Tennessee Valley Authority
Division of Engineering Design
Civil Engineering and Design Branch
Geologic Services

PHIPPS BEND NUCLEAR PLANT

GEOLOGIC FOUNDATION REPORT
DESCRIPTIONS OF FAULTS 1-10

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Knoxville, Tennessee

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PHIPPS BEND NUCLEAR PLANT

GEOLOGIC FOUNDATION REPORT

DESCRIPTIONS OF FAULTS 1-10

Introduction

As of July 31, 1979, ten faults have been mapped in the foundation bedrock at Phipps Bend Nuclear Plant. Three faults are located in the unit 1 reactor building, one in unit 2 reactor building, one in unit 2 fuel building, two in unit 2 turbine building, and three in the CCW pumping station. TVA has employed Dr. Paul D. Fullagar and Dr. Fred Webb, Jr., as consulting geologists to assist in fault investigations. Dr. Fullagar was requested to attempt to date the faults, and Dr. Webb was requested to prepare a detailed structural geologic report on the unit 1 reactor building and CCW pumping station areas. Copies of their reports are contained in Appendixes A, B, and C. Reports referenced in the following general descriptions are transmittals from the TVA Office of Power to the NRC Office of Nuclear Reactor Regulation.

Descriptions

Fault #1, reported on March 21, 1978, is 6 feet north of the axial plane of an asymmetrical syncline and approximately 25 feet north of the unit 1 reactor building east-west baseline (exhibit 1). The fault can be seen in the east wall of the reactor building and extends for less than 10 feet to the east of the excavation, where it terminates into bedding and ends vertically above the floor of the excavation. The fault trends N. 50° E. and dips 86° SE. The associated syncline was traced northeastward to the overlying Quaternary terrace deposits, which were found to be undisturbed. The fault

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zone is approximately 2 feet wide at the top and tapers to a narrow calcite-filled fracture near the bottom of the excavation. The zone exhibits closely spaced calcite-filled fractures with minor folding of the shale.

Fault #2, reported on April 27, 1978, was originally reported as a flexure-slip fold located 65 feet north of the east-west baseline of the unit 1 reactor building (exhibit 1). After excavation was complete this fault was traced to a thrust fault located approximately 48 feet north of the east-west baseline, where it truncates the northern portion of an anticline. The fault at this location splits into two branches. One dips 70° SE.; and the other, on the floor of the excavation, extends nearly horizontal for 20 feet, where it merges with the bedding. Both branches have planar fault zones filled with calcite and trend N. 55° E. The overlying Quaternary terrace deposits remain undisturbed above the fault zones.

Fault #3, described in Appendix B,[1] and reported May 8, 1979, is a thrust fault located on the unit 1 reactor building east-west baseline and extending from the west wall to the east wall of the excavation (exhibit 1). The fault trends N. 56° E. and dips approximately 40° SE. It has sheared the northern portion of an anticline, and exhibits a narrow fault plane filled with calcite. Inasmuch as no key marker beds are contained within the rock strata, the amount of offset cannot be determined. No evidence of disturbance was found in Quaternary terrace deposits overlying the fault.

Fault #4, reported on August 11, 1978, is located in the unit 2 reactor building excavation area (exhibit 2). It is seen on the west wall just north of the east-west centerline and on the east wall inside the tower crane #8

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1. In Appendix B, Dr. Webb has labeled the first three faults as sites 1 through 3, but it should be noted that fault #1 is site 2; fault #2 is site 3; and fault #3 is site 1.

excavation. This thrust fault, which trends N. 56° E. and dips 64° SE., is probably the same as fault #3 located on the east-west baseline of unit 1 reactor building. The fault zone is about 1.5 feet wide and is composed of calcite and weathered shale. To the north bedding is near vertical; south of the fault the beds dip approximately 30° SE. Thorough investigations of Quaternary terrace gravel deposits in the area have indicated no displacement or interruptions. A detailed report on the structural geology of the unit 1 reactor building is included in Appendix B.

Fault #5, reported November 16, 1978, is located in fuel building 2, 95 feet north of fault #4 and 106 feet north of the unit 2 east-west baseline (exhibit 2). It extends 45 feet to the west of the east wall of the fuel building where it terminates, and to the east it extends beyond the excavation beneath the overburden. The fault is defined by a calcite-filled fracture which strikes N. 45° E. and dips 84° NW.; it offsets beds, dipping 68° S., approximately 6 inches. No deformation of the overlying Quaternary terrace deposits was seen.

Fault #6, reported on April 11, 1979, is a transverse fault located 306 feet east of the unit 1 north-south baseline, where it intersects the center-line of the south CCW trench (exhibit 2). From the south wall of the south CCW trench, where it is covered by overburden, the fault extends 24 feet to the north, where it splits into two branches; the two branches continue north-ward to approximately 290 feet south of the east-west baseline, where they transitionally terminate into a near-vertical joint. The fault is defined by a distorted fracture zone which strikes N. 25° W. and dips 60° SW., offsetting bedding (by right-lateral movement) an average of 3 inches. The fault trace can be projected south to the plant excavation slope, where no deformation of the overburden or overlying Quaternary terrace deposits was found.

Faults #7, 8, and 9, reported on April 30, 1979, and described in Dr. Fred Webb's report (Appendix C), represent three main fault groups located in the CCW pumping station (exhibit 3). All three faults exhibit both lateral and vertical movement and have steep to vertical dips which may change direction of dip from NW to SE along the strike. The dominant sense of movement appears to be that of reverse faulting. Subsidiary faults parallel to, or diverging from, the three main faults apparently developed as dip-slip and oblique-slip faults which strike obliquely across bedding planes and exhibit highly variable dips (for detailed structural geologic report, see Appendix C). Examination of the top-of-rock/overburden contact around the perimeter of the excavation has revealed no offsetting of Quaternary terrace deposits.

Fault #10, reported on June 14, 1979, is located north of the northeast corner of the central service facility in turbine building 2, 267 feet east of the unit 1 north-south baseline and 150 feet south of the east-west baseline (exhibit 2). This is a transverse fault defined by a tight, calcite-healed fracture zone striking N. 30° E. and dipping nearly vertical. It originates at the northern terminus of a series of northerly striking en echelon joints, extends a total of 4 feet, and offsets bedding a maximum of 4 inches.

Summary

Faults #6 and #10 are transverse faults formed by stress relief due to pressure from the northwest and southeast during formation of the Saltville fault family (250 mybp). All others are either thrust or reverse faults which resulted from similar stresses during the same time period (Paleozoic Era). No evidence was found during the investigation of the faults which would indicate that they did not occur in the early tectonic development of the

Paleozoic folding and faulting in this area. The area, having been stable for 250 million years, is not considered to be capable of producing ground offsets or generating earthquakes. Therefore, we do not classify any of the faults as capable, within the meaning of Appendix A to 10CFR part 100.

APPENDIX A

THE UNIVERSITY OF NORTH CAROLINA
AT
CHAPEL HILL

Department of Geology

The University of North Carolina at Chapel Hill
Mitchell Hall 029 A
Chapel Hill, N.C. 27514

August 29, 1978

Mr. Arthur D. Soderberg II
Engineering Geologist
Geologic Services Branch, WMGT
160 Liberty Building
Knoxville, TN 37902

Dear Mr. Soderberg:

At the request of TVA I visited the Phipps Bend Nuclear Plant (Tennessee) on August 25, 1978. The purpose of my visit was to determine if the fault zones within the Sevier Shale at the reactor sites contained minerals which could be dated using standard radiometric techniques. During my inspection of the Phipps Bend site I was accompanied by TVA geologist Mr. William M. Seay.

