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Walter A. Anderson, State Geologist

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Title: The Geology of the Passamaquoddy Bay Area, Maine and New Brunswick

Author: Olcott Gates

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SUMMARY

The compilation of a geologic map of the Passamaquoddy Bay area, located on the Maine-New Brunswick border, has provided basic geologic information bearing on the origin of recent seismicity and downwarping in that area. Sources include published maps and reports by a number of geologists, and unpublished mapping for the Maine Geological Survey carried out in part under contract with the U.S. Nuclear Regulatory Commission.

Since the Silurian period, the Passamaquoddy Bay area has been an anomalous part of the northern Appalachians. During the Silurian and Lower Devonian periods, a section comprising as much as 7,000 meters of marine volcanic rocks accumulated in a subsiding extensional fault-block tectonic regime. During the Acadian orogeny that followed, a broad open syncline formed, which trends north-northwest at right angles to the prevailing northeast strike of Acadian folding. In Upper Devonian time, the area was the site of a downfaulted alluvial basin in which coarse conglomerates containing clasts of the underlying volcanics and the granites that intruded them were deposited. Similar basins do not occur elsewhere on the east side of the Appalachians. During the Carboniferous or perhaps the early Triassic period, a major north-northwest trending fault, the Oak Bay Fault, offset the older rocks. This fault has a net slip that plunges about 45° to the north-northwest in the plane of the fault, with a vertical component of about 2 km (east side down) and a horizontal left-lateral component of about 2 km. During the Carboniferous, east-northeast striking faults that extend into central New Brunswick divided the area into separate fault blocks, each with its characteristic lithologies and structural style. In general, the geologic history of the Passamaquoddy Bay area during middle and late Paleozoic time suggests repeated subsidence oriented across the regional northeast-striking structural grain.

Geophysical studies show that this anomalous geologic behavior is reflected in the current seismicity, Bouguer gravity, and aeromagnetic pattern. Many of the recent earthquake epicenters tend to form a lineament with a northwest to north trend parallel to the Oak Bay fault, and in most cases near it. A slightly positive, relatively flat Bouguer gravity field forms an embayment oriented northwest beneath the Oak Bay area. A very steep positive (to the southeast) gravity gradient lies along the coast south of the Bay area and abruptly ends on Campobello Island. The steep gravity gradient extends southwest for 175 km beneath the Gulf of Maine and has been interpreted as a boundary between a block of relatively dense Precambrian and underlying rock beneath the Gulf of Maine and a less dense block of Paleozoic rocks overlying Precambrian basement in coastal Maine.

The aeromagnetic pattern suggests a 25 km left-lateral northwest-trending crustal displacement based on the offset from Campobello Island to Grand Manan of the linear magnetic pattern associated with the Precambrian Coldbrook volcanics. This offset also cuts off the steep coastal gravity gradient.

The current rapid downwarping of the Passamaquoddy Bay region is part of a much larger area of wave-like crustal warping extending from the Bangor, Maine area through New Brunswick and Nova Scotia. A trough of subsidence in this wave-like pattern occurs in southern and central New Brunswick. Whatever crustal stresses are causing this regional subsidence must also be causing the subsidence in the Passamaquoddy Bay area, but the rate of 0.9 cm/year is almost three times that of the subsidence in adjacent southern New Brunswick.

The hypothesis that the comparatively rapid downwarping in the Passamaquoddy Bay area is the result of a weak underlying crust is proposed here. The thick accumulation of Silurian-Lower Devonian volcanic rocks, the subsequent development of the Upper Devonian Perry fault basin, the many faults ranging in age from Silurian to Triassic, the anomalous orientation of the Oak Bay fault across the regional structural grain, and the numerous small earthquakes indicate that the crust beneath the Bay area has had a long history of subsidence and weakness. This relatively weak crust presents less elastic strength to the vertical stresses causing the broad regional subsidence in eastern coastal Maine and New Brunswick.

INTRODUCTION

This report summarizes the bedrock geology, geophysical studies, and geologic history of the Passamaquoddy Bay area in eastern Maine and adjacent New Brunswick. Its purpose is to provide geologic data bearing on the causes of the current crustal downwarping in that area. Sources used in this study include published maps and reports by many geologists, and unpublished results of mapping by the writer for the Maine Geological Survey, in part under contract with the U.S. Nuclear Regulatory Commission. In a few instances where there are differences of opinion about the stratigraphy or structure, I have used the most detailed or the most recent mapping supplemented by my own reconnaissance.

