Maine Geological Survey
DEPARTMENT OF CONSERVATION
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OPEN-FILE NO. 85-72

Title: Faulting in the Grand Falls Area, Kellyland 15-Minute Quadrangle, Eastern Maine

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Date: 1985

Financial Support: Preparation of this report was supported by funds furnished by the Nuclear Regulatory Commission, Grant No. NRC-G-04-82-009.

Contents: 14 page report

INTRODUCTION

Brittle fracture studies conducted in the Fredericton 2-degree Quadrangle for the U.S. Nuclear Regulatory Commission (Ludman, 1978, 1982) coupled with my bedrock mapping of the past decade (summarized in Osberg and others, in press) have resulted in a much-improved understanding of the general bedrock geology of eastern and east-central Maine. Included in the advances is the recognition of three sets of high-angle faults which trend northeast, north, and northwest. In the past few years, there has been controversy in the Maine geologic community about possible modern offset along faults in this region, specifically in the vicinity of a dam and powerhouse operated by the Georgia-Pacific Corporation at Grand Falls on the St. Croix River (in Kellyland).

The purpose of this study was to examine the bedrock exposures at and near the dam/powerhouse complex for signs of faulting, and to ascertain whether or not there had been recent movement along any faults that might be present. The study was conducted in two stages. The first involved detailed and reconnaissance mapping in the Princeton area during the summers of 1982 and 1983 in order to refine the geologic map in the vicinity of Grand Falls. A simplified version of the resulting geologic map is shown in Figure 1. The second stage was a three-day detailed mapping project carried out at the dam site on November 3-5, 1983. One day was spent at the extensive exposures at and immediately downstream from the dam, and a second at exposures approximately 0.25 miles downstream from the dam (Figure 2). A third day was devoted to traversing the extensive network of lumber roads in the immediate vicinity of the powerhouse, searching for striated bedrock pavements in which offset of striations could give evidence for postglacial fault motion. Only exposures on the United States side of the river were studied in this phase of the project.

Location and Topography

The area studied consisted of a 5/8-mile stretch of the St. Croix River at the Maine-New Brunswick border in the Kellyland 15-minute quadrangle (Figures 1, 2). The dam itself is approximately 9.5 miles north-northwest of the town of Woodland and 6 miles east-northeast of the town of Princeton, at 45° 16' 30" North Latitude, 67° 28' 30" West Longitude. The area near the dam consists of gently rolling NNW-SSE trending hills that stand 60-80 feet above swamp and lake-filled lowlands. Most of the hills are composed of glacial deposits, but lumber operations roads have revealed a few bedrock exposures one to two feet below general ground level on the higher parts of some of the hills. Many of the hills are probably bedrock-cored with a relatively thin glacial till cover across the tops, but actual exposures of bedrock are very scarce. Bedrock outcrops comprise less than 1% of the area near the Grand Falls dam site, but the St. Croix River has cut through the till to expose nearly continuous outcrop in the study area.