I examined the several faults exposed in the excavations for the reactors. I also examined a selection of fault zone samples obtained during an early phase of the excavation. In all cases the only mineral found in the fault zone was calcite. It is not possible to obtain a meaningful radiometric age by analyzing calcite.

Cordially,

Paul D. Fullagar

Paul D. Fullagar
Professor

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STRUCTURAL GEOLOGY OF REACTOR BUILDING EXCAVATION

PHIPPS BEND, TENNESSEE

by

Fred Webb, Jr.

This report was compiled and written by Fred Webb, Jr. It is submitted to the Tennessee Valley Authority on May 26, 1978.

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STRUCTURAL GEOLOGY OF REACTOR BUILDING EXCAVATION
PHIPPS BEND, TENNESSEE

Introduction

The Tennessee Valley Authority's (TVA) Phipps Bend, Tennessee, nuclear reactor construction site was visited and studied on May 24, 1978. The purpose of this investigation was to examine and interpret the structural geology present at the reactor building excavation.

Regional Geologic Setting

The site lies within the Valley and Ridge geologic province which is characterized by folded and faulted sedimentary rocks of Paleozoic age. Phipps Bend lies just southeast of the Carter Valley and Saltville faults which are typical Appalachian reverse faults. The Pulaski thrust fault is located approximately 10 miles southeast of the site. The dominant fold in the area is the Bays Mountain synclinorium which has its axis four miles to the southeast of Phipps Bend.

Bedrock units in the environs of the reactor site are mostly southeast-dipping Cambrian and Ordovician carbonates and fine-grained calcareous clastic rocks which make up the northwest limb of the synclinorium. The Cambro-Ordovician carbonate succession present on the north limb and the quartzose sandstones of the Bays Formation present in the axial portion of the synclinorium lie below and above, respectively, the mostly shale and siltstone Middle Ordovician Sevier Formation which forms bedrock at the site.

The Bays Mountain synclinorium is composed of numerous smaller anticlines and synclines with common reversals of plunge direction. Most of the folds in the area are asymmetrical and more steeply dipping northwest limbs. Calcite-filled fractures are present throughout much of the bedrock in the area and most of the Southern Appalachians. There are also numerous small thrust and reverse faults present throughout the region which has, in essence, been deformed by compressive stress that acted along a northwest-southeast line. The age of deformation has been determined to be post-Middle Ordovician and pre-Triassic (Cooper, 1961; King, 1964; Swingle, 1973; Bryant and Reed, 1970; and Lowry, 1974).

Site Geology

Bedrock at the site is mapped as Middle Ordovician Sevier Formation which is composed of dark bluish-gray calcareous shale, siltstone, and very fine-grained impure sandstone. Bedding is thin to very thin and regular. Many calcite-filled fractures are present in most exposures.

Although bedrock generally strikes N.55°E. and dips 20°+ S., there are at least three west-plunging folds present. These folds have orientations that are in harmony with the much larger Bays Mountain synclinorium upon whose northwestern limb they are superimposed.

Many bedding planes in the sequence are marked by slickensided layers of white to light gray calcite that range in thickness from 1 to 20 mm. Although calcite-filled fractures are generally parallel to bedding and may be traced across fold axes where dip directions change, calcite-filled fractures oblique to bedding are also common.

Distinctive lithologies useful for tracing structures and correlation of units are rare. However, as calcite-filled fractures are so persistently confined to bedding planes, it is possible in most instances to delineate structures and correlate units over small distances (up to 140 feet) by careful tracing these fractures.

The geologic map of the site compiled by Gary Hartman, site geologist for TVA, accurately depicts the geology. Discussions in the section of this report detailing structural interpretations are referenced to the draft version of the geologic map (Figure 1).

Interpretation and Discussion of Structures

Specific structural features studied in detail at the site are numbered in sequence anticlockwise from 1 at the east to 3 at the north. Each site (Figure 1) is shown by means of structure sketches in cross section and is discussed separately.

Marked similarity in orientation between Phipps Bend folds and fractures with much larger Bays Mountain synclinorium structures is noteworthy. Classic interpretations of similar occurrences in the Appalachians and elsewhere involve deformation by predominantly flexural-slip folding with concomitant development of drag folds in stratigraphic sequences such as this where shaly rocks are sandwiched between more brittle rocks such as carbonates (the Knox Group) and sandstones (much of the Bays Formation). Figure 2 illustrates the principles of this deformation as given in a standard structural geology textbook by M. P. Billings (1972).

Note that stress in Figure 2 is more effectively transmitted in the overlying and underlying stippled units (representing the Knox and Bays formations, non-respectively) than it is in the intervening shaly unit (the Sevier) which crumples (= drag folds) during Paleozoic deformation that produced the larger folds and faults in the region. Note, too, that units tend to thin on limbs and thicken in axial areas during deformation. This relationship is also important for understanding and interpretation of the Phipps Bend structures.

Drag features of the type present at Phipps Bend have been widely recognized and reported by numerous geologists in the Southern Appalachians. Reports include those of Butts (1940), Cooper (1944, 1961, and 1971), Lowry (1971), and Swingle (1973). Reports of crumpling of shaly rocks such as the Sevier generally indicate the presence of numerous fractures, faults, and calcite-filled veins such as those present at Phipps Bend. Figure 3 shows an example of these phenomena from Virgina. The fracture cleavage shown in Figure 3 was produced by shear stress where more brittle rocks broke rather than yielding by folding as a shaly unit such as the Sevier would.

A model for interpretation of fractures which, if stress application continued after their formation, may experience movement and develop into faults, is shown in Figure 4. Note that this diagram shows both shear joints and tensional joints that develop in response to fold-producing stress. It is also important to note the rotation of joints about the crest of anticlines where shear stress has "dragged" joints that were originally inclined at 90 degrees to bedding.

Price (1966) states that not all of the joints shown in Figure 4 are always formed as conditions that produce joints are dynamic and interrelated. Consequently, early formed joints and structures not only are reoriented by later stress, but also contribute to the reorientation of stress trajectories.

For example: tensional fractures (= joints) that form normal to bedding early in the deformational sequence tend to become rotated is later shear stress is applied (Figure 4). This, as is shown below, may be important in the development of small ramp faults.

Fractures (= joints) and faults that are parallel to bedding tend to be localized in shaly units for considerable distances and break upward more or less normal to bedding for a variable thickness through somewhat more brittle layers into a higher shaly bed which they tend to follow for more distance parallel to bedding. This phenomenon produces ramping of faults, bedding plane faults, wedging, and other features described by Cloos (1964) and shown in Figure 5. Bedding plane faults are known to cover hundreds of feet as reported by Cloos (1964).

Calcite-filled fractures are ubiquitous in the Appalachians. The abundance of carbonate rocks and diagenetic processes that involve dissolution, transport, dewatering, and recrystallization of calcite in particular, are largely responsible for this mineralization. As the Sevier is rich in calcite and relatively fine grained, both the source and the site are favorable for fracture filling by calcite. Specific locations and patterns were controlled by locations and patterns of permeable and impermeable regions within the Sevier. Thus, calcite-filled fractures are limited not only by fracture and fault locations, but also by the distribution of impervious rock.

Site 1

The fault at this site (see structure sketch) is concordant with the orientation of the axial plane of the asymmetrial anticline which it cuts. Although the displacement is difficult to determine, beds on the north limb of the fold do not appear to have been moved more than a few centimeters. The fault is an example of axial plane "cleavage" developed on a mesoscopic scale. Thus, its origin is by shear stress which was produced during Paleozoic tectonism when overlying beds within the sequence were sliding upward toward the crest of the fold in a manner such as that illustrated in Figure 2. This relation of fault orientation to fold axial plane orientation is similar to that described by Swingle (1973) in calcareous siltstones of Knox County, Tennessee.