The accompanying geologic map (Plate 1), the correlation chart (Figure 1), the schematic cross-section of the Eastport region (Figure 2), and the geophysical maps (Figures 3, 4, and 5 present the basic data. The following text explains and amplifies the information shown on the figures. For details of specific areas and rock units the reader should consult the publications listed in the references.

STRATIGRAPHY

Stratified rocks of Precambrian, Ordovician, Silurian, and Devonian age are exposed in the Passamaquoddy Bay area. They can be divided on the basis of major hiatuses into three groups: pre-Silurian, Silurian and Lower Devonian, and Upper Devonian. Figure 1 summarizes the pre-Upper Devonian stratigraphy.

PRE-SILURIAN STRATIGRAPHY

Precambrian. The Coldbrook Formation crops out in the northeastern part of Campobello Island (McLeod, 1976). The Belle Isle fault separates the Coldbrook Formation from the Lower Silurian Quoddy Formation except for one small area (see Plate 1) where McLeod (1976) reports that the Quoddy Formation unconformably overlies the Coldbrook. The Coldbrook Formation continues northeastward along the south side of the Belle Isle fault to the St. John, New Brunswick area, where it is unconformably overlain by fossiliferous Cambrian rocks.

The Coldbrook Formation consists of completely recrystallized quartz-feldspar-biotite volcanic rocks and thinly-bedded fine-grained tuffaceous sediments (McLeod, 1976). The unit has undergone two episodes of metamorphism and three phases of deformation of probable pre-Silurian age.

Ordovician. The Cookson Formation occurs in the Calais-St. Stephen area north of Passamaquoddy Bay, and it or its equivalent extends westward to at least Penobscot Bay. Graptolites found on Cookson Island in Oak Bay establish a Lower Ordovician age. The base of the formation is not exposed, but on Cookson Island it is overlain unconformably by the Silurian Oak Bay conglomerate (Ruitenberg, 1967). It is composed of black slate, phyllite, quartzite, and minor basalt flows (Ruitenberg, 1967; Ludman, 1978). Regionally it is in the greenschist metamorphic facies, but in contact metamorphic zones around Acadian plutons the rocks are converted to staurolite-andalusite schists.

SILURIAN-LOWER DEVONIAN STRATIGRAPHY

The Silurian-Lower Devonian marine volcanic sequence is exposed on both sides of Passamaquoddy Bay in Maine and New Brunswick. It is part of the Coastal Volcanic Belt (Boucot, 1968) which also crops out to the west in the Mt. Desert Island area, Penobscot Bay and near Newbury, Massachusetts. Bastin and Williams (1914) initially mapped the Eastport Quadrangle and named the formations there. The following brief descriptions of the various formations are organized according to age from oldest to youngest. Figure 1 illustrates the probable correlations.

Lower Silurian. The Quoddy Formation underlies the Quoddy fault block south of the Lubec fault zone in Maine (Gates, 1975) and south of the Beaver Harbor fault on Campobello Island (McLeod, 1976). Graptolites establish an Upper Llandovery age (Gates, 1975). Neither the top nor the bottom of the formation is exposed in Maine, but McLeod (1976) reports that the Quoddy Formation unconformably overlies the Coldbrook Formation on Campobello. In Maine, the Quoddy Formation is composed dominantly of pyrite-bearing and rusty-weathering black siltstone and siliceous argillite with feldspathic ash beds. Volcanic rocks, including basaltic and rhyolitic flows and tuff-breccias, become predominant to the southwest and upwards in the section. On Campobello Island turbidite beds are