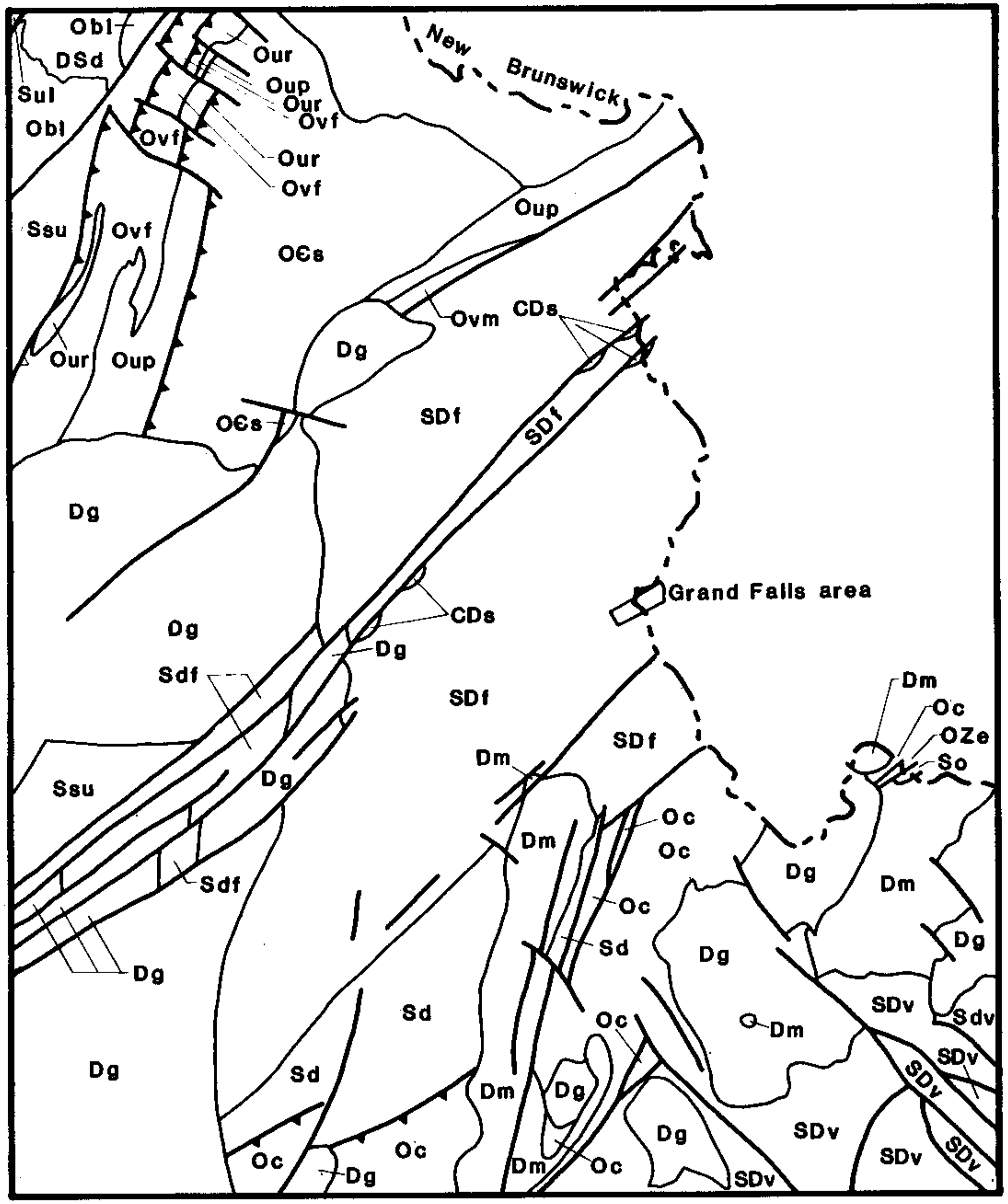


Figure 1a.
Geologic setting of Grand Falls area
(Modified from Osberg, Hussey, and Boone, in press).
Scale = 1:500,000

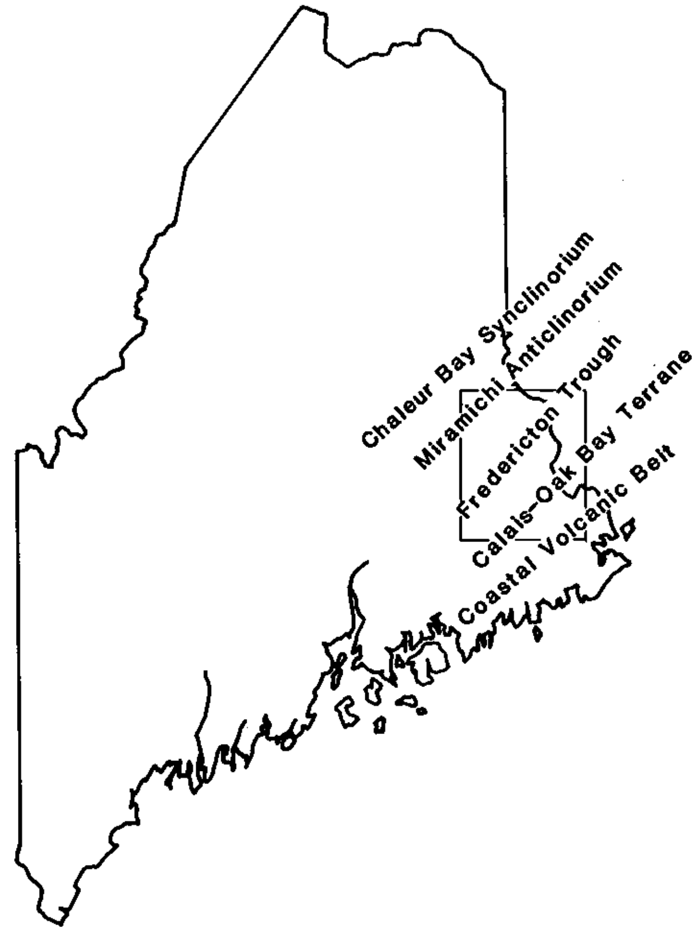


Figure 1b.
Tectonic Map and Index Map
(Area shown in Figure 1a.)

EXPLANATION OF SYMBOLS

Fault

Thrust Fault

Stratigraphic or Intrusive Contact

International Boundary

ROCK UNITS

CDs	Post-Acadian red conglomerate, sandstone, and mudstone
Dg	Granitic plutons, undivided
Dm	Mafic plutons
DSd	Daggett Ridge Formation
SDf	Flume Ridge Formation
SDv	Coastal volcanic sequence, undivided
Sd	Digdeguash Formation
So	Oak Bay Formation
Sul	Unnamed argillaceous limestones
Ssu	Unnamed Silurian(?) sandstones and slates
Obl	Belle Lake Formation
Ovf	Felsic volcanic rocks
Oup	Unnamed pelitic rocks
Our	Unnamed euxinic pelites and sandstones
Ovm	Mafic volcanic rocks
Oc	Cookson Formation undivided
OЄs	"Baskahegan Lake Formation"
OZe	Ellsworth Formation

Figure 1a. Continued.