Site 2

This fault is located approximately 2 meters north of the axial plane of an asymmetrical syncline (north limb dip = 40° S.). Calcite-filled fractures and fault surfaces parallel to bedding were produced by shearing of beds during folding as each bed slid upward, with respect to the bed below it, toward the crest of the adjacent anticline. This is the same principle as shown in Figure 2. Thus, there was shear stress that produced fractures that are incipient small ramp faults such as those shown in Figure 5. As additional folding and slippage along bedding planes occurred, minor displacement of bedding resulted from the shearing motion shown by the disruption of calcite-filled bedding faults truncated by the near-vertical fault here. Calcite-filled fractures of lesser size and near normal-to bedding orientation are of tensional origin. These small tension fractures were formed by the stretching of beds on the fold limb as thinning and thickening as illustrated in Figure 2 took place.

This somewhat indistinct fault extends for less than 20 feet to the east where it dies out on the excavated bedrock bench. Examination of the floor of the reactor site to the west reveals that the fault trace dies out within 15 feet of the excavation wall.

Site 3

The fault at this location is an excellent example of bedding plane faulting that locally breaks across bedding by ramping upwards through beds that are slightly more brittle (see Figure 5). As displacement of overriding beds took place as these beds moved higher toward the crest of the anticline, the space necessary to accomodate the volume change that accompanied the displacement was provided at sites where the fault broke across bedding. A series of these breaks occurred here and, as is shown in the structure sketch, enough space for accomodation of the beds was produced. Thus, a combination of shear faulting along bedding planes and shear and (or) tensional faulting normal to bedding intersect to provide and integrated network of displacement avenues and space.

Conclusions

There is no evidence that any of the faults or joints (= fractures) at the Phipps Bend reactor building site are capable faults. To the contrary, all faults and folds are compatible with the regional geologic setting and exhibit the same style and variety of features produced during the Paleozoic creation of all major Appalachian structures. Specific indications of non-capability include the following:

1) all faults show a relationship to folds that is consistent with a drag fold-induced genesis and are, therefore, related in time to the major folds and faults of the region

2) none of the faults extends into residuum or high-level terrace gravels adjacent to the site on the east

3) the marked parallelism of faults and bedding indicates that the time of fault origin and folding was essentially the same. Folding must have occurred while there was sufficient thickness of overburden (measured in thousands of feet) to provide sufficiently high confining pressure for rocks to deform plastically. Were origin to have been shallow at a geologically more recent time, overburden thickness would have been too thin to generate confining stress needed for plastic deformation and the faults would exhibit marked non-parallelism with respect to bedding and structures.

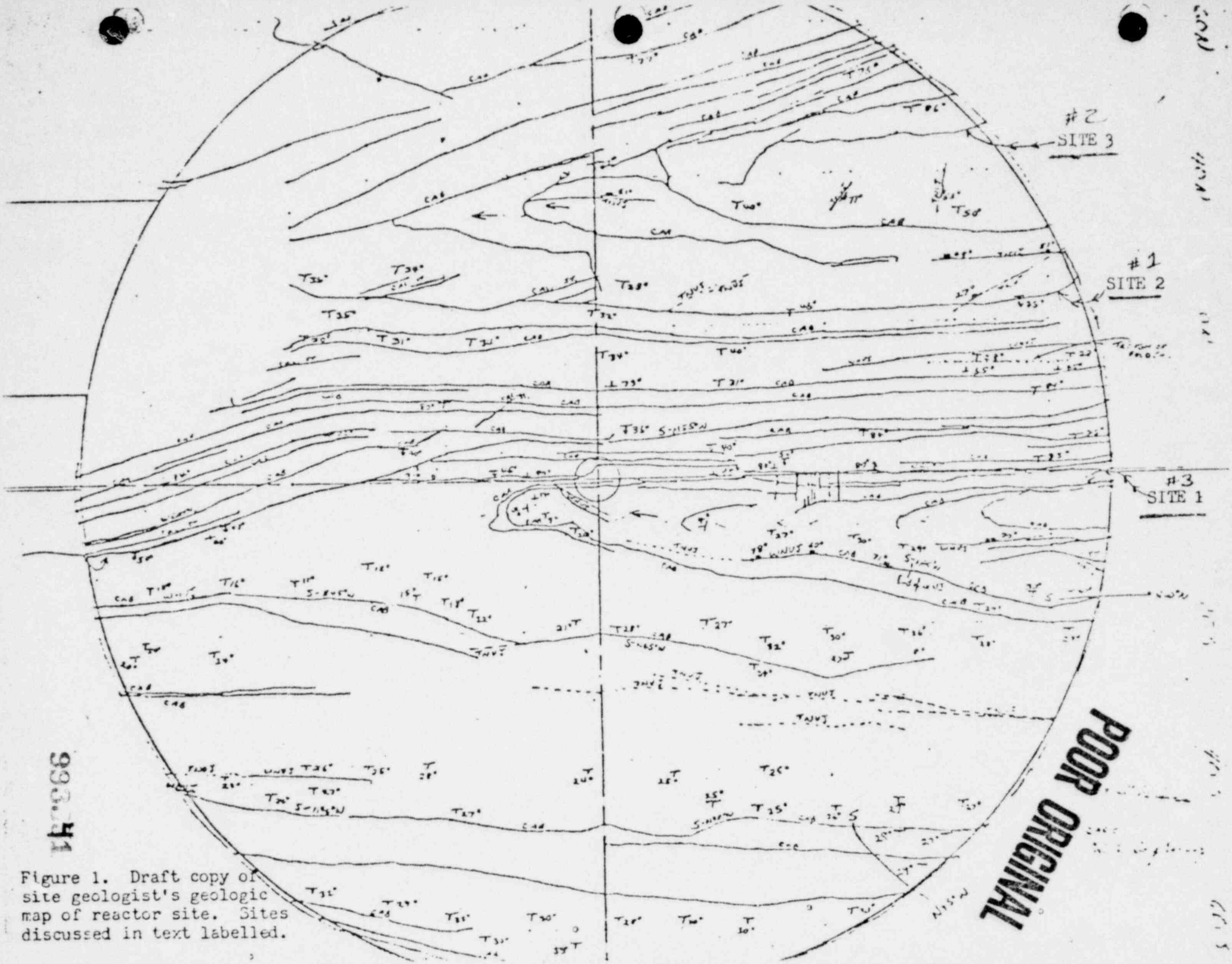


Figure 1. Draft copy of site geologist's geologic map of reactor site. Sites discussed in text labelled.

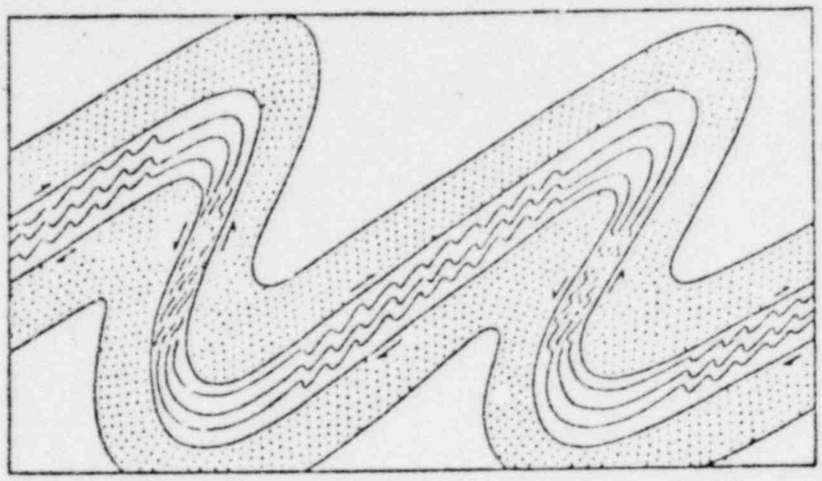


Figure 2. Structure section of overturned folds showing relation of drag folds and direction of shearing. (from Billings, 1972) Note that orientation of folds at Phipps Bend would be obtained with north on right of this diagram.