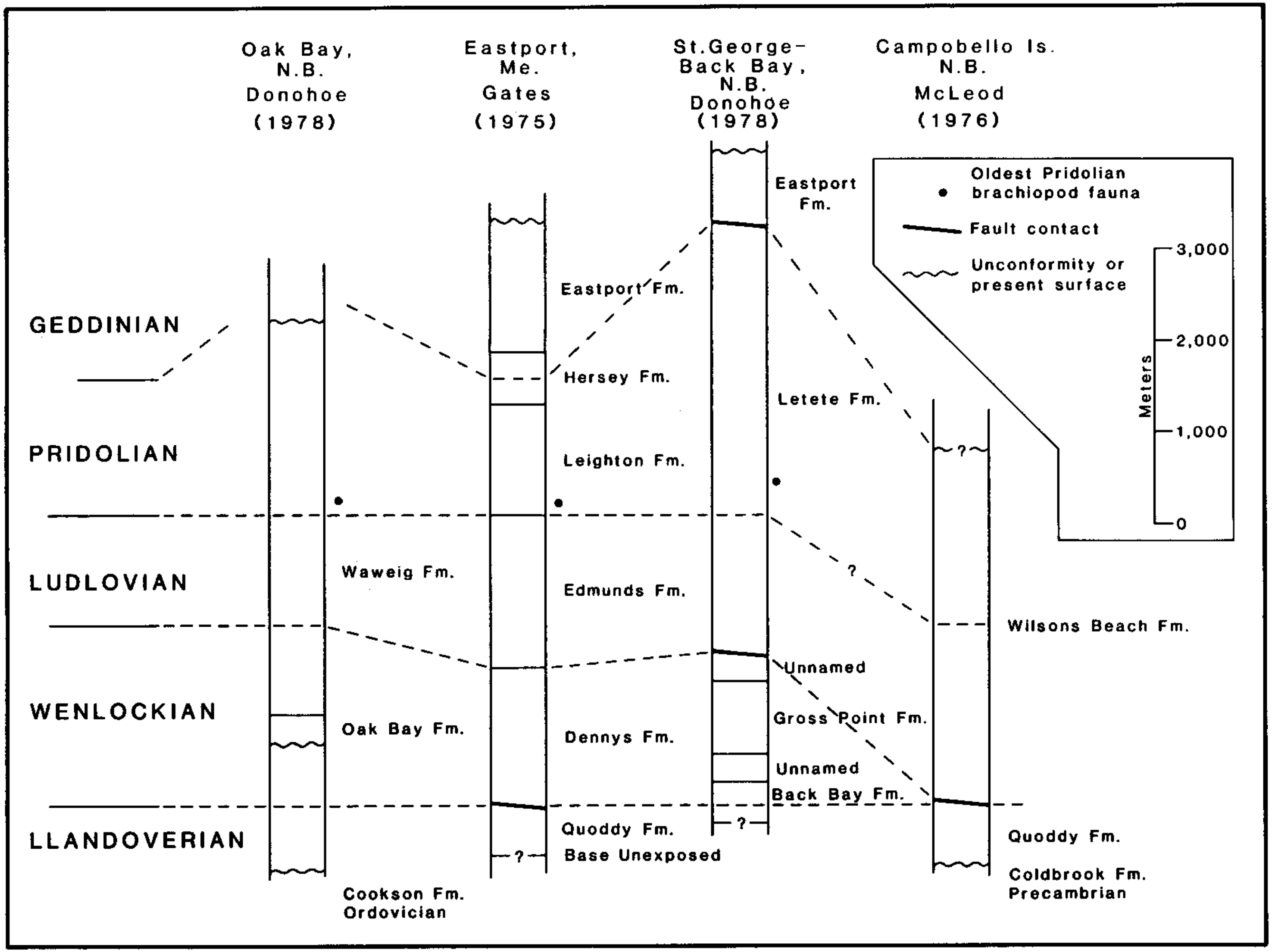

Figure 1. Correlation of the Silurian - Lower Devonian stratified rocks in the Passamaquoddy Bay area. (Adapted from Gates (1975), McLeod (1976), and Donohoe (1978))

interlayered with volcanic rocks (McLeod, 1976). Rocks similar to those of the Quoddy Formation ("Su" in Plate 1) occur inland north of Dennysville, Maine, but are too poorly exposed to make lithologic correlation certain.

Middle Silurian. The Dennys and Edmunds Formations in Maine crop out in the large Cobscook anticline north of the Lubec fault zone. A diverse marine fauna of brachiopods, gastropods, trilobites, and corals suggest Wenlockian and Ludlovian ages respectively (Berry and Boucot, 1970; Gates, 1975). The two formations consist of a varied suite of marine volcanic rocks including basalt flows, rhyolite flows and domes, coarse tuff-breccias, and bedded tuffs together with interbedded fossiliferous shales and siltstones. The proportion of basaltic rocks is higher in the Dennys Formation than in the Edmunds.

Between the Back Bay and Letang Harbor faults in New Brunswick, Donohoe has mapped four units, the Back Bay and Gross Point Formations and two unnamed volcanic units, all of which have been combined under the Gross Point Formation symbol on Plate 1 because of the small map scale. They contain volcanic rocks, both flows and tuffs, interbedded with shales, siltstones, and limestone. A very sparse brachiopod fauna suggests a Lower to Middle Silurian age (Donohoe, 1978). Compared to the Quoddy and Dennys Formations, with which Donohoe correlates them, the four units have less volcanic material and more detrital and carbonate rocks. It is probable that the New Brunswick section is the distal equivalent of the Quoddy and Dennys Formations deposited further from the volcanic source region.

