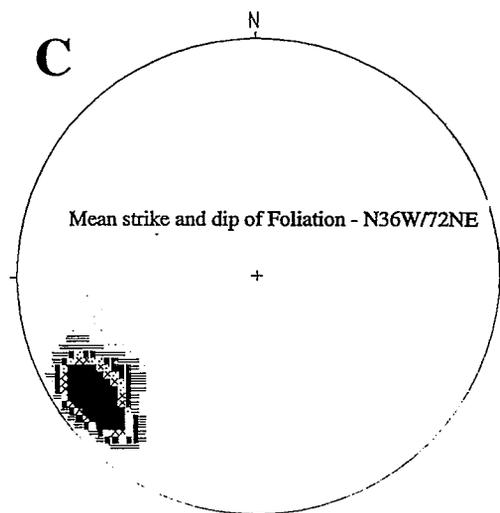
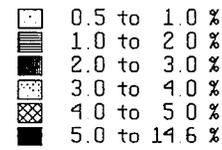
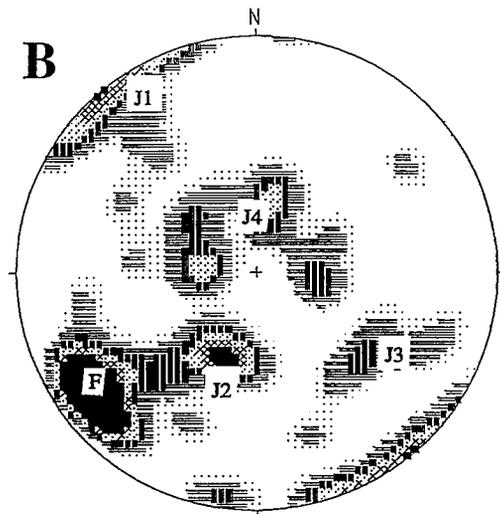
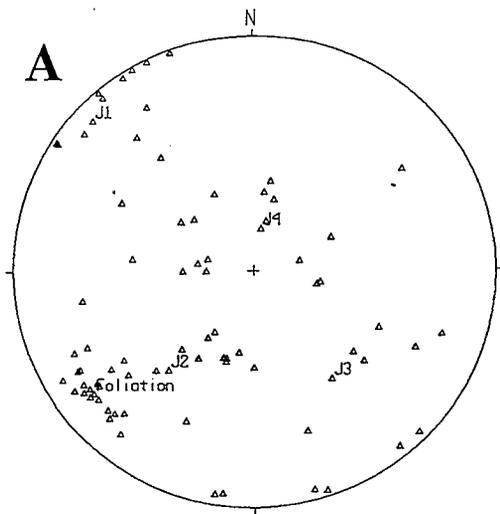
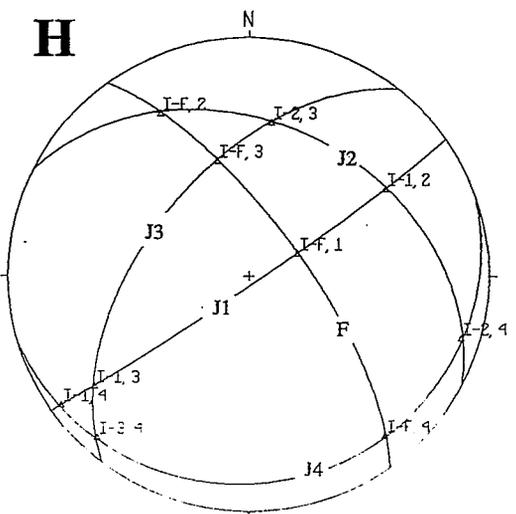
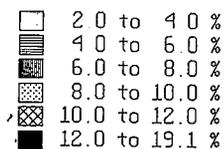
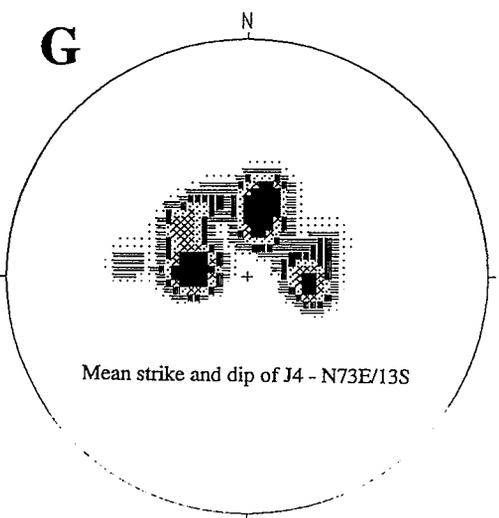
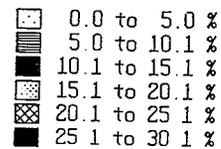
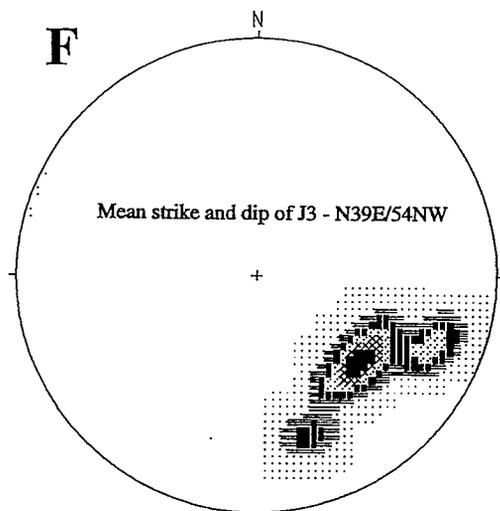
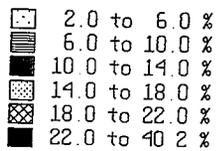
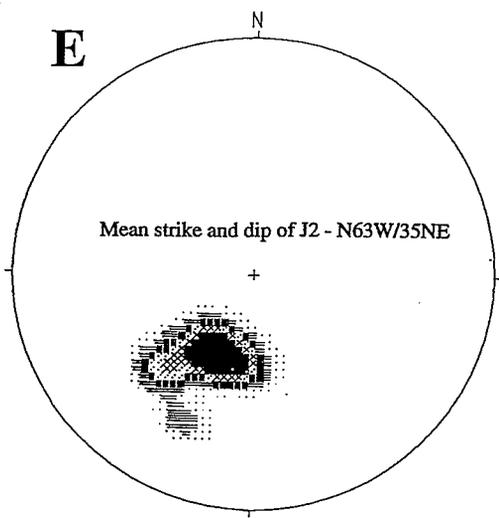


FIGURE 4 - In place rock mass fabric bordering rock topple (lower hemisphere Schmidt projections, spherical Gaussian distributions). A) Discontinuity poles; B) Discontinuity pole density distribution with key to pole concentrations; F = foliation, J_n = joint set n; C) Foliation pole density distribution; D) J₁ pole density distribution.



Bearing and Plunge of mean discontinuity intersections

IF,1 -	N72E/72	I1,3 -	S53W/21
IF,2 -	N29W/22	I1,4 -	S54W/4
IF,3 -	N15W/48	I2,3 -	N8E/35
IF,4 -	S40E/12	I2,4 -	S73E/7
I1,2 -	N57E/32	I3,4 -	S42W/6

FIGURE 4 (continued) - E) J₂ pole density distribution; F) J₃ pole density distribution; G) J₄ pole density distribution; H) Mean discontinuity planes; IF_n = line of intersection between foliation and joint set n; I_{n,m} = line of intersection between joint sets n and m.

FIGURE 5A
Field Foliation Friction Measurements - Paired Phyllite Surfaces

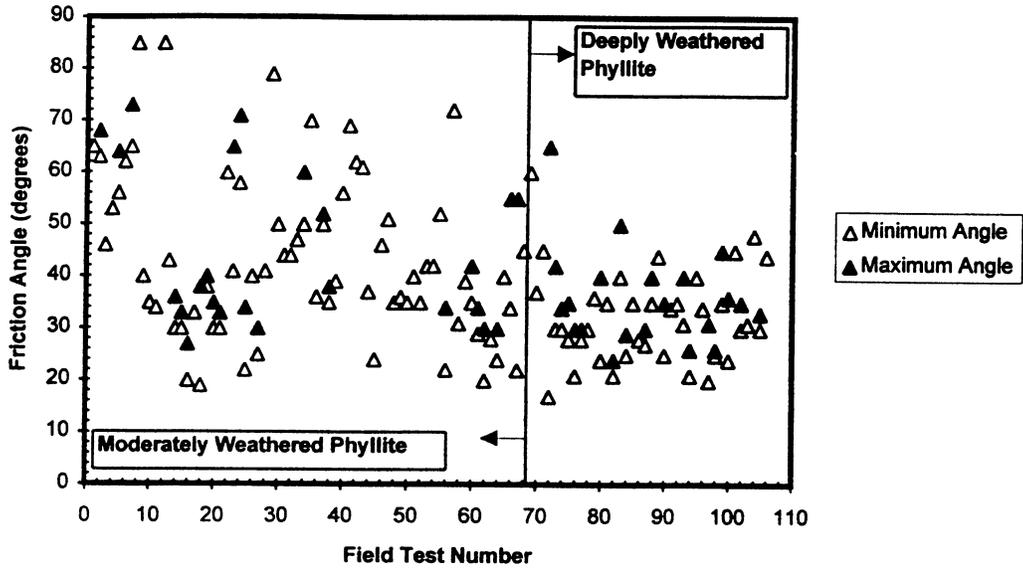


FIGURE 5B
Field Foliation Friction Angle Measurements - Unpaired Phyllite Surfaces