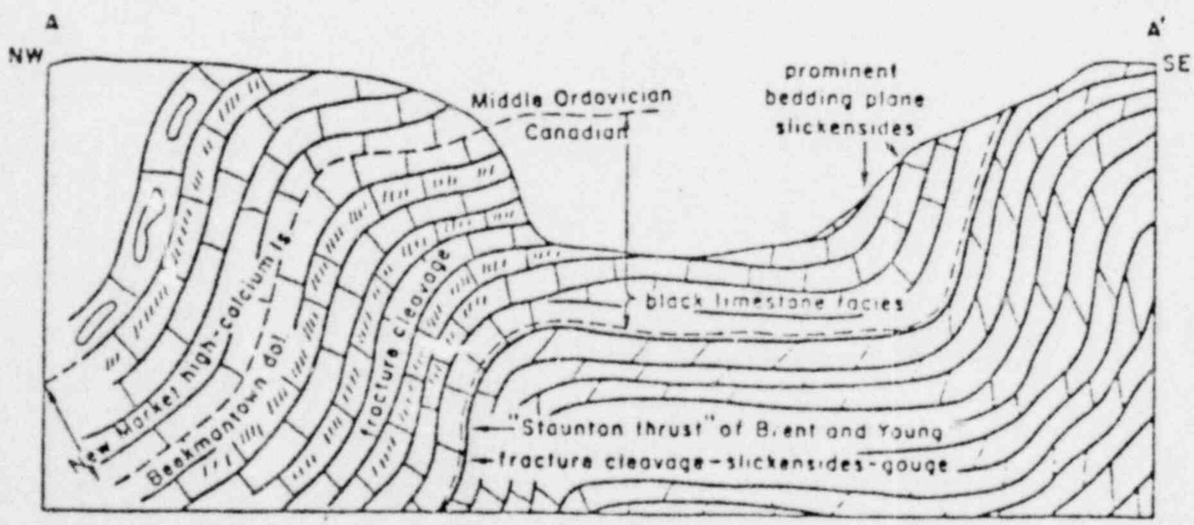


Figure 3. Cross section of Betts Quarry near Harrisonburg, Virginia, showing typical occurrences of shear fracture cleavage and slickensides associated with folding and faulting. From W. D. Lowry, 1971.

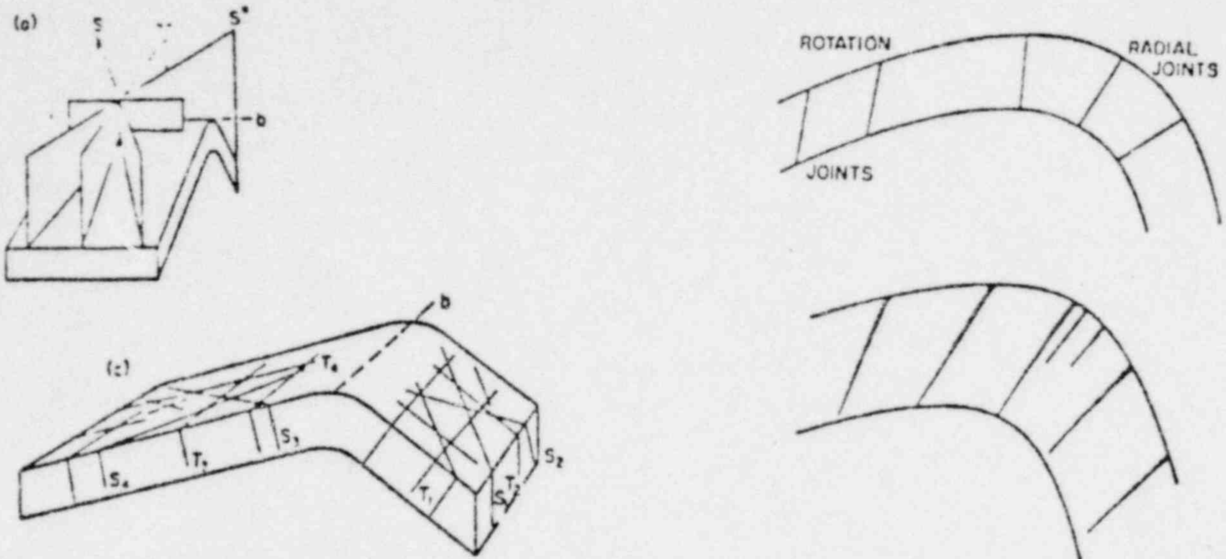


Figure 4. Relation of joint patterns to bedding in folded rocks (Price, 1966). Diagrams at left show 3-D view of shear joints (labelled S_1, S', etc.) and tension joints (labelled T_1, T_2, etc.). The diagrams at the right show radial joints and rotation joints (labelled at top), and axial plane joints filled by mineral deposits (lower diagram).