Upper Silurian. The rocks assigned to the Upper Silurian on Plate 1 have a distinctive shallow-water brachiopod Salopina fauna that Berry and Boucot (1970) assign to the Pridoli stage. The first appearance of that fauna is shown on Figure 1. In Maine the Leighton Formation rests conformably on the Edmunds in the Cobscook anticline and is overlain conformably by the Hersey Formation. The Leighton Formation is composed of gray shales and siltstones with intercalated basalt flows and tuff-breccias, and rhyolitic flows and tuff-breccias, all deposited in shallow water. The Hersey Formation consists of maroon siltstones and shales, locally calcareous, and has a restricted gastropod-pelecypod-ostracode fauna. It probably was deposited in tidal flats and lagoons. Ostracodes suggest that the Silurian-Devonian boundary lies within the Hersey Formation (Berdan, 1971).

In New Brunswick, on the peninsula south of St. George, and on Deer Island between the St. George and Back Bay faults, Donohoe (1978) has assigned a Pridoli age to the Letete Formation on the basis of a small brachiopod collection. The formation is fault-bounded without stratigraphic bottom or top. It consists of gray siltstones and shales, some local red-siltstones, volcaniclastic conglomerates, quartz and feldspathic wackes, and flows and tuffs (Donohoe, 1978).

The Wilsons Beach Formation on Campobello Island, between the Belle Isle and Beaver Harbor faults, lithologically and structurally resembles the Letete Formation and has been assigned an Upper Silurian age (McLeod, 1976).

Middle to Upper Silurian rocks crop out in the Oak Bay, New Brunswick, area north of and intruded by the belt of Acadian plutons. On Cookson Island in Oak Bay, the Oak Bay Formation, a polymict conglomerate containing round pebbles and cobbles, unconformably overlies the Ordovician Cookson Formation and is overlain conformably by the Waweig Formation (Ruitenberg, 1967). The Waweig Formation has Middle to Upper Silurian brachiopods in its lower part and the Salopina brachipood fauna in its middle and upper parts (Pickerill, 1976), and thus is partly equivalent to the Leighton, Letete, and Wilsons Beach Formations. It consists largely of feldspathic and lithic graywackes, siltstones, and shale with some volcaniclastic units near its base. Near contacts with the intrusive rocks of the plutonic belt it is metamorphosed to mica schists with minor cordierite, andalusite and staurolite (Ruitenberg, 1967).

Lower Devonian. In Maine, the Eastport Formation is exposed in a fault block in the Lubec fault zone and in the east limb of the Cobscook anticline. It is cut off to the north of Boyden Lake and up the St. Croix River by the Devonian plutonic belt. In New Brunswick, the Eastport Formation makes up several islands between the Back Bay and Letang Harbor faults. It also crops out north of the St. George fault and along the north shore of Passamaquoddy Bay northward to the plutonic belt (Pickerill and Pajarie, 1976). Its ostracode fauna suggests a Geddinian age (Berdan, 1971). Throughout the Passamaquoddy Bay area, the Eastport Formation consists of flows and tuff-breccias of basaltic andesite; shallow intrusions, flows, domes, and ash-flows of rhyolitic composition; and variegated gray, green, and maroon siltstones, shales, and pebble conglomerates. It carries a brackish water assemblage of ostracodes, pelecypods, gastropods, and linguloids. Some of the volcanic rocks are subaerial, and the fossiliferous sedimentary rocks were deposited in tidal flats and shallow lagoons.

The Silurian-Lower Devonian volcanic rocks of the Passamaquoddy Bay area are perhaps as much as 7 kilometers thick. They thin rapidly to the east and west. The volcanic components are dominantly of basaltic and rhyolitic mineralogy and chemical composition, with very few andesitic rocks. Gates and Moench (1980) have proposed an extensional tectonic regime for these bimodal volcanic rocks, perhaps one of normal faulting and subsidence permitting the accumulation of a locally thick section (Figure 2). In general, the lithologies and faunas of successive formations from the Quoddy to the Eastport indicate a gradual shallowing of the marine waters in which the rocks were deposited as the volcanic pile thickened, ending with subaerial and brackish water conditions in the Early Devonian.