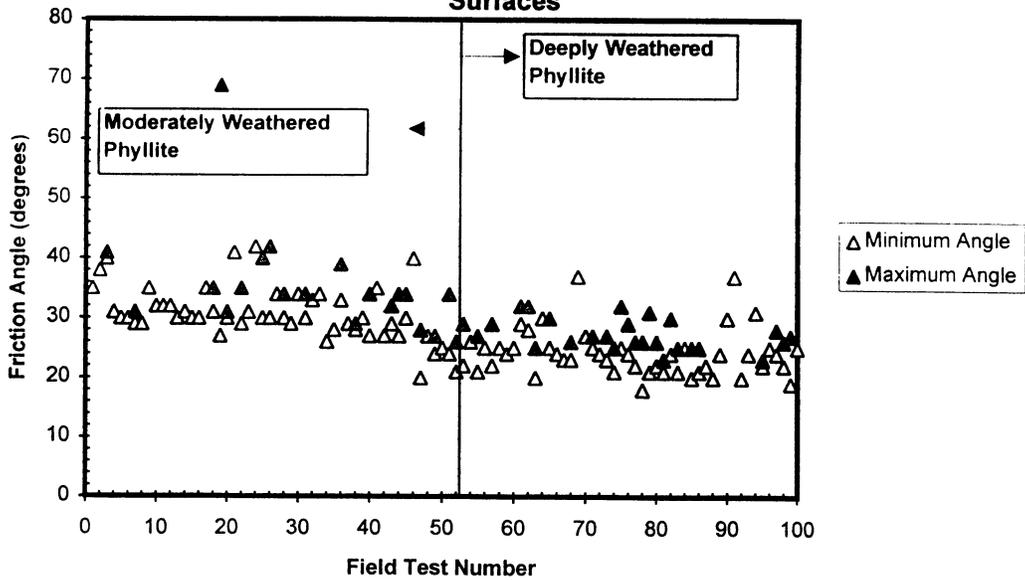
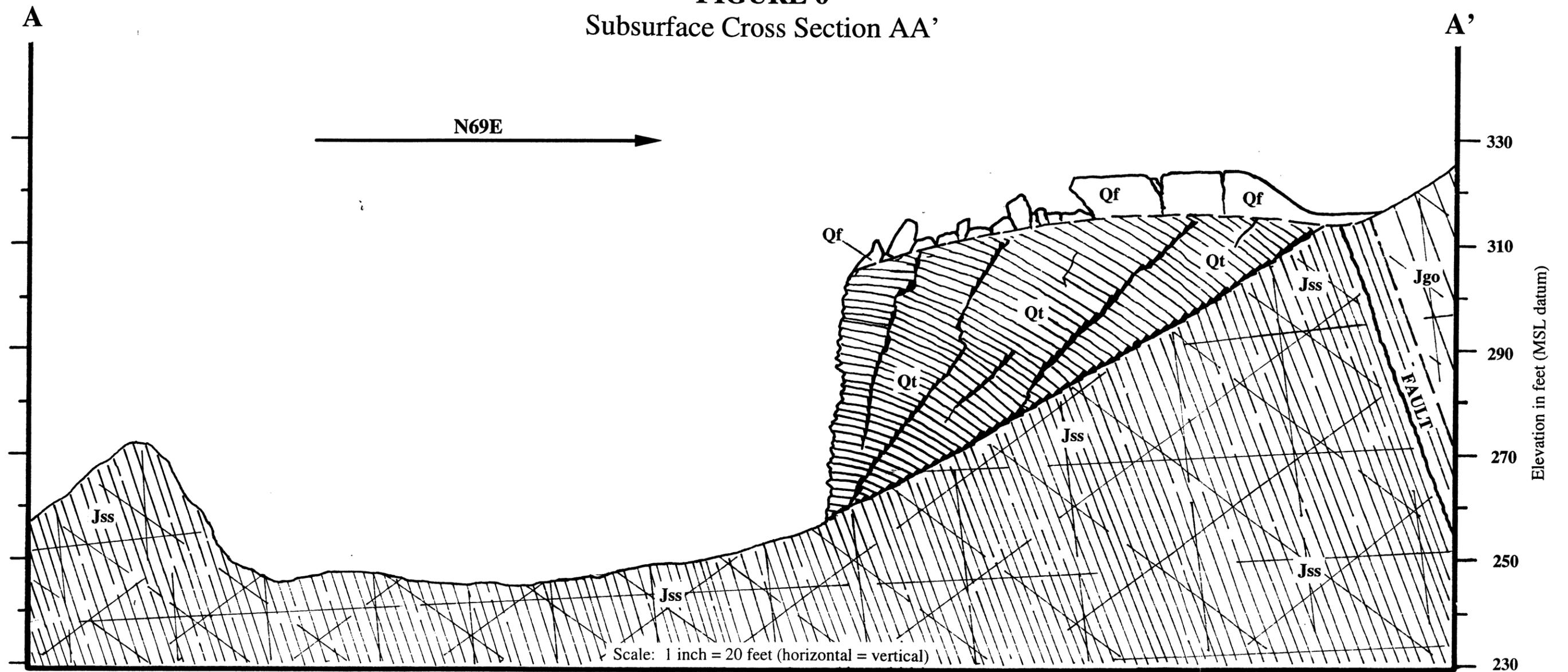


FIGURE 6
Subsurface Cross Section AA'



Geologic Units

Quaternary	[Qf	-	Artificial Fill
		Qt	-	Rock Topple
Jurassic	[Jss	-	Salt Springs Phyllite
		Jgo	-	Meta-tuff and volcanic breccia of the Gopher Ridge Volcanics