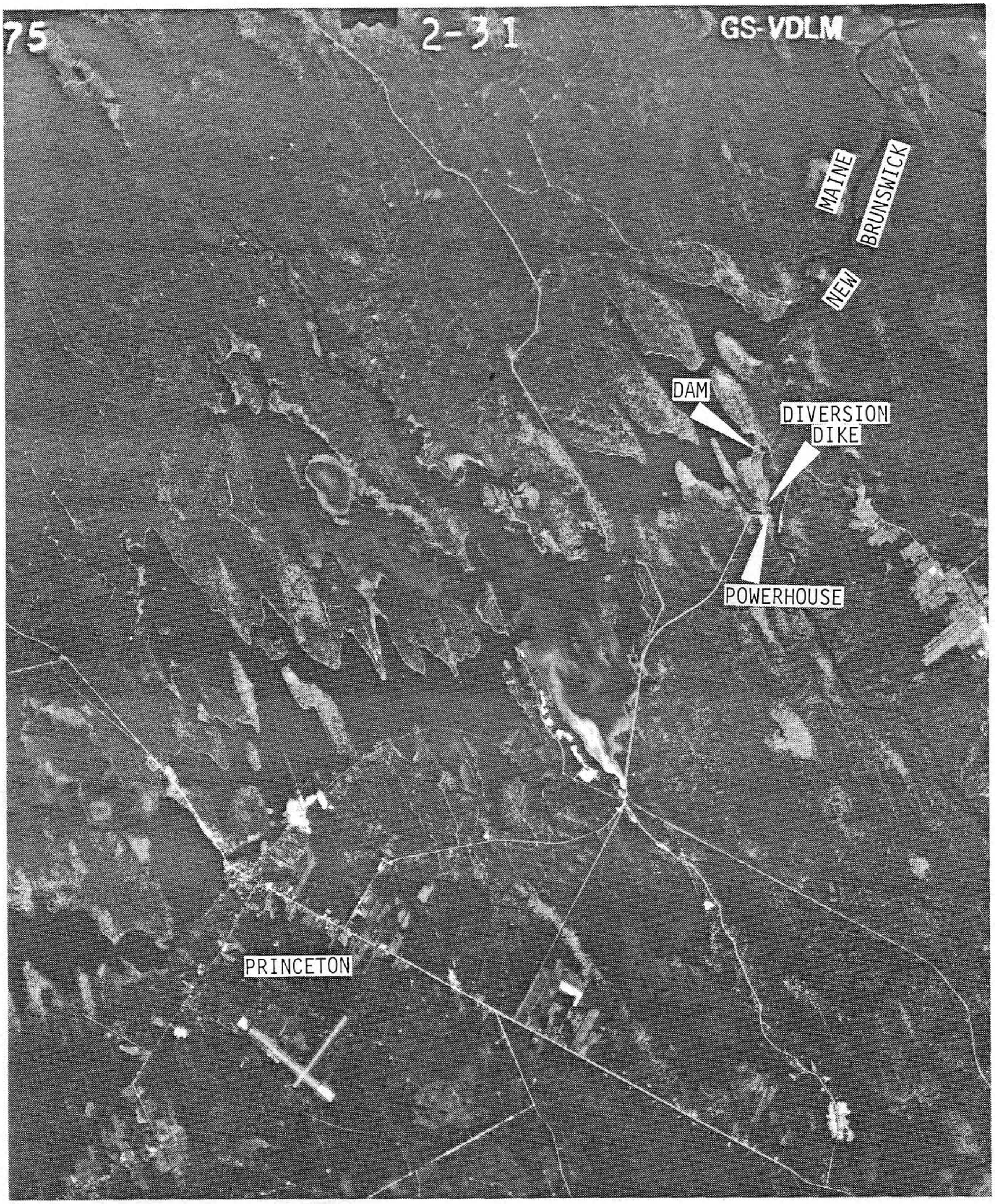


Figure 2.
Aerial photograph of Grand Falls study area and vicinity
Scale = 1:76,250

0 1 2 Miles

The Grand Falls dam is oriented 010-190°, and is at right angles to the flow of the St. Croix River. At Grand Falls, the dam has created an extensive ENE-trending lake system and diverted the flow of the river to an outlet to the southwest where combined lake flowage and river water are channeled through the powerhouse turbines (Figure 2). Just below the dam, the eastern channel of the river makes an abrupt turn and flows nearly due south. There are several such abrupt changes in the course of the St. Croix between the dam and Vanceboro, 15 miles to the north, and several such bends are clearly fault-controlled (Ludman, 1982).

Geologic Setting

The Grand Falls area is situated in the midst of the Fredericton Trough, a 24-mile wide belt of metasedimentary rock of probable Silurian and Siluro-Devonian age (Figure 1). Two units of formation rank are recognized in the Fredericton Trough in eastern Maine. The oldest is the Digdeguash Formation, a unit consisting of non-calcareous polymictic lithic wackes and gray-black slates. It is overlain, apparently conformably, by calcareous micaceous quartzwackes and green-gray slates of the Flume Ridge Formation. Both units exhibit upright isoclinal folds with essentially vertical hinge surfaces. The rocks at the Grand Falls dam and in the vicinity of the powerhouse are typical chlorite-grade metasandstones, metasiltstones, and metapelites of the Flume Ridge Formation.