Upper Devonian. The Perry Formation is exposed around the margins of Passamaquoddy Bay and probably underlies most of it. Plant fossils indicate an Upper Devonian age. It rests along an angular unconformity on

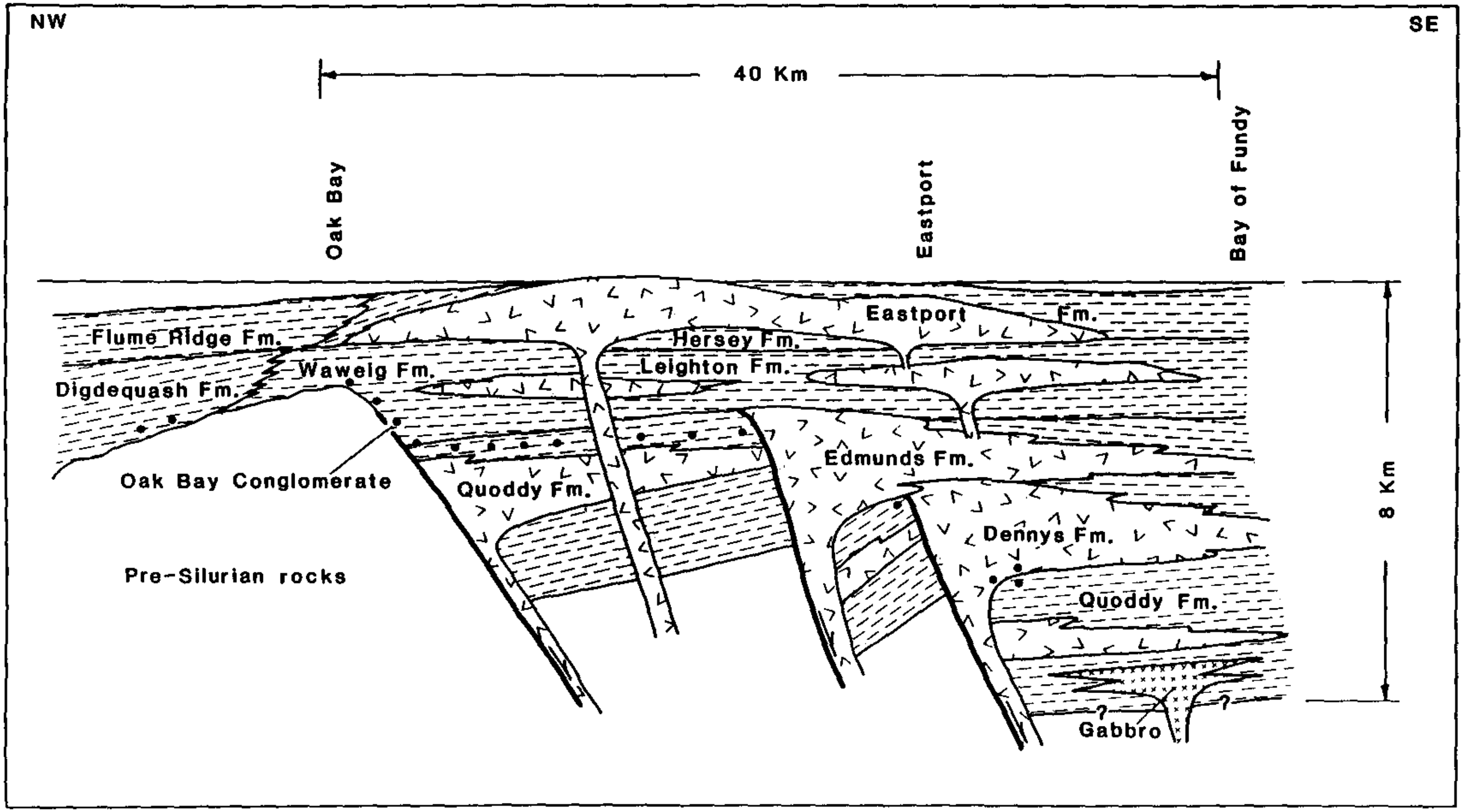

Figure 2. Schematic cross-section of the Eastport region illustrating the relationship of Silurian faults to the volcanic stratigraphy. (Gates and Moench, 1980)

the Silurian-Lower Devonian volcanic section and on the Acadian plutonic rocks which intrude the latter. It consists of maroon alluvial conglomerates, arkosic sandstone, red shales, and lacustrine beds (Schluger, 1973). It also contains two basalt flows. The Perry Formation is a post-tectonic molasse deposited in a fault basin during uplift following the Acadian orogeny.