FIGURE 7
Estimated Fill Surface Displacement Vectors

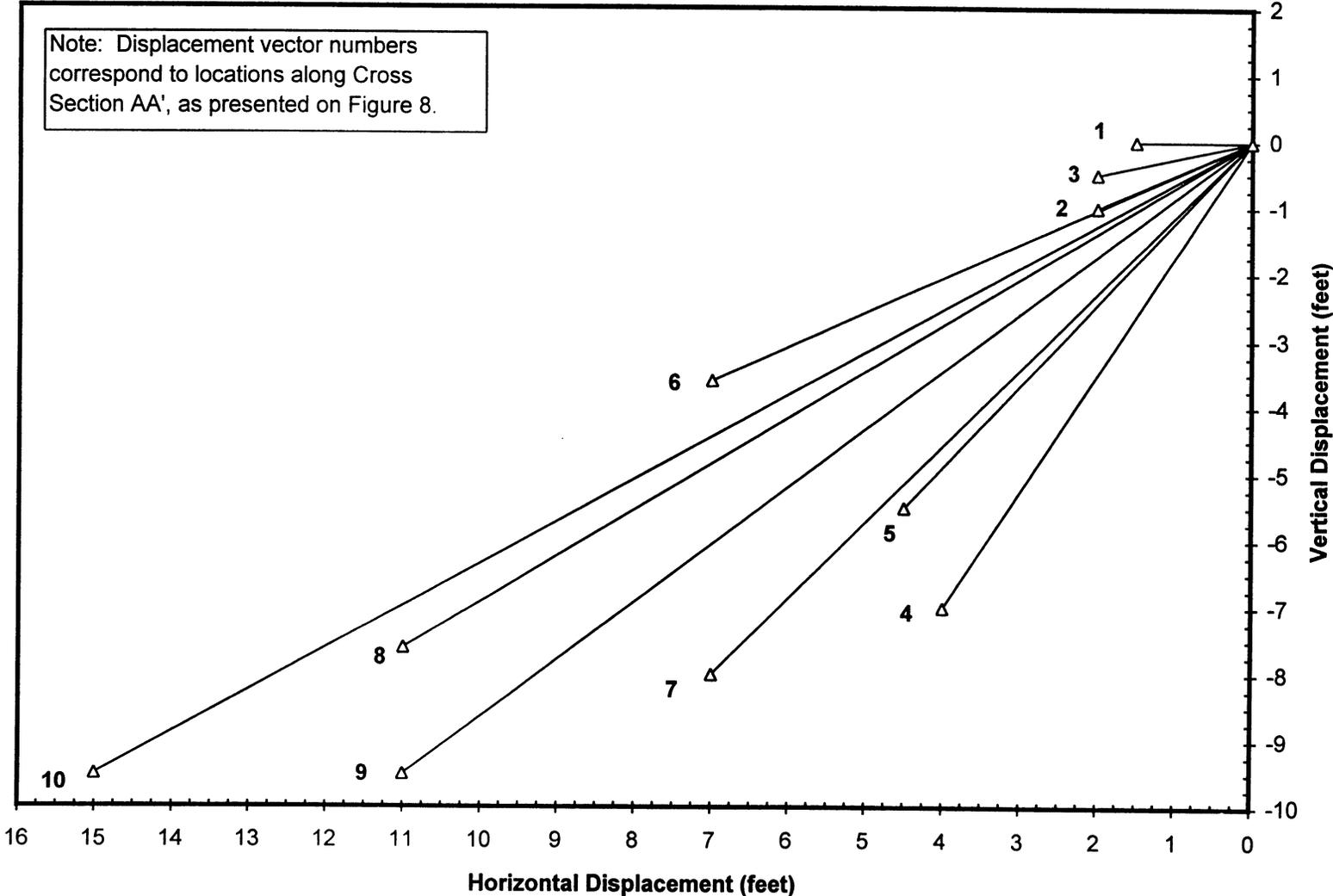
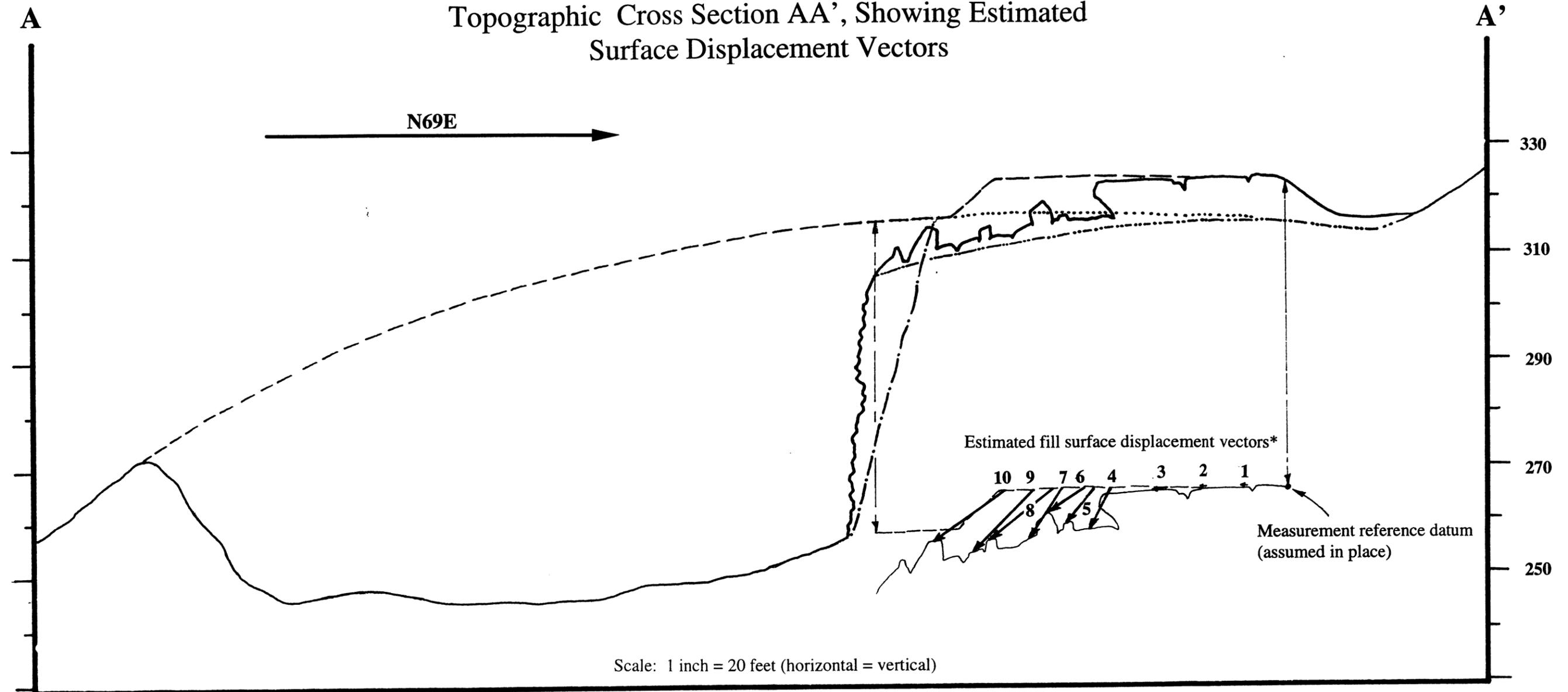
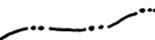


FIGURE 8

Topographic Cross Section AA', Showing Estimated Surface Displacement Vectors



LEGEND

-  Existing grade
-  Estimated original grade (prior to spillway outlets)
-  Estimated slope configuration following excavation from spillway outlets
-  Estimated existing bedrock/fill contact
-  Estimated original bedrock/fill contact (prior to spillway outlets)
-  Estimated fill surface displacement vectors

*Note: Fill surface displacement vectors determined by constructing a balanced cross section from survey data. Displacement vector numbers correspond to the displacements presented on Figure 7.

FIGURE 9A
Comparison of Surface and Shallow Depth Toppling Displacements
Base Friction Model Test #1

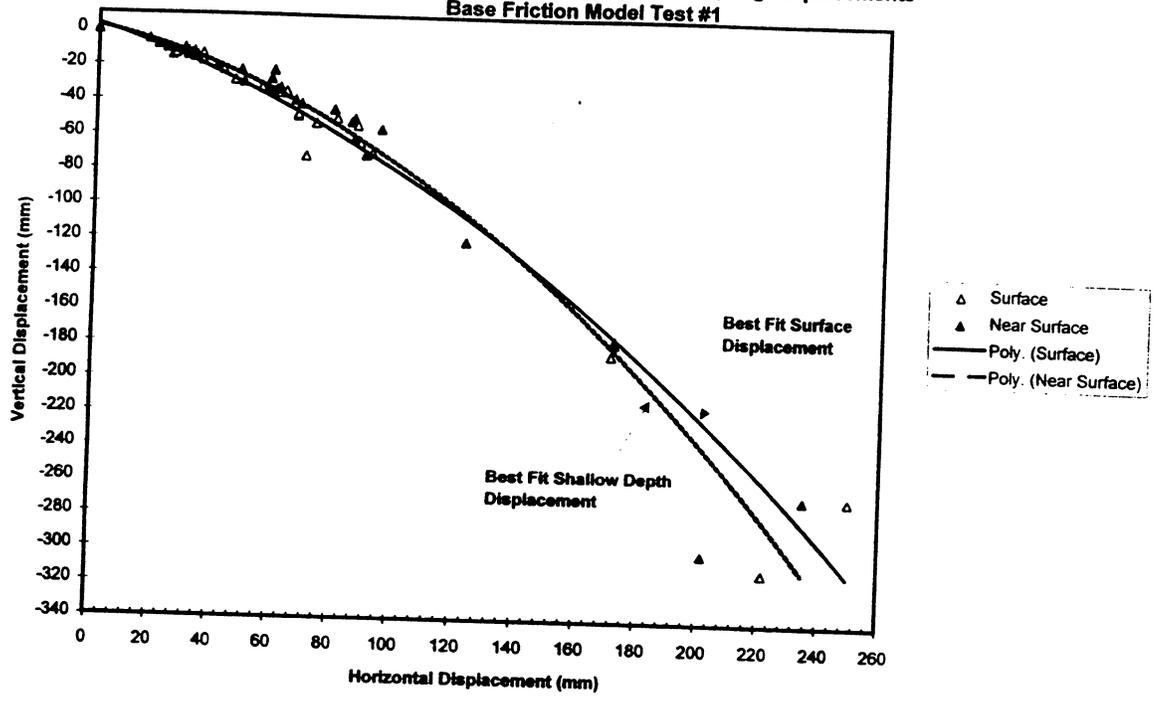


FIGURE 9B
Comparison of Surface and Shallow Depth Toppling Displacements
Base Friction Model Test #2

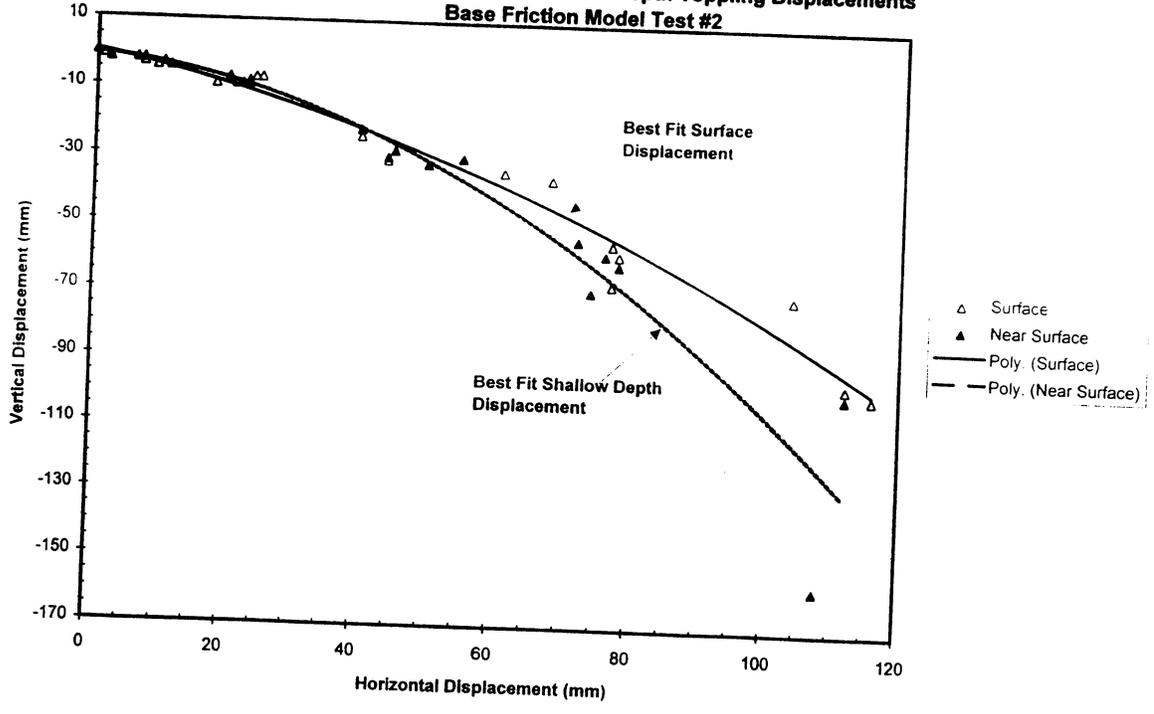


FIGURE 9C
Comparison of Surface and Shallow Depth Toppling Displacements
Base Friction Model Test #3