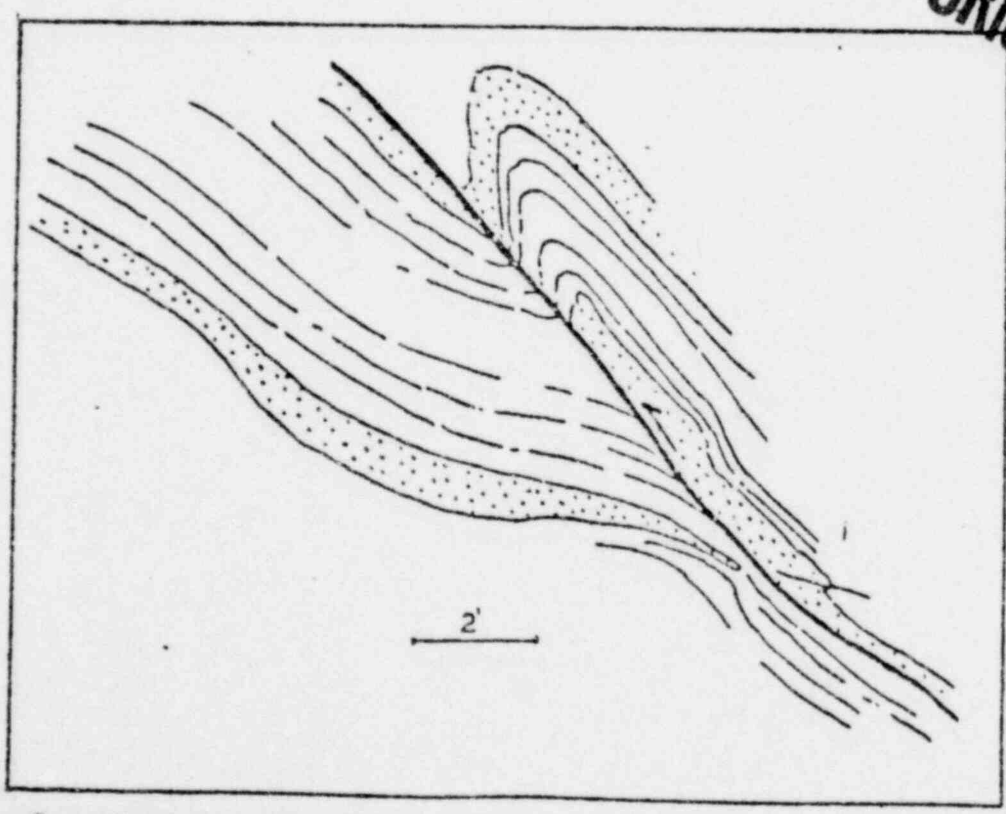
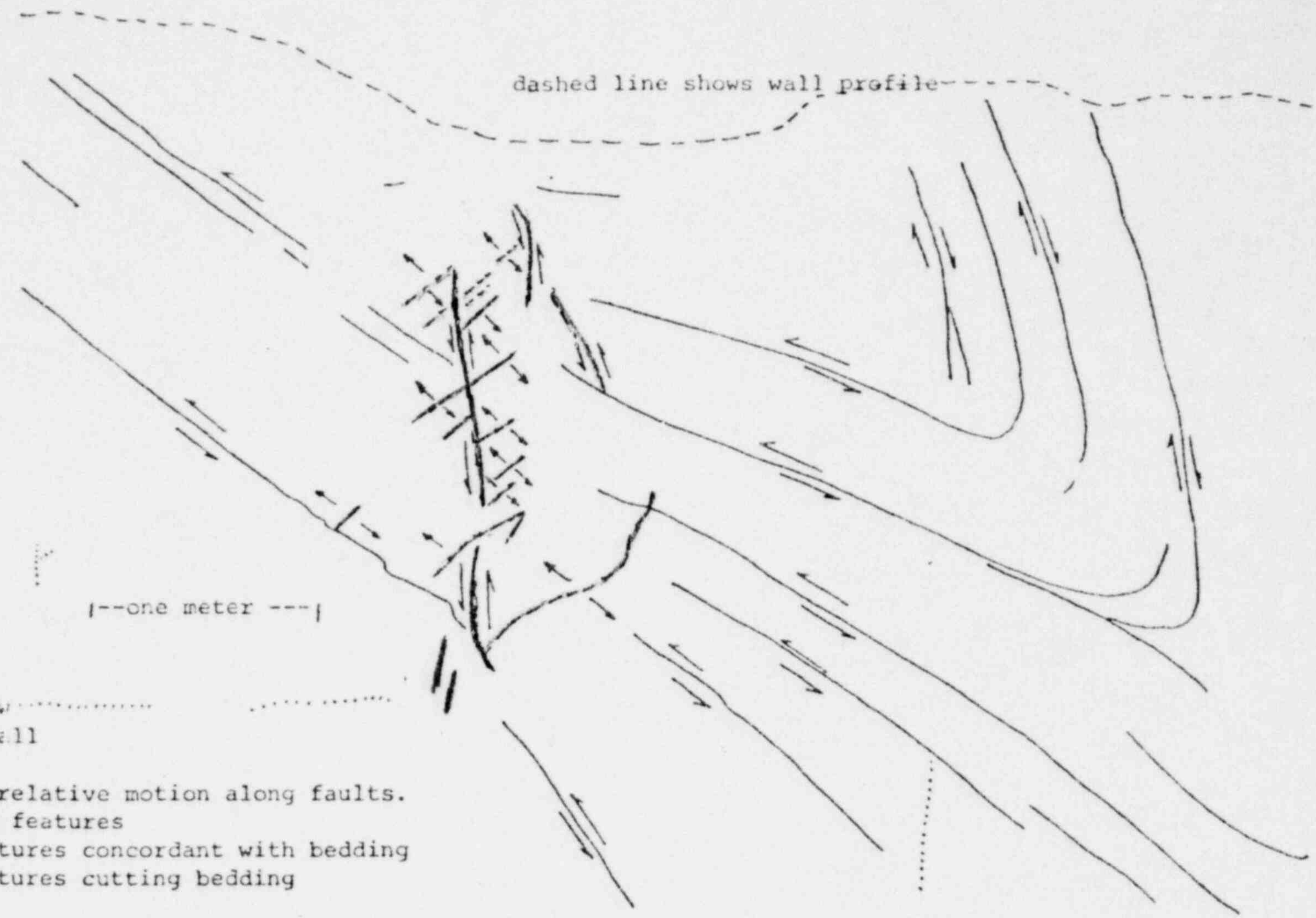


Figure 5. Wedge and fold. Lower sandstone is wedged; upper sandstone, only folded. Wedge may have formed prior to folding because the order of magnitude is different. Road cut east of Hancock, Maryland, Catskill. From Cloos, 1964

Note the migration of the bedding plane fault across overlying bed by ramping.

STRUCTURE SKETCH OF MAJOR FEATURES AT SITE 1. View toward northeast. Arrows indicate relative motion of fault. Dotted lines indicate painted markings of rocks. Most of beds shown are marked by slickensided calcite-filled layers.

STRUCTURE SKETCH OF MAJOR FEATURES AT SITE 2.
View is toward the northeast



dotted lines show ....
paint marks on wall

Arrows indicate relative motion along faults.
—— = tensional features
—— = shear features concordant with bedding
—— = shear features cutting bedding

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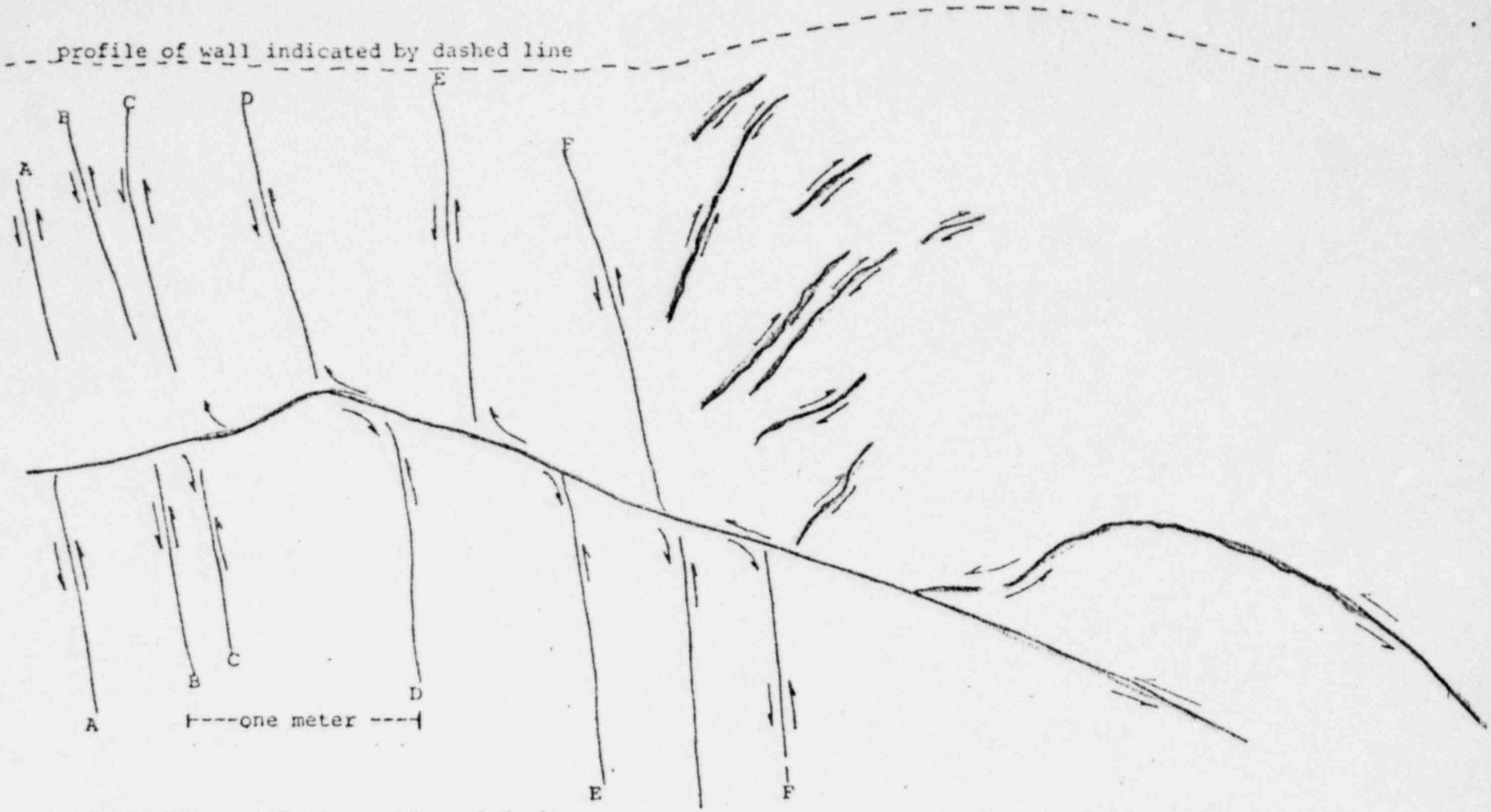
STRUCTURE SKETCH SHOWING MAJOR FEATURES AT SITE 3. View toward the northeast.