INTRUSIVE ROCKS

On the geologic map (Plate 1) intrusive igneous rocks are divided into two groups. Within the Silurian-Lower Devonian sequence are numerous dikes, sills, and small irregular plutons consisting largely of diabase, including the diabase that intrudes the Quoddy Formation south of the Lubec fault zone. These intrusions have chemical and mineralogical compositions similar to those of the volcanic formations they intrude and are thus believed to be about the same age as their host formations.

A flow-banded bulbous rhyolite, the Letang rhyolite, intrudes the Gross Point Formation between the Back Bay and Letang Harbor faults and has been assigned a Lower Devonian age by Donohoe (1978).

The belt of large plutons of gabbro-diorite and granitic rocks inland across the head of Passamaquoddy Bay intrude all the Silurian-Lower Devonian stratified rocks and represent the plutonic phase of the Acadian orogeny. In Maine, the initial magmatic activity was emplacement of mafic plutonic rocks, predominantly gabbro but including layered norite and hypersthene gabbro (Amos, 1963). Along contacts with later granitic rocks, the mafic rocks have been altered to quartz gabbros and hornblende diorites. The granitic rocks consist of a varied suite of diorite, granodiorite, quartz monzonite, and biotite granite in several different intrusions, all younger than the mafic rocks (Amos, 1963).

In New Brunswick, the corresponding mafic rocks and later felsic intrusions have been named the Bocabec complex (Pajarie, 1976). The mafic rocks consist largely of coarse ophitic gabbro plus a few local lenses of layered gabbro with cumulate textures. The felsic intrusions include hornblende and biotite granodiorite, rapakivi granite, and red biotite granite (Pajarie, 1976). Hybrid intermediate rocks along some of the gabbro-granitic rock contacts reflect chemical and mineralogical reactions between the intrusive granitic rocks and the host gabbro. The Bocabec complex is intruded by the St. George pluton which extends eastward from Digdeguash Lake on Plate 1. It is a coarse-grained granite with phases of porphyritic granite, megacrystic granite, and aplite (Pajarie, 1976).

Compilations of isotopic dates by Donohoe and Pajarie (1973) and Pajarie (1976) give ages of 393 ± 6 m.y. for the Red Beach granite near Red Beach in Maine and 396 ± 20 m.y. for the felsic rocks of the Bocabec complex. The St. George pluton, however, may be of Late Devonian to Early Mississippian age (Pajarie, 1976).

The youngest intrusion in the Passamaquoddy Bay area is a diabase dike that strikes east-northeast and crops out along the shore on both sides of the St. Croix River north of Robbinston and St. Andrews. Burke and Stringer (1981) identify the dike as Triassic. In hand specimen and outcrop its color, texture, and lack of alteration resemble those of Triassic dikes in the Machias quadrangle and the Triassic sill on Grand Manan Island.

STRUCTURE

Five episodes of faulting - Silurian, Middle Devonian (Acadian), Late Devonian, Carboniferous, and Triassic - have been identified in the Eastport 2-degree sheet (Gates, 1978, 1982), although not every fault has sufficient criteria for establishing its age. On the geologic map (Plate 1), stratigraphic evidence suggests that the arcuate north to northeast-trending fault north and west of Dennysville, which separates the Edmunds Formation from the Silurian undifferentiated (Su) unit, is contemporaneous or nearly so with deposition of those units.

Faults that cut Acadian folds but in turn are cut by Acadian plutons, such as those that form a fan-like pattern cutting the Cobscook anticline, are assigned a Middle Devonian age. Some of the northeast-striking faults that drop the Perry Formation down against the Eastport Formation are bordered by wedges of coarse boulder conglomerate extending into the Perry Formation, the clasts of which are of the rocks on the upthrown side. Such faults probably formed during development of the Perry fault basin during the Late Devonian.

Faults that displace Acadian plutons or cut off the Late Devonian Perry faults are probably of Carboniferous age. The most conspicuous Carboniferous faults are the through-going, northeast-striking ones such as the St. George, Back Bay, Letang Harbor, Beaver Harbor, and Belle Isle faults. They displace the Perry Formation, cut Acadian plutons to the northeast in New Brunswick, or bound Carboniferous fault basins in New Brunswick (Potter and others, 1968). Lack of post-Carboniferous rocks along the faults prevents determination of post-Carboniferous fault movement, although the parallelism of Triassic faults bordering the Bay of Fundy suggests the possibility of such movement on the Carboniferous faults. Detailed study of small structures along some of the faults in the Passamaquoddy Bay area suggests that the latest movement was dip-slip (Donohoe, 1978).