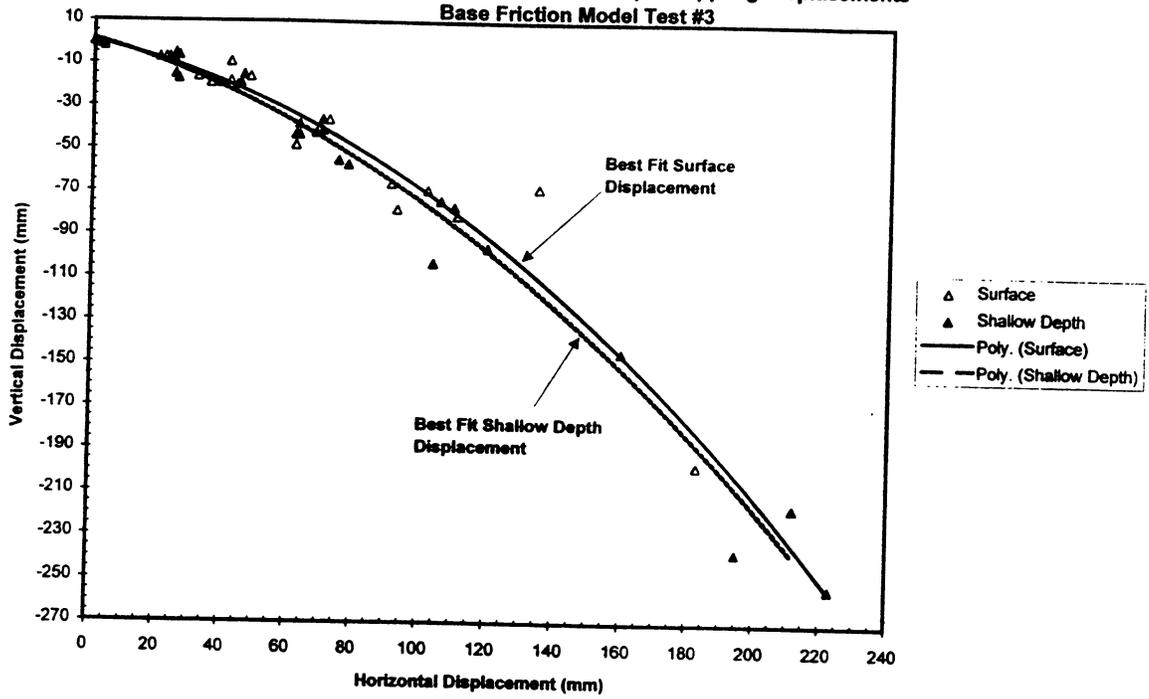


FIGURE 9D
Comparison of Surface and Shallow Depth Toppling Displacements
Base Friction Model Test #3

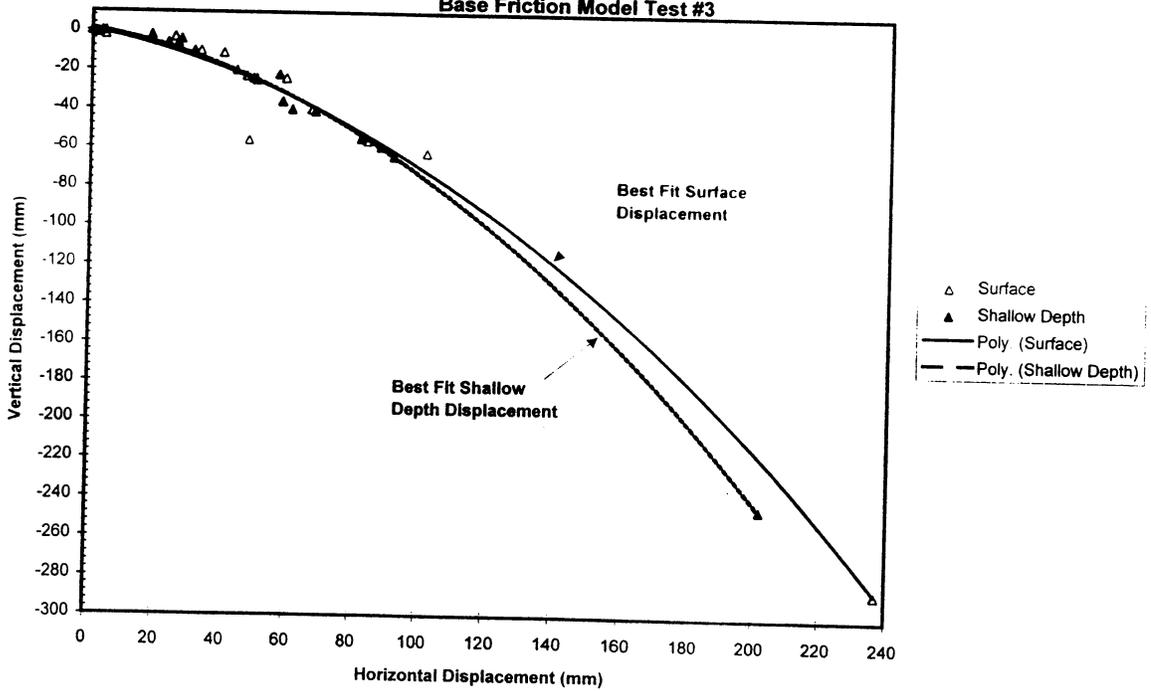
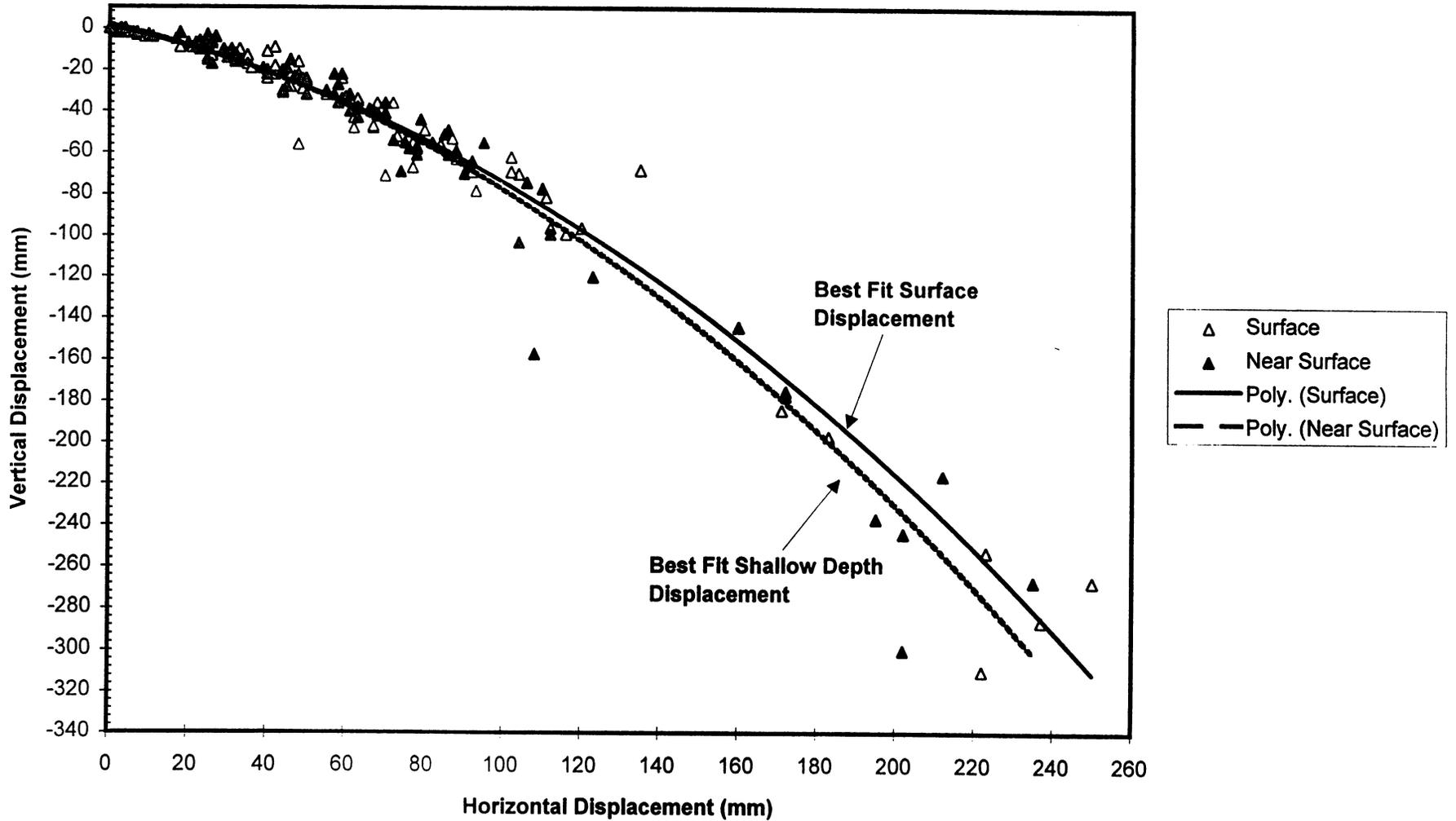