East-northeast trending faults of the Norumbega Fault System have been traced through the Fredericton Trough by Wones and Thompson (1979) and Ludman (1982; Osberg and others, in press). These faults are high-angle structures with dominant right-lateral separation, although a late stage of dip-slip motion has been postulated (Ludman, 1982). One fault mapped by Ludman (in press) in the Big Lake quadrangle cuts gabbros on Pocomoonshine Mountain and is nearly on strike with the Grand Falls dam. Although it is farther south than the faults generally grouped in the Norumbega System, this Pocomoonshine Mountain Fault is certainly related to the forces that created the Norumbega.

BEDROCK GEOLOGY OF THE GRAND FALLS AREA

The St. Croix River provides extensive exposures of Flume Ridge strata at Grand Falls and for nearly three quarters of a mile downstream to the powerhouse. Exposures are nearly continuous in this stretch of the east channel of the river, but differ markedly in the amount of three-dimensional relief present. Those outcrops near the dam form cliffs up to 25 feet high, and as much as 15 feet of relief is visible near the powerhouse. Between those two areas, outcrops rise only 1-2 feet above the river bed, and are generally covered by the St. Croix River during the spring and early summer. Water level below the dam was extremely low in early November, 1983, so that a continuous traverse could be made along the entire river section between the dam and the powerhouse.

A diversion dike was built in 1983 by the Georgia-Pacific Corporation in an attempt to divert some of the river's spring discharge from the walls and foundation of the powerhouse. This dike is constructed from blocks of intensely fractured, quartz-veined Flume Ridge metasandstones that are among the most fractured Flume Ridge rocks in the region. However, these rocks come from a quarry south of Princeton rather than from the Grand Falls Dam area.

Lithology

Rocks in the river outcrops are variably bedded, orange-brown weathering, gray calcareous metasandstones intercalated with calcareous metasiltstones and greenish gray non-calcareous slates. Beds are mostly in the range of 1-4 inches in thickness, with a few more massive beds up to 2 feet thick. Many of the beds are well enough graded to permit facing direction to be determined. Zones of sandstone and siltstone in 3-4 inch beds alternate with zones characterized by thinner (1/2-1 inch) interlaminated siltstone and slate. A slaty cleavage is well developed in the siltstones and slates, whereas the sandstones exhibit a generally less well-developed cleavage. Bedding is easily recognizable in all exposures except those coated with river mud and vegetation.

Nearly all of the sandstones are micaceous quartzwackes with prominent detrital muscovite flakes oriented parallel to bedding. Most of these rocks are fine-grained sandstones, but a few contain clasts up to 1.5 mm in diameter whose mineralogy can be identified. The coarser rocks are feldspathic wackes, and many similar rocks from the Flume Ridge prove to be volcaniclastic. No detailed petrographic work has been carried out yet on the rocks from the dam site. The orange-brown weathering rind characteristic of the rocks is due to oxidation of finely disseminated pyrite crystals and small ferroan-carbonate grains.

Quartz veins are prominent in the river exposures because of their white color and their resistance to weathering. These veins range from one-eighth inch to nearly a foot in thickness in most cases, and are oriented parallel to either bedding or small-scale faults. Most are parallel to bedding, and many are composite quartz-carbonate assemblages.

Structures

The two areas studied in detail presented very different structural aspects, although at first glance both appeared to be simple homoclinal sequences in which beds strike NE-NNE and dip uniformly to the northwest at 55-70°. The dam exposures proved to be broken by numerous small-scale faults, whereas those outcrops between the diversion dike and the powerhouse exhibit tight to isoclinal folds with little indication of the faults that are so apparent just upstream. Accordingly, the two areas will be discussed separately.

Area 1 - Dam exposures: Beds at the dam vary somewhat in their attitudes, but in general strike NNE and dip steeply to moderately to the northwest. Figure 3 is a stereonet showing poles to 25 beds from a representative study area close to the dam. The spread in the diagram is misleading; attitudes are not random, but are instead controlled by location relative to numerous faults that cut bedding at a high angle and produce drag folds. These drag folds are well defined by both the beds and cleavage, indicating that the faults postdated the upright isoclinal folding of the region. Figure 4 shows the typical relationships, with beds striking approximately 010° far from the faults and dragged into 030-040° attitudes along the faults.