The Lubec fault belongs to this northeast-striking regional Carboniferous fault system, but its correlation with companion faults in New Brunswick is uncertain. Donohoe (1978) favors correlation with the St. George fault offset along the Oak Bay fault. On the other hand, correlation with the Beaver Harbor or Belle Isle fault maintains continuity of the block of Quoddy Formation south of the fault.

The strike of the Oak Bay fault is normal to the regional structural grain and the regional Carboniferous faults. The Oak Bay fault appears to have determined the trend of the St. Croix River and the west side of Passamaquoddy Bay. It is exposed only on Cookson Island and the adjacent shores of Oak Bay, where it is a zone of sub-parallel faults nearly a kilometer wide. It is likely that the fault's continuation beneath Passamaquoddy Bay is also a fault zone rather than the single fault schematically mapped. The fault zone offsets the Oak Bay Formation, intrusive contacts of the plutonic belt, a lava flow in the Perry Formation, and the Lubec fault and its probable extension, the Beaver Harbor fault. The Letete Formation on Deer Island terminates at the fault zone and has not been identified to the west. Apparent displacement on the fault zone is left lateral, but a descriptive geometric construction suggests a large vertical component of net slip. If the average dip of 60° on the base of the Oak Bay Formation on each side of the fault zone is extended downwards in the plane of the fault zone to the intersection with the contact between the Waweig Formation and the plutonic belt (a contact that appears to be vertical according to its topographic trace), the net slip can be determined. This construction gives a net slip plunging about 45° to the north-northwest in the vertical fault plane, with a horizontal slip component of about 2 km and a vertical component of about 2 km, east side down.

Most of the displacement on the Oak Bay fault zone occurred before emplacement of the Triassic dike and is thus of Carboniferous to Late Triassic age. Although the dike shows no displacement on the map, the possibility exists of later minor movements not perceptible at the map scale.

The Fundian fault (Johnson, 1925) parallels the shoreline beneath the Bay of Fundy. It forms the northwest margin of the Late Triassic to Early Jurassic fault basin that underlies the Bay of Fundy (Ballard and Uchupi, 1975) and is the youngest fault identified in the Passamaquoddy Bay area.

The regional Carboniferous faults just described divide the stratified rocks of the Passamaquoddy Bay area into several fault blocks each containing its own style of folding and in some cases distinctive stratigraphy. In the following description of folding, the designations F_1, F_2, etc. apply only to the sequence of folding within a fault block, not regionally.

North of the plutonic belt and inland from the area shown in Plate 1, the Ordovician Cookson and the Silurian Waweig Formations have upright, east-northeast striking, gently plunging F_1 folds with a slatey axial-plane cleavage. These in turn have been folded by recumbent F_2 folds that have gently plunging hinge lines and gently dipping axial-plane cleavage (Ruitenberg, 1968; Ruitenberg and Ludman, 1978). Steeply plunging S-Z shaped F_3 folds occur near faults and contacts with granitic plutons. F_4 folds are kink bands. F_1 and F_2 folds are attributed to the

Acadian orogeny, F_3 and F_4 folds may be Devonian to Carboniferous (Ruitenberg and Ludman, 1978). No pre-Silurian folding of the Cookson Formation has been identified, although the unconformity beneath the Oak Bay Formation indicates that structural discontinuity of some kind must be present.

South of the plutonic belt and west of the Oak Bay fault, the Cobscook anticline, an F_1 structure containing the Dennys, Edmunds, Leighton, Hersey, and Eastport Formations, is the major structure (Gates, 1975). It is a broad open fold plunging to the east. Dips on the south limb near the Lubec fault zone are vertical to overturned, and a very strong cleavage accompanied by isoclinal F_2 folds with gently plunging hinge lines parallels the Lubec fault zone and occurs within it. The faulting appears to have steepened and sheared out the south limb, presumably during the Carboniferous. The east limb dips from 20° to 60° east-northeast and strikes into the plutonic belt which intrudes it. F_2 folds and accompanying local cleavage occur along some of the faults that cut the anticline. A regional northeast-striking and steeply dipping cleavage cuts obliquely across the Cobscook anticline and parallels the Lubec fault zone, suggesting a Carboniferous age.