FIGURE 9E
Comparison of Surface and Shallow Depth Toppling Displacements
Combined Base Friction Model Test Results



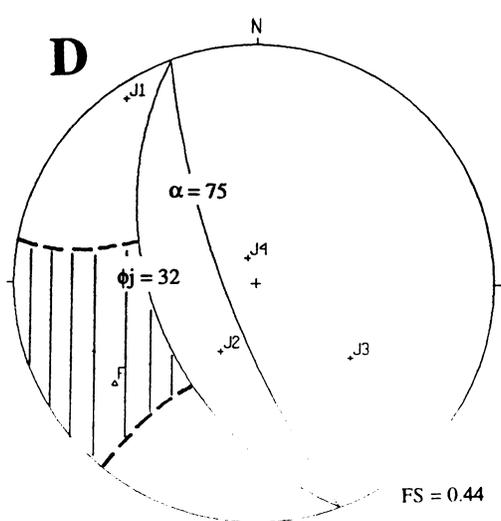
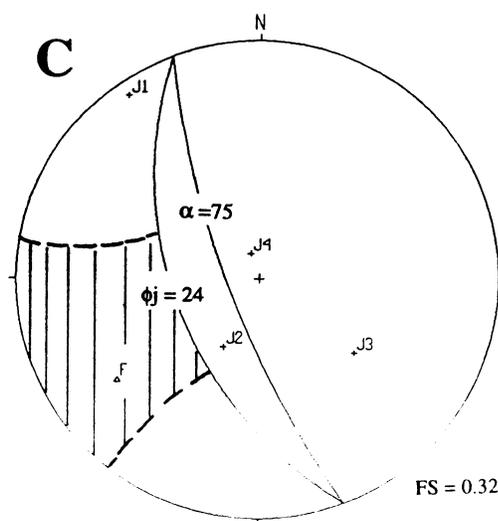
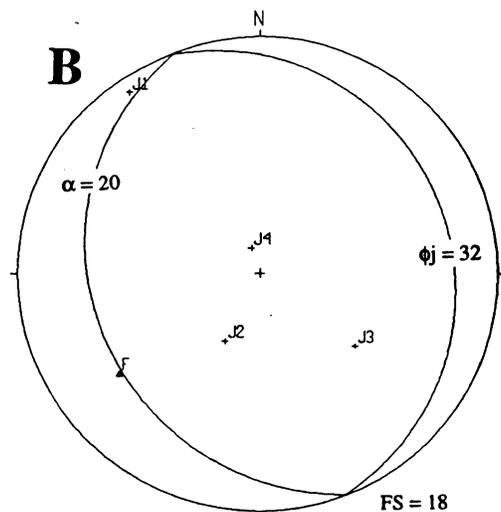
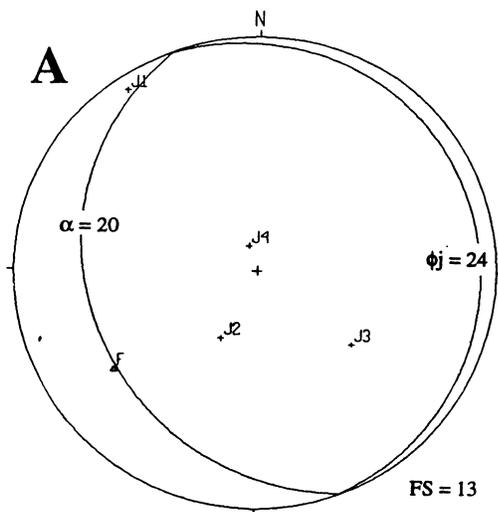


FIGURE 10 - Limit equilibrium stability analysis of toppling failure (lower hemisphere Wulff projections). Toppling failure is kinematically possible with respect to a discontinuity when the pole to the corresponding discontinuity plots within the ruled region. Factors of safety computed by the relation $FS = \tan\phi_j / \tan\phi_{j,required}$, where $\phi_{j,required}$ represents the joint friction angle required for limiting equilibrium. Foliation = F; joint set n = Jn; joint friction angle = ϕ_j ; slope angle = α (degrees); FS = factor of safety with respect to foliation. A) and B) Stability with respect to estimated original slope configuration; C) and D) Stability with respect to estimated slope configuration following excavation from spillway outlets.

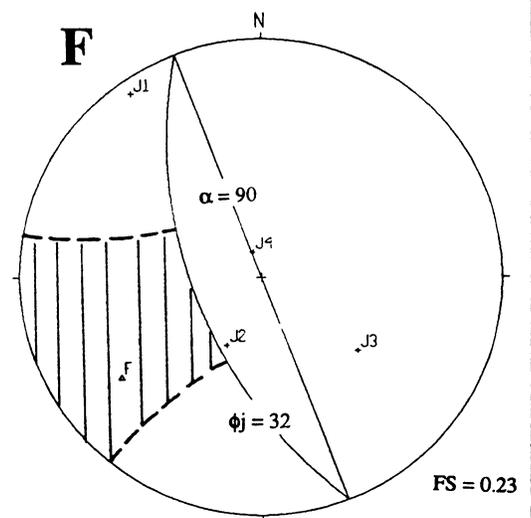
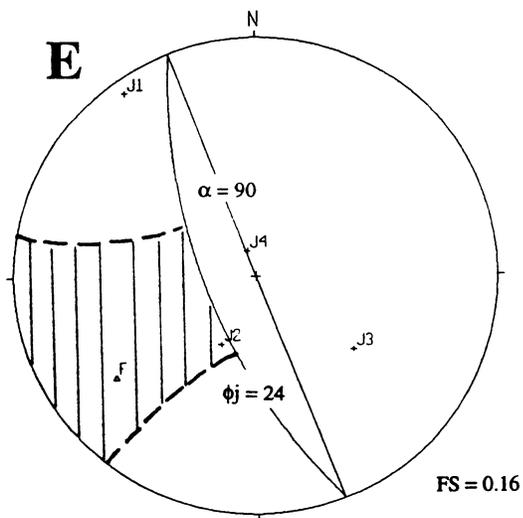


FIGURE 10 (continued) - E) and F) Stability with respect to existing slope configuration.

PHOTOGRAPHS

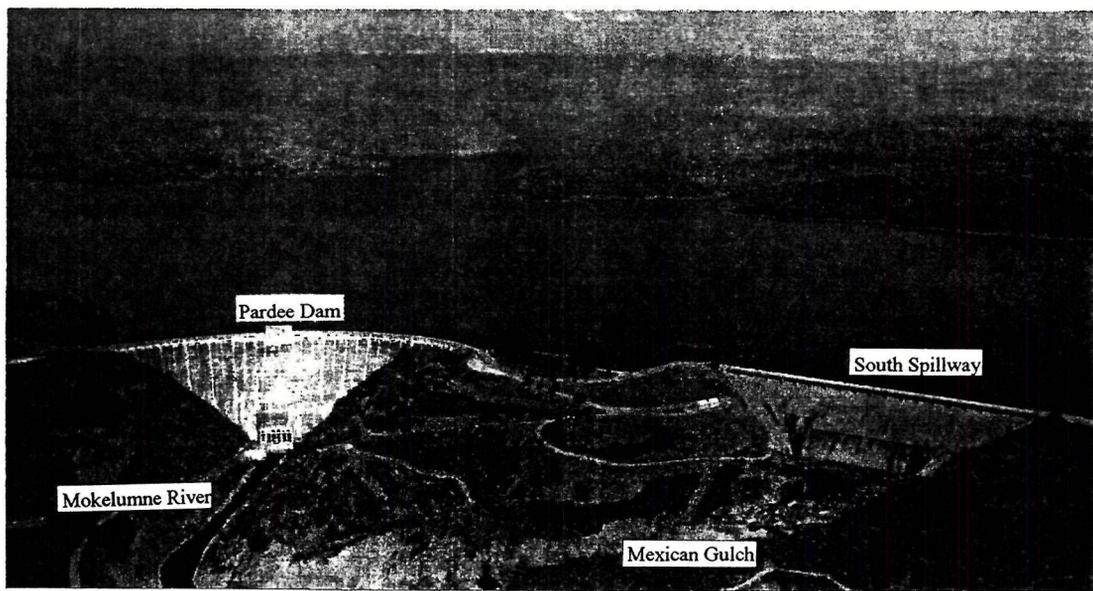


PHOTO 1 - Aerial site overview, looking eastward (photograph: Woodward Clyde Consultants, 1994)



PHOTO 2- View of Mexican Gulch - first spill from south spillway, May 11, 1930.