Figure 5 is a stereonet showing poles to faults observed in the northern part of the Grand Falls Dam exposure. The slickensides also shown in Figure 5 clearly indicate the strike-slip nature of the faulting, and the ubiquitous drag folds such as those shown in Figure 4 demonstrate that the faults were dextral (right lateral). The faults are readily identified in the field by a combination of features: systematic rotation of bedding as shown in Figure 4; quartz veins filling the fault zones; small amounts of fine-grained gouge; slickensides; and differential weathering. The fault zones are typically narrow, generally less than 1/2 inch wide, but the secondary porosity provided by the broken rock has permitted enough water flow through the faults to preferentially dissolve the calcareous sandstones in the fault zones. A definite crack or notch develops along the traces of the faults, and is most easily observed in those exposures with the greatest vertical relief. Several individual faults can be traced for 150 to 200 feet across the outcrop.

The faults are unevenly spaced at the dam site. Spacings of 3-8 inches are typical of the more fractured areas, while at other exposures faults are much less numerous and may be as much as 10-20 feet apart. Faults are found throughout the outcrop, however, and are most abundant at the southern end. There, the concentration of faults has produced the largest notch, a "chasm" 20 feet wide and 10-15 feet deep. Faults in the lowest part of this chasm are 3-6 inches apart and are all dextral. Near the almost vertical walls that flank the chasm, the faults are not as abundant, but have produced much wider gouge zones and zones of vein quartz up to 1.5 feet wide. This exceptional relief is not totally natural, and is in part man-made. According to Mr. Ken Gordon, chief mechanical engineer of Georgia-Pacific's Woodland plant, much of the riprap used in building the dam was locally derived. The construction engineers blasted the already badly fractured bedrock at the south end of the exposure, since this material was already partly disaggregated, and removed it to produce the chasm.

Just downstream from the chasm, the river makes an abrupt southward turn. Exposures in this downstream stretch are nearly devoid of signs of the faulting just described. On a quadrangle-scale map, I would map a fault through the chasm. The general 060-070° trend of most of the faults and their dextral strike-slip nature confirm their association with the regional Norumbega Fault System. In some instances the amount of offset

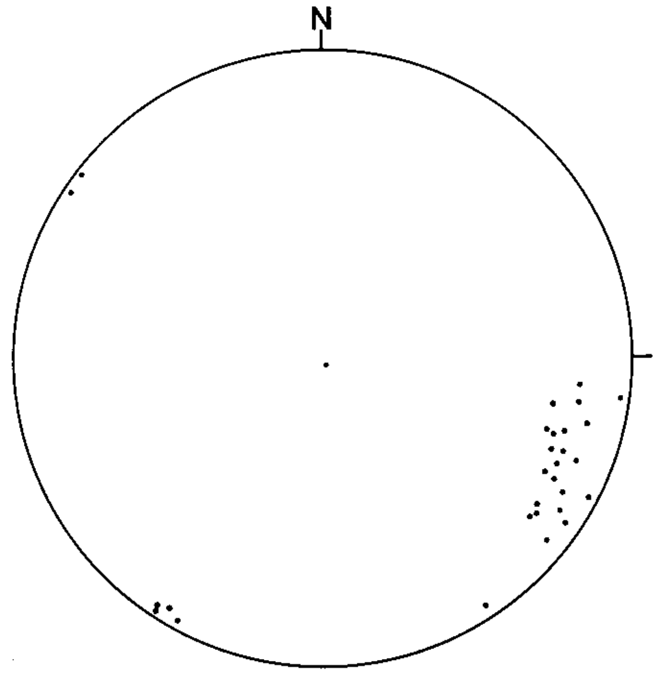


Figure 3.
Stereonet showing poles to bedding from
representative study area near Grand Falls Dam.

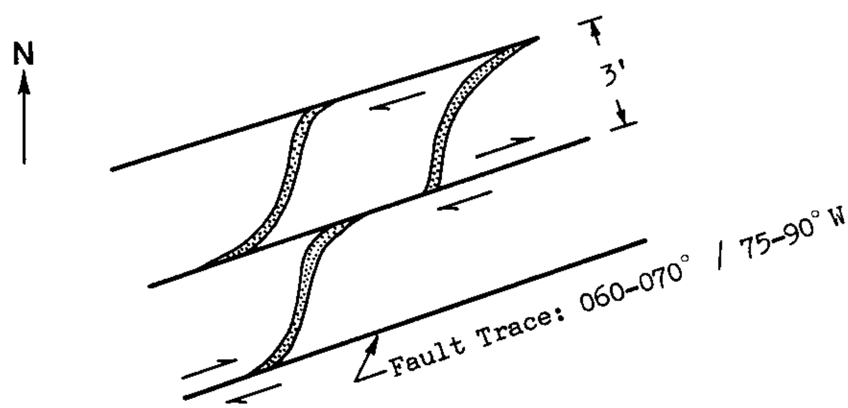
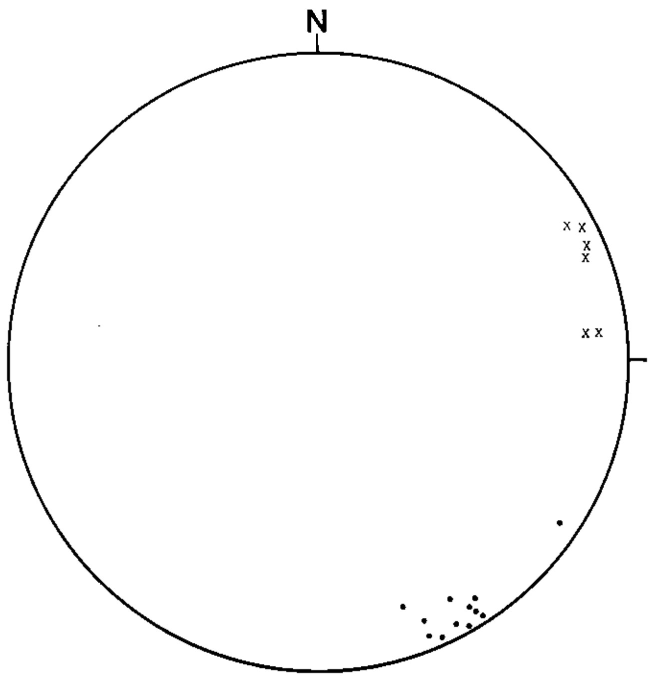