Arrows indicate relative motion of faults.
Letters show correlations of bedding plane calcite-filled fractures.
Note how displacement along fault marked in red (▬) decreases toward the north where its displacement is translated into bedding plane motion by ramping upward into bedding plane faults labelled A - F. Faults shown in green (▬) are folded or tilted by drag effect associated with the anticline present here.

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APPENDIX C

STRUCTURAL GEOLOGY OF SEVIER FORMATION FOLDS AND FAULTS
AT PHIPPS BEND NUCLEAR PLANT SITE

Report Submitted to the Tennessee Valley Authority

by

Fred Webb, Jr.

Date submitted by Fred Webb, Jr., PH. D., Geology: May 16, 1979

Fred Webb, Jr.

Fred Webb, Jr.

STRUCTURAL GEOLOGY OF SEVIER FORMATION FOLDS AND FAULTS AT PHIPPS BEND NUCLEAR PLANT SITE

Folds and faults at the CCW Pump Station and Turbine Building 2 sites have developed in response to the same stress system that formed the larger regional structures which include the Saltville Fault to the north and the Bays Mountain Synclinorium to the south. The stress system that produced the structures here and elsewhere in the Southern Appalachians is best described as a dominantly compressive stress that was directed along a northwest-southeast line. The minimum stress axis was approximately vertical whereas the intermediate stress axis was oriented approximately N. 45° E. Fig. 1 illustrates the general relationship of the stress axes to the structural features in the area of the Plant and the Southern Appalachians.

Although the entire sequence of rocks at the sites are classed and mapped as the Sevier Formation, rock types present consist of somewhat non-uniform alternating layers of shale, siltstone, and very fine-grained sandstone. Interbedding of these three lithologies is an important factor in the study of the mechanics of deformation because changes in rock type modify stress distribution and structural behaviour (see Whitten, 1966, p. 211, for example).

The principal mechanism of deformation at the sites is best described as flexural slip (= flexure) folding as described by Ragan (1973), Spencer (1969), Billings (1972), and Whitten (1966). Folds produced by flexure are described as having concentric (= parallel) geometry. Although there are some indicators such as fractures and other planar structures oriented approximately parallel to axial planes of folds, of similar folds at the site, most structures are more closely approximated by the flexural slip origin.

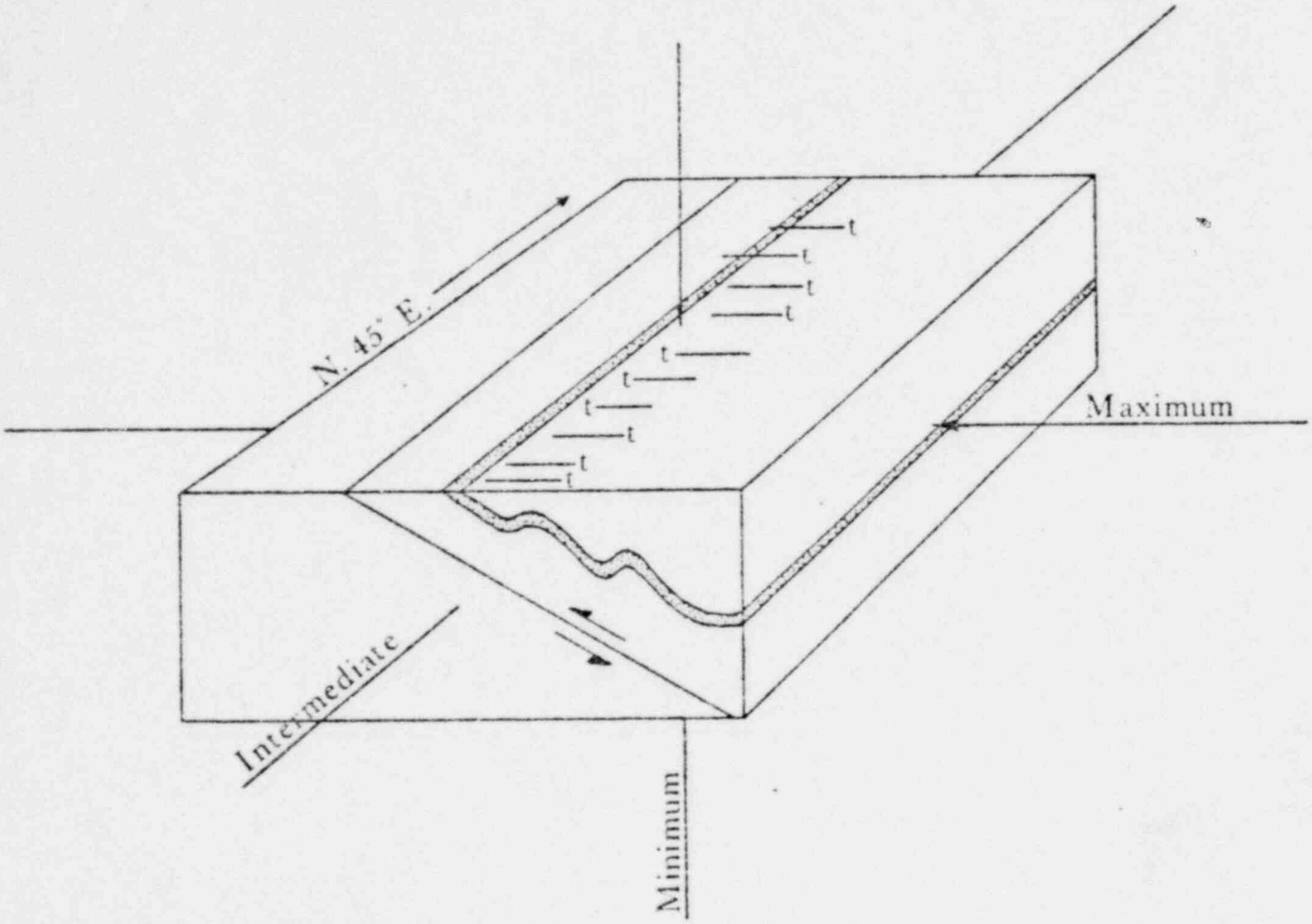

Figure 1. Orientation of stress axes compatible with structural features present in the Phipps Bend, Tennessee, area. Faults and folds are shown diagrammatically. Symbols: t = tensional fractures, arrows show relative motion of fault blocks, and axes are labelled. Modified isometric base distorts right-angle relations.