PHOTO 3- Mexican Gulch, June 7, 1930; 1600 c.f.s. flow. Note road fill and car at left of photo.



1691

PHOTO 4 - Mexican Gulch, May 12, 1935; 1100 c.f.s flow. Note right channel bend in lower portion of photo.



PHOTO 5 - Mexican Gulch, January, 1969. Note hydraulic excavation of rock mass in lower center of photo (compare to right channel bend in photo 3). Note road fill in left center of photo, dipping about 20 degrees toward channel.



PHOTO 6- Deep seated rock topple in phyllite, view downstream Mexican Gulch. Brown material is deeply weathered, gray material is moderately weathered. Note discordance of foliation along gray/brown contact.



PHOTO 7- Deep seated rock topple in phyllite, view downstream Mexican Gulch, near confluence with Mokelumne River. Note block of fill material beneath center of dam.

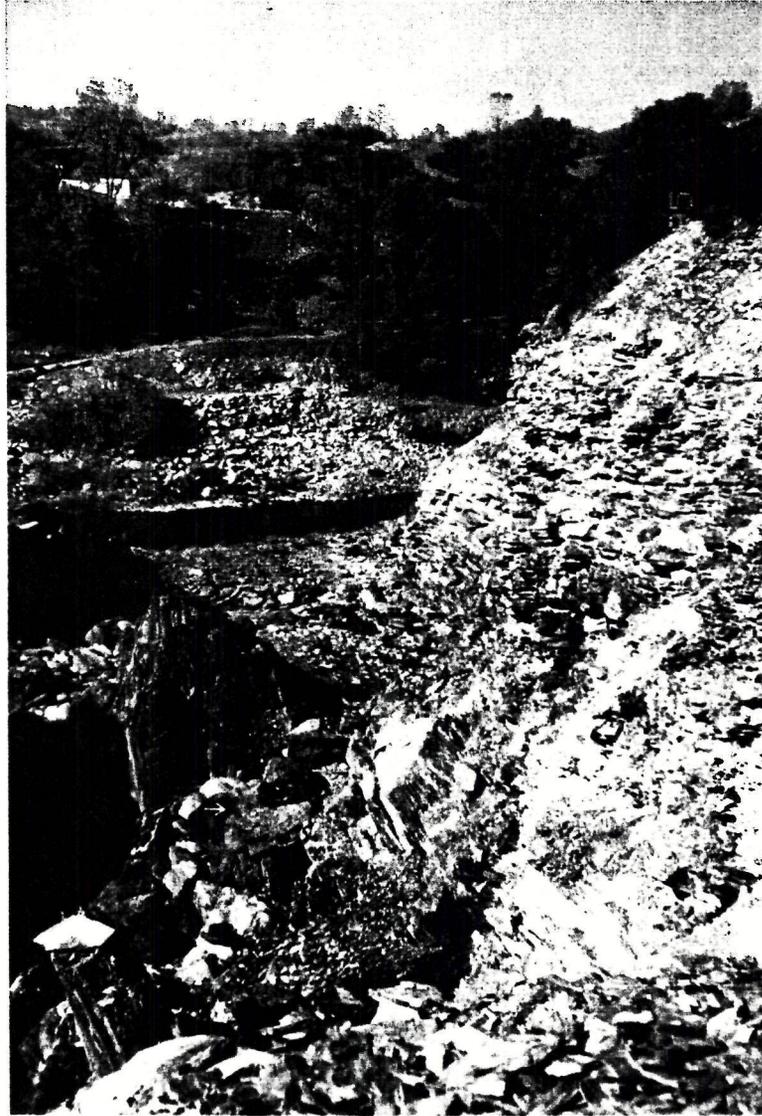


PHOTO 8 - Deep seated rock topple, view downstream Mexican Gulch at confluence with Mokelumne River. Note discordance of foliation between the gray (moderately weathered) and brown (deeply weathered) phyllite.

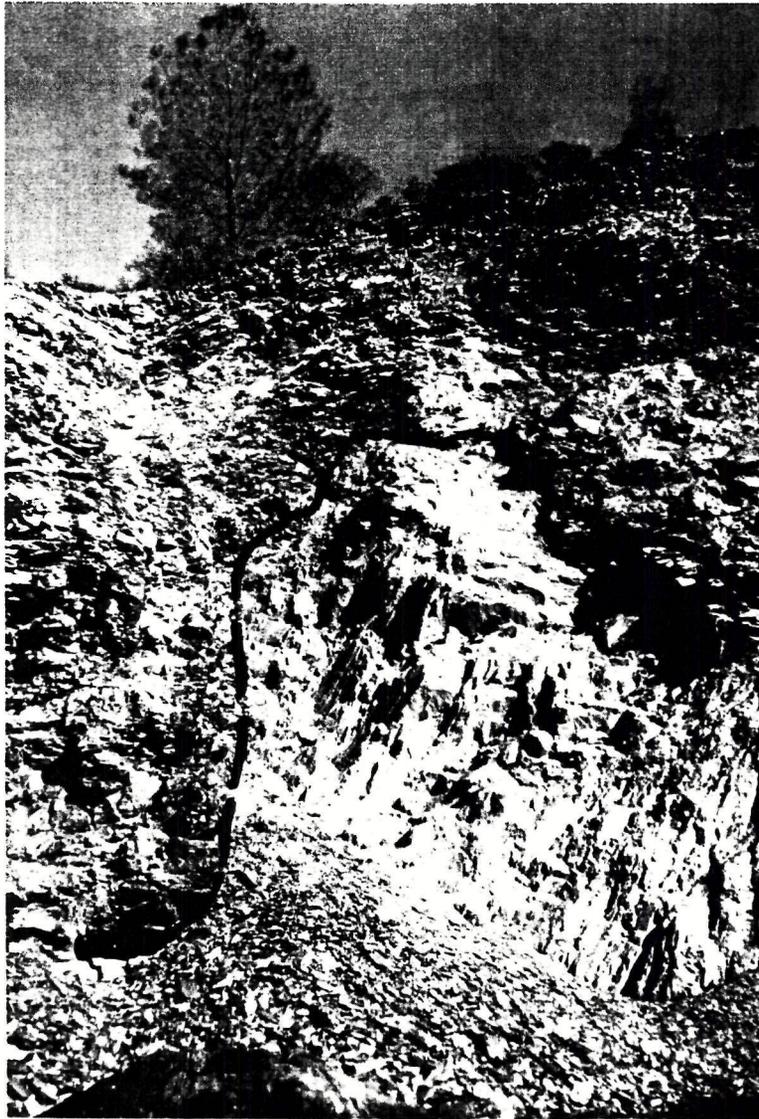


PHOTO 9 - Deep seated rock topple. Dashed black line delimits basal failure hinge.



PHOTO 10 - Typical exposure of basal failure hinge.



PHOTO 11 - Slickensides in rock topple mass formed by flexural slip along foliation.



PHOTO 12 Surface displacement of fill overlying phyllite bedrock, along Subsurface Cross Section AA' (Figure 6). Note progressive rotation of fill blocks in direction of channel.



PHOTO 13 - Tension crack in phyllite bedrock, near crest of deep seated rock topple.