Figure 4.
Sketch showing typical drag folds
at Grand Falls Dam (Map view).



• = Poles to fault planes

x = Slickensides

Figure 5.
Stereonet showing attitudes of fault planes and slickensides from representative area at Grand Falls Dam.

on the small-scale faults visible at the dam can be estimated; but in most cases this is not possible. Separations of a few inches were measured in some of the small faults near the dam; and in one of the faults that bordered the chasm, as much as eight feet of separation may have occurred.

The east-northeast trending lowland occupied by the chain of lakes that empties into the St. Croix River at the powerplant is probably produced by differential erosion of rocks broken by faults related to those mapped at the dam. Some indications of continuation of this fault group beyond the dam into Canada is provided by lineaments on the aerial photographs of the area (Figure 2) and on Landsat imagery for the region. In my compilation of the Fredericton 2-degree quadrangle for the new state geologic map, I did not show a fault through this lowland (Osberg and others, in press). I would be tempted to do so now, if I could show it as a dashed line.

Area 2 - St. Croix River between the diversion dike and the powerhouse: Just downstream from the diversion dike, the St. Croix River's eastern channel is itself split in two by a small wooded island. The westernmost channel thus created is a narrow steep-walled bedrock gorge with 15-20 feet of relief, while the easternmost is much broader, has numerous low-relief outcrops, and is bordered by glacial and fluvial deposits. Although the bedrock exposures are continuous in both channels, the western one was chosen for detailed mapping because of the freshness and greater relief of the outcrops.

One of the most striking features of this area was the total absence of faults comparable to those visible at the dam exposures just a few hundred yards upstream. About ten joints with attitudes parallel to those faults were measured in this second area, but no offset was apparent across them, no quartz veins were present in them, and no slickensided surfaces were associated with them. The dominant structural features visible in this area were large south-plunging isoclinal folds (Figures 6, 7). Much of the exposure is part of a large isoclinal anticline that plunges moderately to the south and has a moderately to steeply dipping hinge surface inclined to the west (Figure 7). Only where the fold nose has been preserved is this structure apparent, as the two limbs are so nearly parallel to one another. Toward the southern end of this study area, however, the nose is well exposed in two places, permitting direct measurement of the plunge and trend of the hinge, and measurement of several bedding/cleavage lineations (Figure 7). Part of a syncline is preserved to the east of the major fold, but is cut off by a quartz-filled shear zone with an attitude of 038°/vertical. The hinge surface of the anticline can be traced along the outcrop for a distance of over 100 feet, and shows several gentle undulations in that distance that are probably related to small-scale shear zones. Graded bedding exposed in one of the outcrops of the fold nose indicates that the anticline and syncline are both upright.