Characteristics of concentric folds generally include maintenance of both uniform bedding thickness across folds and constant bed length in portions of individual folds (spencer, 1969; Ragan, 1973). During flexural slip deformation, individual beds in the sedimentary sequence are displaced by parallel slip or shear along bedding planes as each layer in the pile shifts upward relative to its underlying neighbor. A commonly cited example of this process is the flexing or bending of a stack of computer cards.

Where well-bedded lithologies are subjected to compressive stresses that exceed the elastic limit of the rocks, stress is accomodated by a combination of methods that include folding, some thickening and thinning, fracturing, and faulting. Gray (1979) describes these strain-accomodation structures in the southwestern Virginia area. The development of strain-accomodation structures results from the movement of incompetent material into potential hinge spaces of folds, development of limb thrust faults, shearing off of beds, and partial hinge collapse (Gray, 1979).

As sandier beds in the sequence are more competent to transmit stress than are the finer-grained shales, the shales are generally transected by more shear fractures that tend to be oriented at acute angles to bedding. Fractures in sandier beds tend to be oriented at nearly right angles to bedding. Thus, the bedding-to-fracture relationship illustrated in Fig. 2 is common.

The tendency for fracture planes to be refracted where passing from beds of differing competencies leads to the development of imbricated limb thrust faults which have curved slip surfaces and stratigraphically variable displacements. Plate 1 illustrates the type of imbrication and variable stratigraphic displacement which are characteristic of the Appalachian region and the CCW Pump Station site. Typical crumpling and faulting that occur as a consequence of partial hinge failure are also shown in Plate 1.

Fig. 1 shows fractures of a tensional origin oriented along northwest-southeast lines. Structures at both sites where tensional origin is probable include calcite-filled gashes and lateral faults of small displacement (such as located at the Turbine Building 2 site). Inasmuch as these features developed during folding and associated thrust faulting, the tensional fractures are locally offset and folded. In other instances, however, tension fractures offset bedding, thrust faults, and folds.

Bedrock at the Plant contains calcite cement and rare beds of limestone. Thus, abundant white, coarsely crystalline calcite is present in most joints, and along bedding planes and faults. This secondary calcite was deposited in these locations by pore water redeposition following dissolution from cement and movement to the present locations. Calcite deposits with slickensides are often indicators of relative directions of movement along faults (Spencer, 1969). Slickensides along bedding or on fractures cutting across bedding indicate that the surfaces on which they are located were active boundaries duirng folding.

The sense of motion provided by slickensides is valid for only the last motion along discontinuity surfaces. Thus, interpretation of slickensides must be done with caution for minor last movement of but a fraction of an inch might mask or obliterate more extensive earlier movement in an opposite direction. Hobbs, Means, and Williams

(1976, p. 303-305) discuss the erasing and overprinting of slickensides. At the CCW Pump Station site, however, most directions of motion indicated by slickensides are compatible with those shown in Fig. 2.

Folds at the sites developed as drag folds such as those shown by Spencer (1969, p. 189 and 201), and discussed by Gray (1979). Continued application of stress produced asymmetrical folds with vertical to locally overturned beds. Consequently, bedding plane and oblique-shear slip surfaces located at vertical to overturned bedding sites show vertical to southward steeply dipping faults as shown in Plate 2.

Thus, south-dipping faults that have apparent normal displacement (as defined by Billings, 1972) are compatible with the regional structural pattern that developed prior to and contemporaneously with the Saltville fault. Complexity of structure is compounded by the general lack of unique marker beds for determination of stratigraphic displacement. Variable angles of fold plunge toward the southwest also complicates structural interpretation through creation of curving outcrop patterns of fault traces and bedding. Fold plunge also creates structural highs and lows over which beds and folds have been displaced with a component of rotational motion. Thus, individual fault displacements are non-uniform with respect to beds and structures that are transected.

In summary, there are no indications of structural features of an origin later than the Saltville fault at the Plant. All folds and faults conform to regional tectonic patterns of Late Paleozoic age.

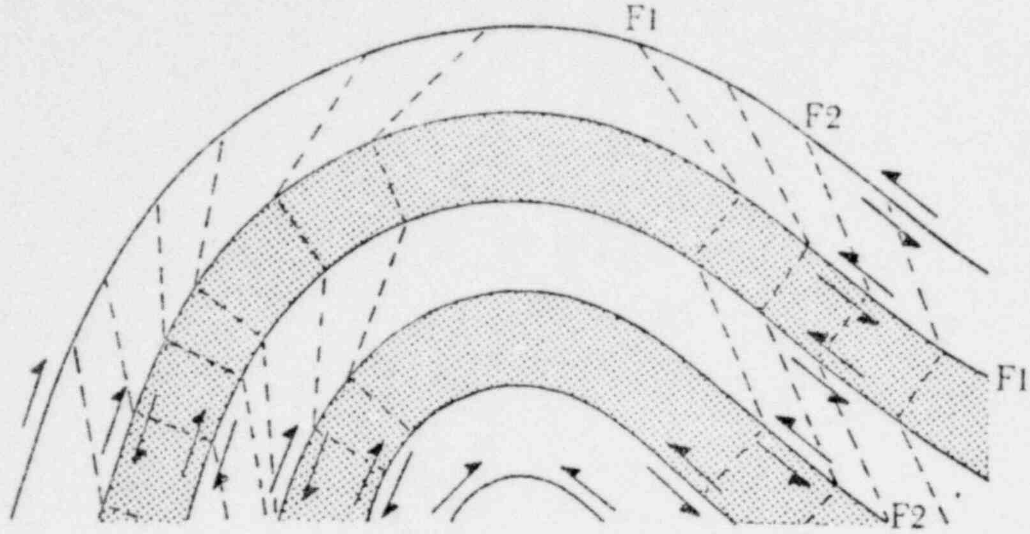

Figure 2. Typical orientation, generalized, of fractures in inter-bedded shales and more competent sandy units. Arrows show relative movement directions along bedding planes during flexure folding; dashed lines, F1 and F2, show two examples of possible thrust fault trajectories. Stippled pattern shows sandy units; other units not marked are shaly beds.

Explanatory Text for Plates 1 and 2

Plate 1 shows three stages in the evolution of faults and folding such as are present at the sites. Chronological order is indicated by numbers 1 - 3 (oldest to youngest). Eventual lines of faulting are shown by dashed lines. Faults are labelled FF and F'. Beds are labelled 1 - 5 for purposes of showing displacement along faults. Note that as folding becomes progressively tighter, bedding plane thrust becomes imbricate as fault F' forms. Arrows show relative motions along faults. Note that bed 2 in the sequence on the hanging wall block is in apparent conformable sequence with respect to bed 1 of the footwall block in places where the bedding plane thrust occurs. However, the imbricate block in stage 3 has considerably more structural discordance across the fault.