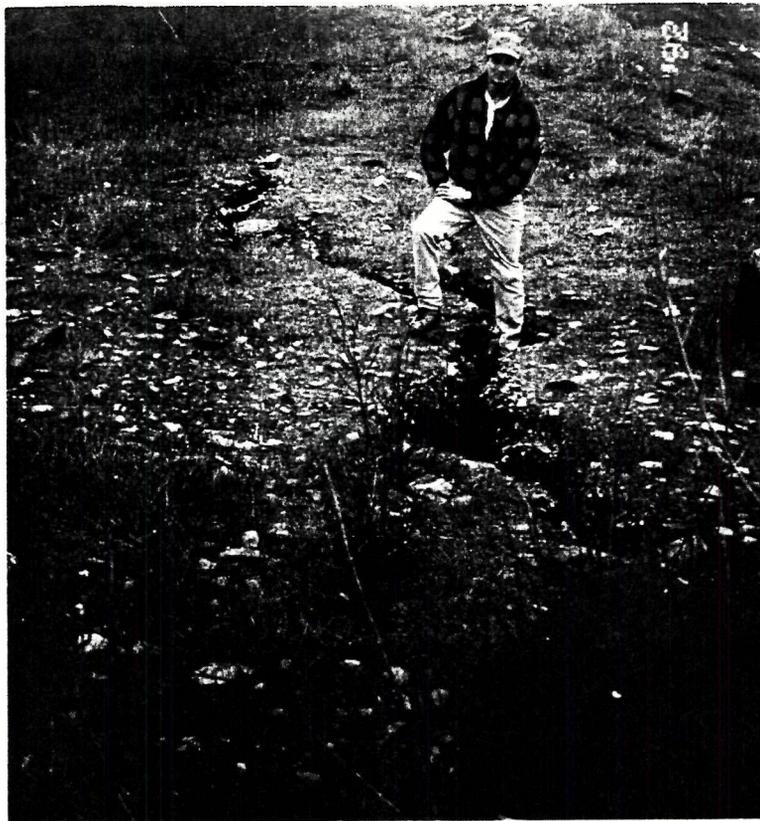
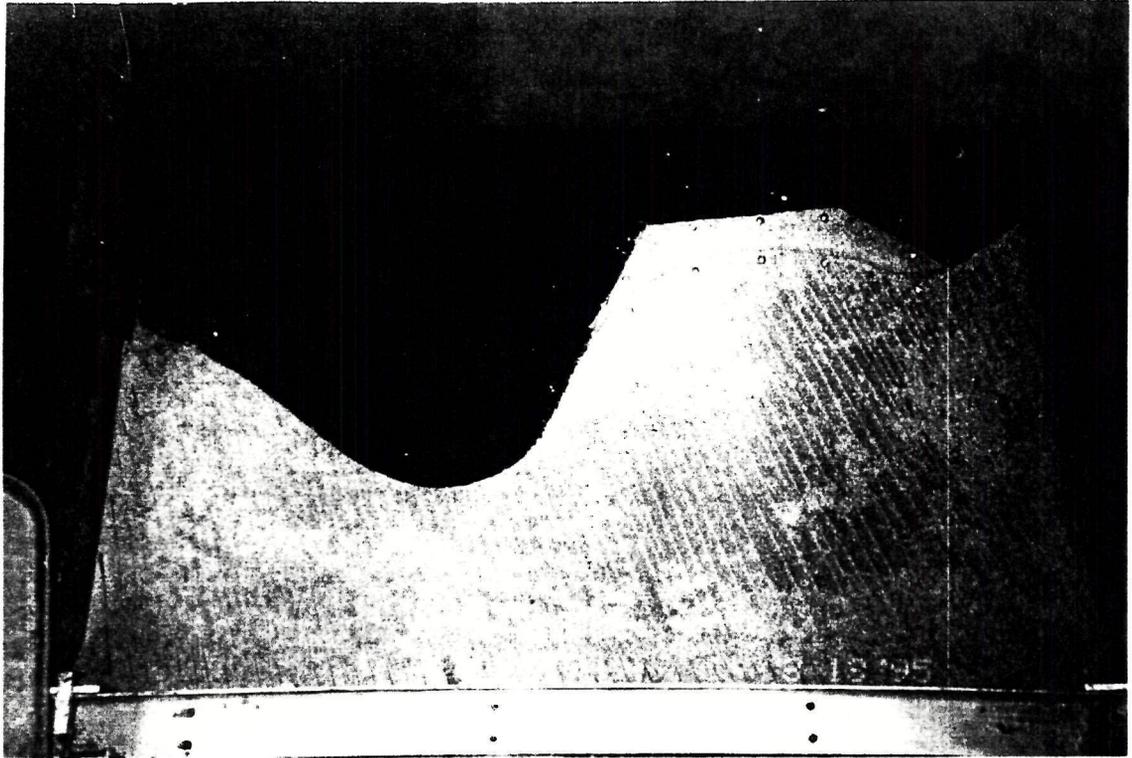


PHOTO 14- Tension crack in fill material, along Subsurface Cross Section AA' (Figure 6).

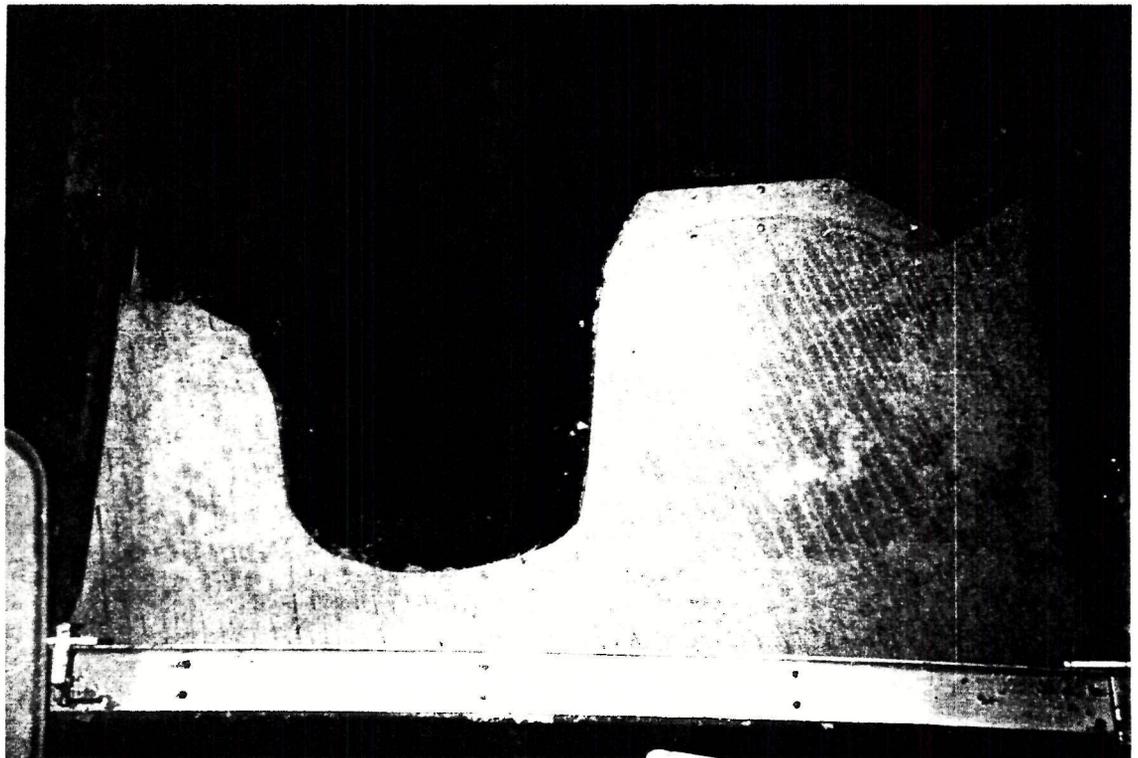


PHOTO 15- Reverse facing scarps (downdropped in direction opposite to free slope face) along crest area of deep seated topple, with approximately 2 feet maximum relief.