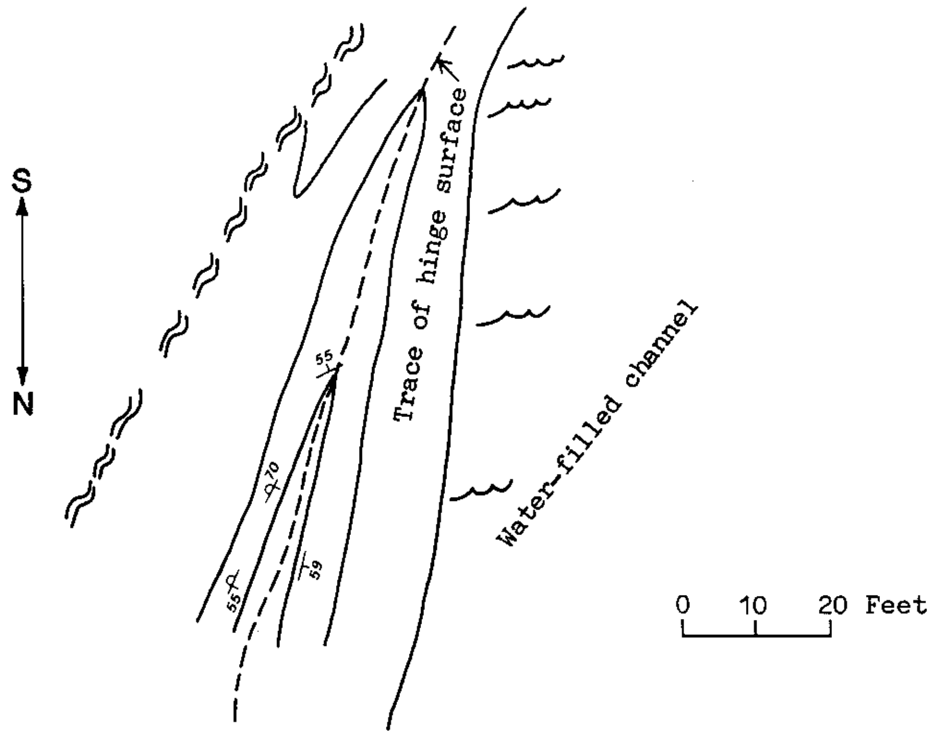


Figure 6.
Sketch showing structural relationships between diversion dike and powerhouse.(Map view)

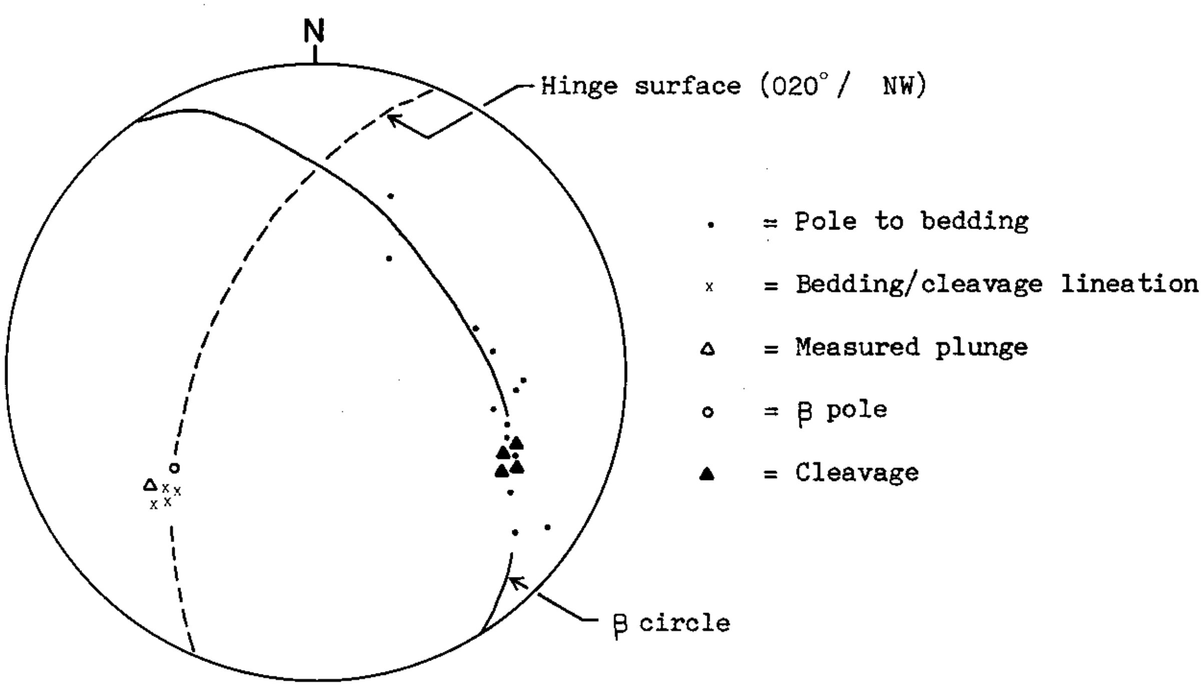


Figure 7.
Stereonet of poles to bedding from. major isoclinal anticline shown above.

AGE OF FAULTING

Since the principal objective of this study was to determine whether fault displacements are occurring in this area today, special attention was paid to detecting signs of post-Pleistocene movements. However, no evidence of recent faulting was found.

Examination of the dam and the foundation of the powerhouse showed no visible signs of offset attributable to faults. No tremors were felt in my three days in the area, and no dust was seen rising from the fault zones. Unfortunately, there are very few pavement exposures close to the dam on the U.S. side of the border that preserve glacial striations, but those few that have been found do not exhibit postglacial offsets. Similarly, in my ten years of mapping in eastern Maine, I have seen no clear-cut offset of glacially striated pavement outcrops.

The faulting in area 2 (between the diversion dike and the powerhouse) is probably related to the isoclinal folding itself, and is most probably of Acadian (Early Devonian) age. The ENE-trending faulting visible at the dam exposures, however, is clearly younger than the isoclinal folding of the Flume Ridge Formation. One branch of the related Norumbega Fault cuts the Bottle Lake Pluton and is thus definitely younger than Early Devonian. In adjacent New Brunswick, Mississippian sedimentary rocks are cut by the Fredericton Fault (a continuation of one of the Norumbega branches), but Pennsylvanian strata are seemingly unaffected by it (Rast, personal communication). These regional considerations suggest that the movements along the Norumbega and related faults were dominantly post-Early Devonian through Mississippian. My own belief is that most of the strike-slip separation along the Norumbega faults had ended by the time that the Bottle Lake Pluton was emplaced, and that the fault zone traced through that pluton represents one of the last movements. The last stage of movement along the Norumbega faults was probably a Late Mississippian dip-slip reactivation of the system.