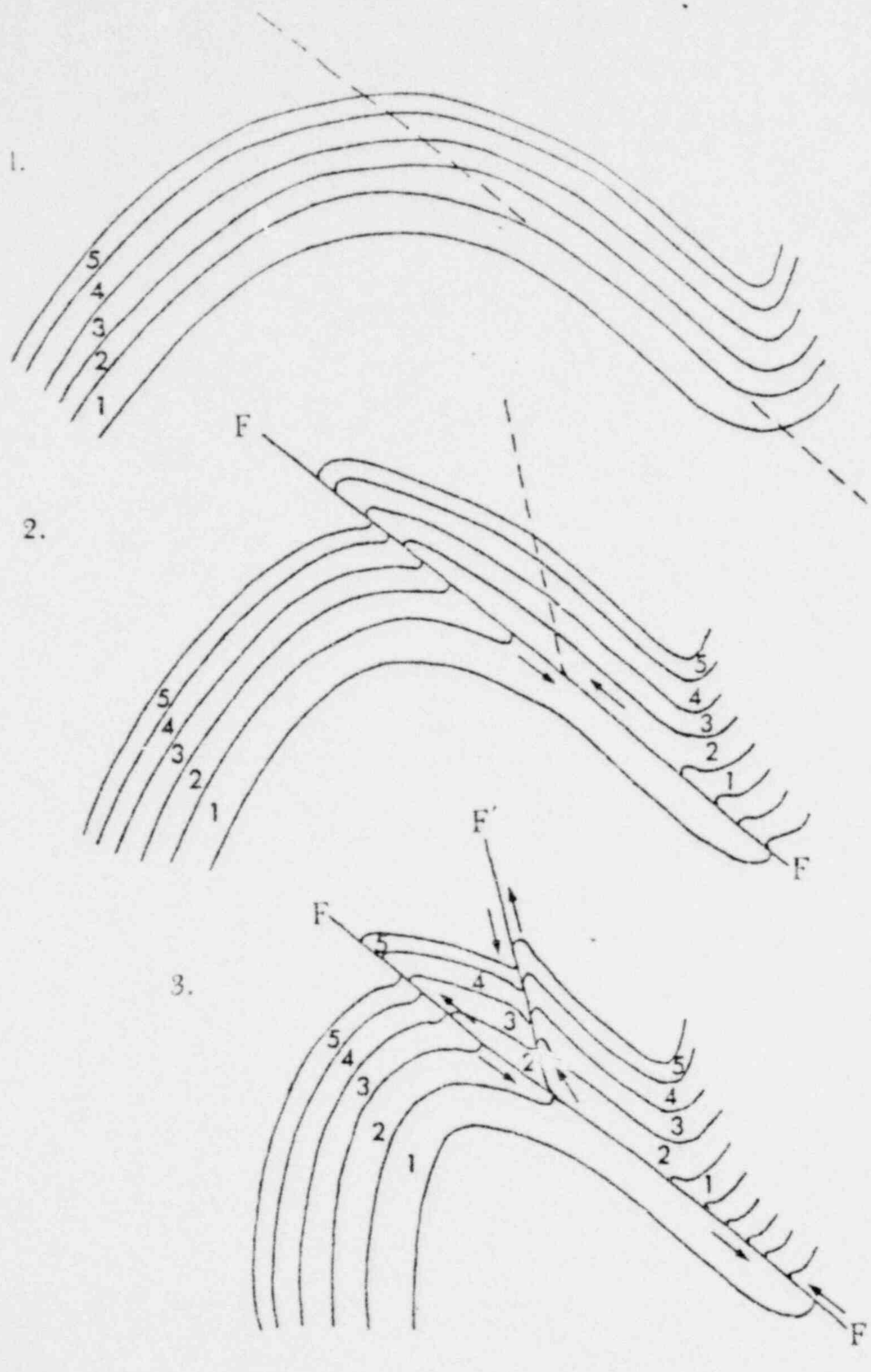

Plate 1. Development stages in formation of imbrication and variable stratigraphic displacement characteristic of the Phipps Bend area. Note crumpling and faulting that occur as partial hinge collapse occurs. FF and F' show faults; arrows indicate movement directions.

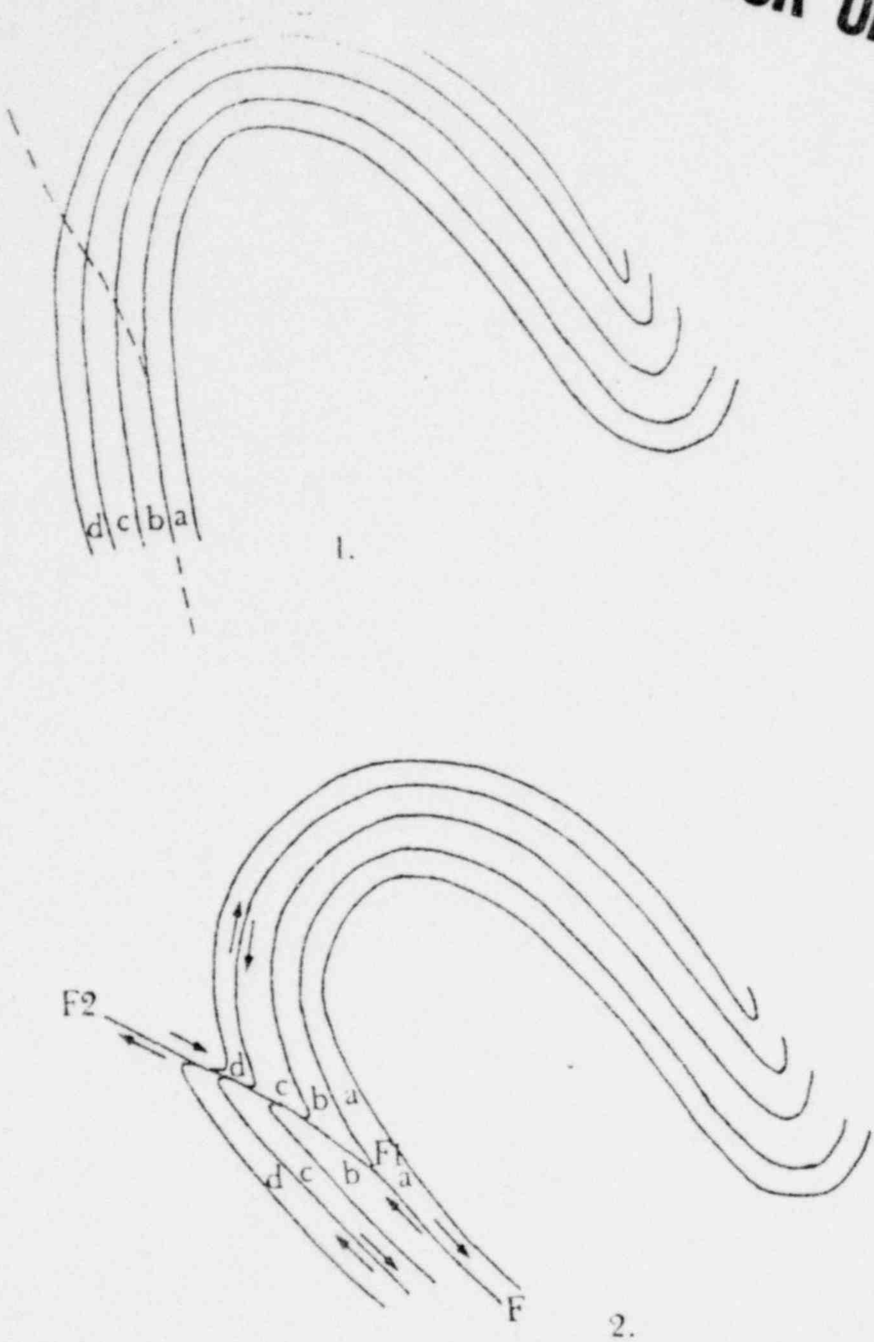

Plate 2. Orientation of oblique-shear and bedding-plane slip surfaces associated with development of strong asymmetry of folds. Top sketch, numbered 1, is initial stage while number 2 sketch is later faulted stage. Note that from F to F1 fault is overturned thrust parallel to bedding and that from F1 to F2 the fault is oblique to bedding. Letters a - d on beds are for matching purposes.

Plate 2 illustrates an initial and final stage in the development of overturned bedding-plane and oblique-shear thrust faults that have an apparent "normal" sense of motion. Note that as the fold becomes tighter the fault labelled F-F1-F2 develops along the line shown as a dashed line in sketch 1. The displacement along the fault progressively becomes more pronounced as the fault becomes oblique to bedding between F1 and F2.

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