16A

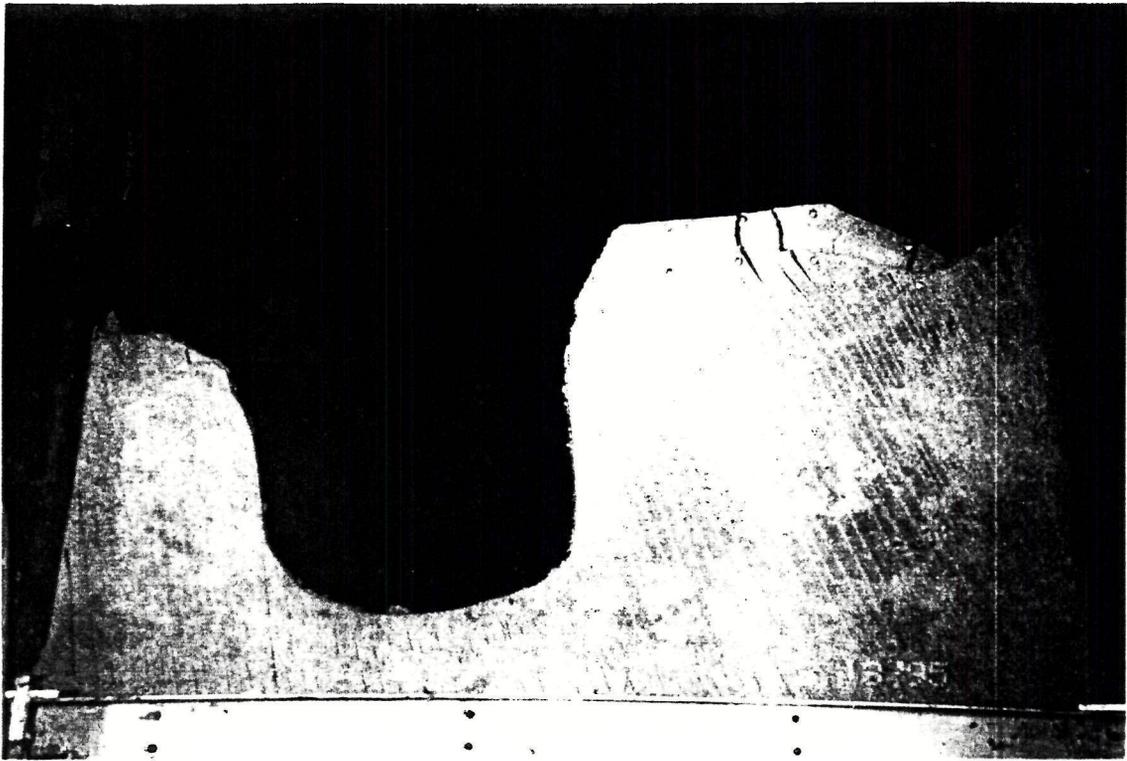


16B

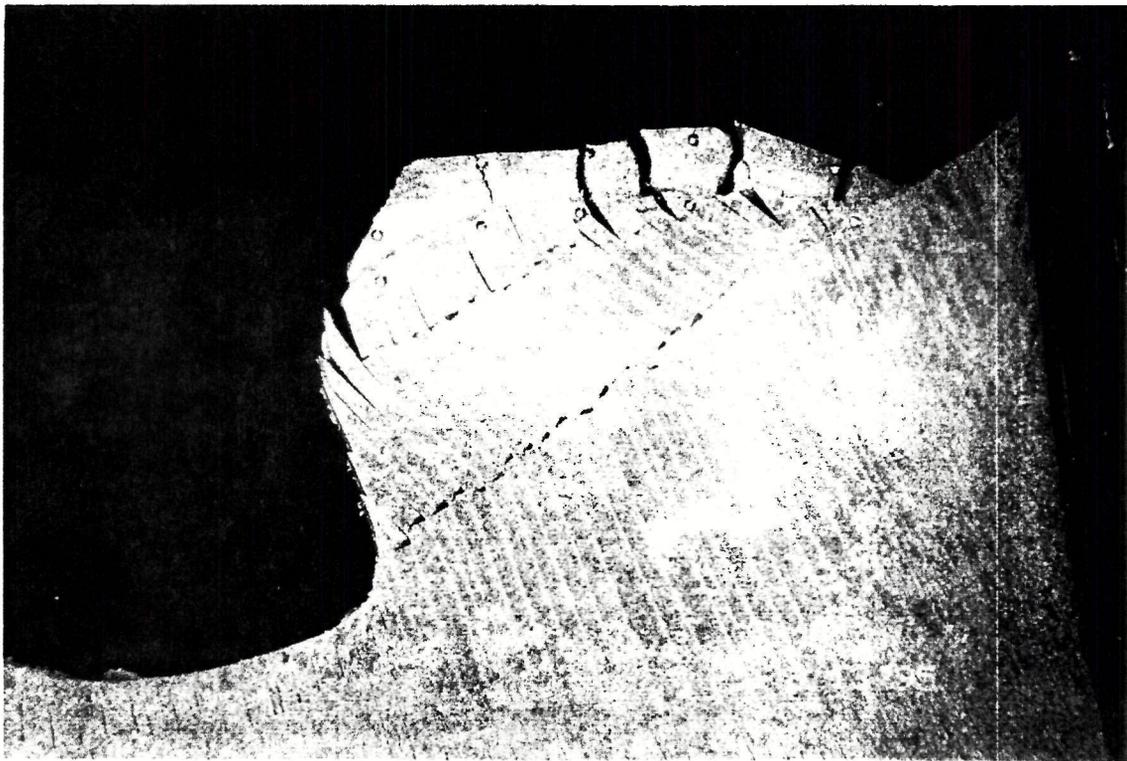


PHOTOS 16 A through 16G - Representative base friction model test, comparing surface and shallow depth toppling displacements. A) Simulation of original slope configuration, prior to spillway outlets (slope configuration stable under model conditions). Silver dots represent points of measured displacements throughout test.; B) Simulation of hydraulic excavation resulting from spill outlets; C through E (following pages) - progressive deformation of modeled bedrock and overlying fill. Compare photo 16 G to Subsurface Cross Section AA' (Figure 6) .

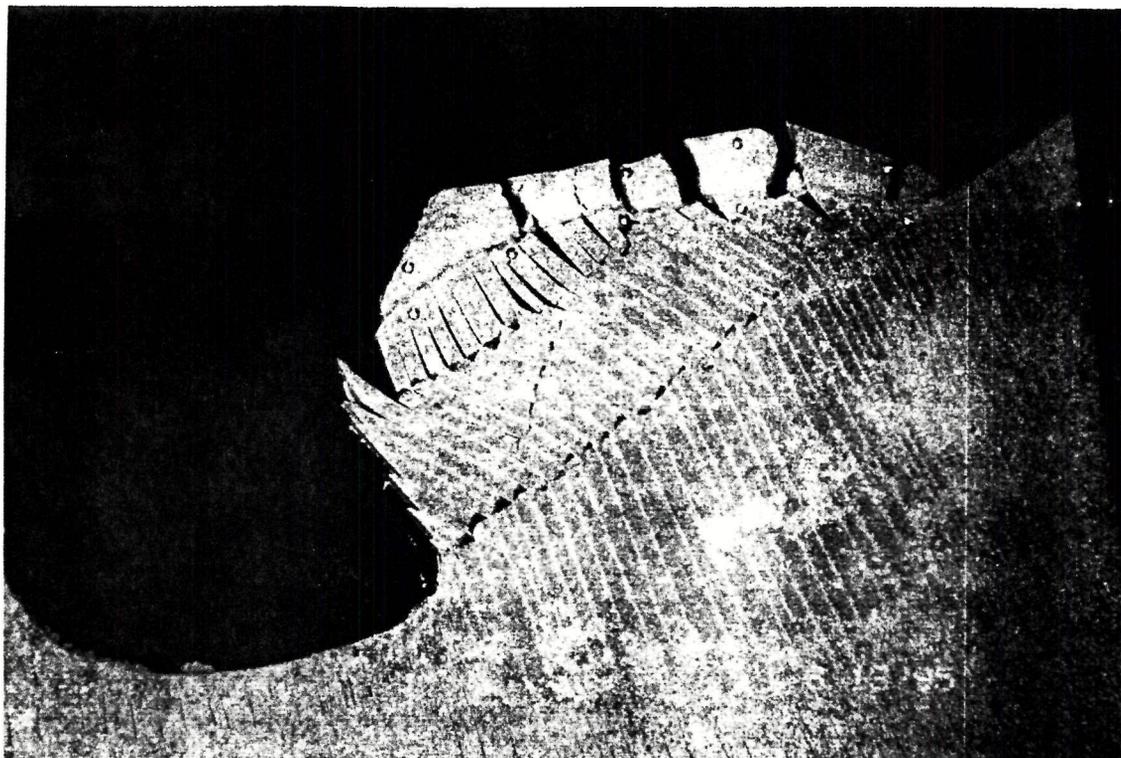
16C



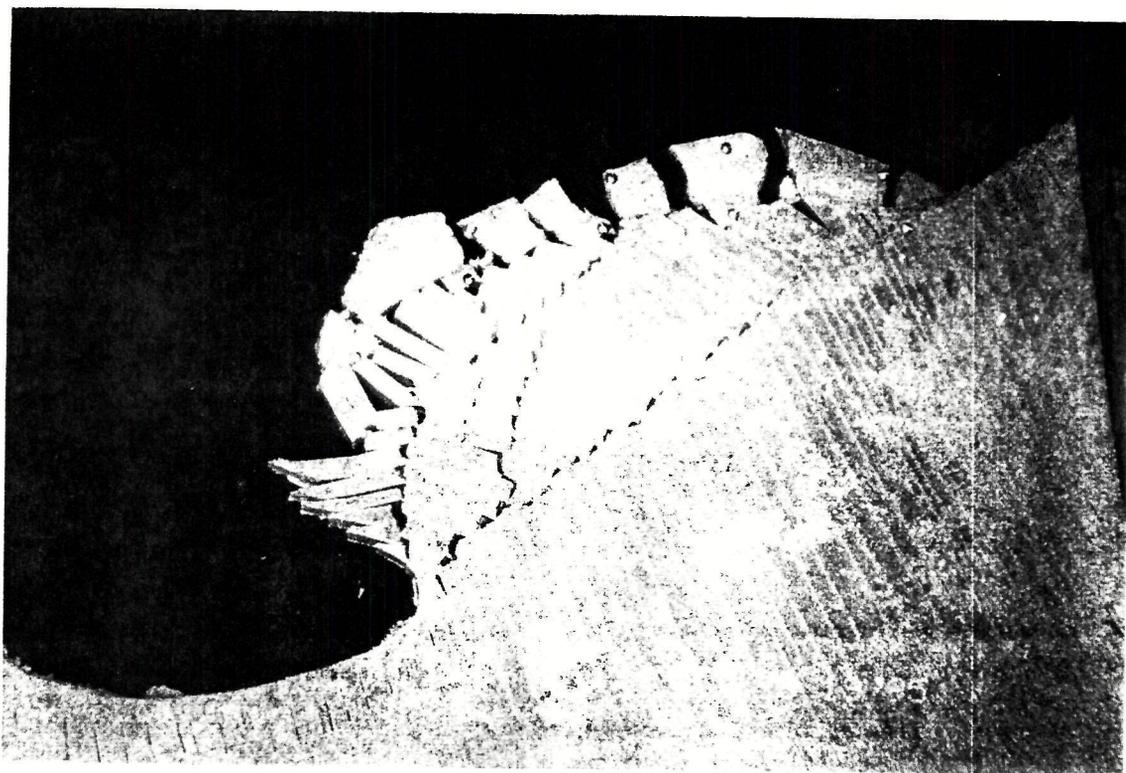
16D



16E



16F



16G