Analysis of topographic maps for the area suggests the possibility, albeit very weak, of recent offsets. Figure 8 is a somewhat reduced version of portions of the Kellyland and Waite 15-minute qudrangles in the vicinity of Grand Falls, and shows the distribution of glacial hills whose contour lines might be interpreted as indicating sinistral offset along faults parallel to the Norumbega system. Alternate contouring, however, might remove these apparent offsets. That Norumbega-related faults are present in the Grand Falls area is unarguable, but the sinistral sense of separation is contrary to all the evidence collected at the dam and described above. These apparently offset hills probably do not represent postglacial deformation.

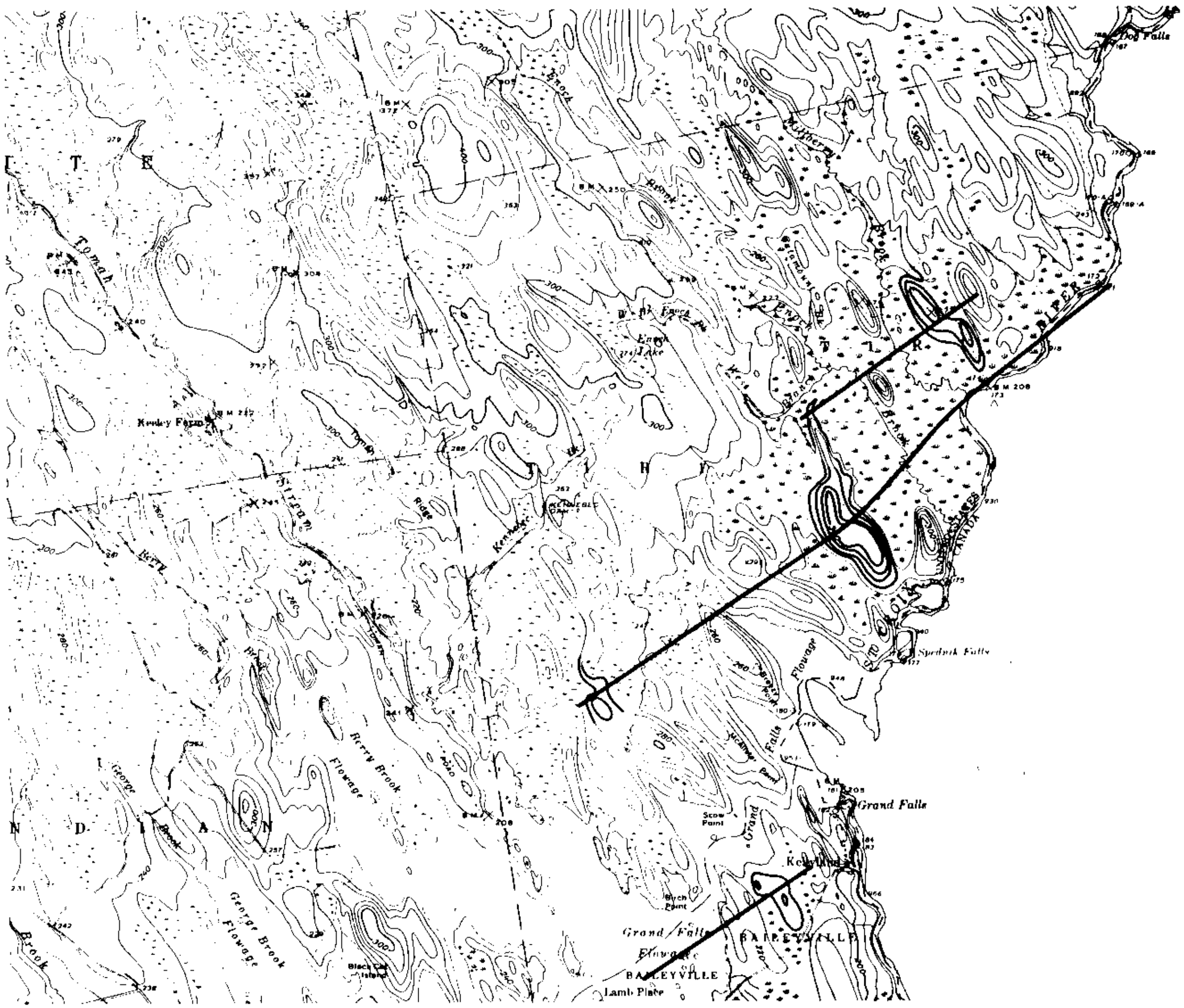


Figure 8.
Portions of Waite and Kellyland Quadrangles (reduced scale) showing possible offset hills and faults inferred through these areas.

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