The east limb of the Cobscook anticline forms the west limb of a broad open syncline of Eastport Formation around the head of Passamaquoddy Bay, south of the plutonic belt and east of the Oak Bay fault. Like the Cobscook anticline, the syncline contains only one episode of folding (Donohoe, 1978; Ruitenberg, 1968).

The Silurian-Lower Devonian stratified rocks of the Cobscook anticline and the syncline of Passamaquoddy Bay are intruded by the Acadian plutonic belt and overlain along an angular unconformity by the Upper Devonian Perry Formation whose conglomerates carry clasts of the underlying volcanic rocks and granitic rocks of the plutonic belt. The folding is thus a part of the Acadian orogeny.

The east limb of the Cobscook anticline strikes almost at a right angle to the east-northeast strike of the folding in the Cookson and Waweig Formations north of the plutonic belt. There is also a marked contrast in the style and complexity of the folding north and south of the plutonic belt. Perhaps a major regional fault guided the ascending magmas of the plutonic belt.

A single open folding, like that of the Cobscook anticline and of the Eastport Formation of Passamaquoddy Bay, also occurs in the block of Quoddy Formation south of the Lubec fault zone and the Beaver Harbor fault on Campobello Island (Gates, 1975; McLeod, 1976), and is accompanied locally by an axial-plane cleavage and by minor folds and strong shearing in the Lubec fault zone.

In contrast to the relatively simple open folding of the syncline of Passamaquoddy Bay, the Cobscook anticline, and the Quoddy fault block, the rocks of the Letete Formation in the St. George - Back Bay fault block and of the Gross Point Formation between the Back Bay and Letang Harbor faults have a history of multiple deformation. Ruitenberg (1968), McLeod (1976), and Donohoe (1978) have all commented on this contrast. Donohoe (1978) has mapped upright isoclinal F_1 folds plunging steeply to the northeast with an accompanying steeply dipping cleavage marked by metamorphic chlorite, muscovite, and biotite and a northeast plunging lineation of elongated clasts and granulated minerals. F_2 folds are also upright with hinge lines plunging northeast to southwest and a local crenulation cleavage. F_3 and F_4 are successive episodes of kink-banding. Donohoe attributes all four phases of folding to the Acadian orogeny and has not identified any penetrative deformation associated with the major Carboniferous faults that bound the blocks. No correlation between F_1 and F_2 folding of the Cookson and Waweig Formations and those of the Letete and Gross Point Formations can be made because the configurations and plunges of the fold systems are not the same.

The Wilsons Beach Formation in the Beaver Harbor - Belle Isle fault block forms an assymetrical overturned gently plunging F_1 syncline with minor tight folds on the limbs and an axial-plane cleavage marked by metamorphic muscovite and granulated minerals (McLeod, 1976). This was followed by an F_2 crenulation of the cleavage and an episode of kink-banding.

These contrasts in structure from fault block to fault block and the confinement of certain stratigraphic units to certain fault blocks suggest that the fundamental regional structure and stratigraphy of the Passamaquoddy Bay area has not yet been determined. Much more work clearly needs to be done. Meanwhile, I hazard the very tentative working hypothesis that the Passamaquoddy Bay area is underlain by two plates of a thrust, one above the other, each with its own stratigraphy, one with a relatively simple Acadian deformation plan, the other with a complex one. One or the other of these plates is brought to the present level of exposure in the different fault blocks depending on the amount and sense of vertical displacement on the bounding faults.

GEOLOGIC HISTORY

During the Silurian and Lower Devonian, the marine volcanic rocks now exposed in the Passamaquoddy Bay area accumulated to form a thick volcanic pile in a subsiding, extensional tectonic regime. Acadian deformation, while not well understood, produced fold structures of differing complexity and differing regional strike. Intrusion of Acadian mafic to felsic magmas was largely confined to a linear plutonic belt. After the Acadian orogeny and during the Upper Devonian, a local fault basin filled with coarse alluvial clastic sediments derived from erosion of the volcanic pile and the Acadian plutonic belt. During the Carboniferous, large regional northeast-striking faults and the anomalous north-northwest striking Oak Bay fault divided the rocks of the Bay area into a number of discrete fault blocks with different stratigraphies and structural styles. A Triassic diabase dike is the youngest rock in the area. The last recorded faulting, the Fundian fault, delineated the northwestern margin of the Late Triassic to Early Jurassic fault basin now beneath the Bay of Fundy.

GEOPHYSICS

Three geophysical anomalies set the Passamaquoddy Bay area apart from surrounding eastern coastal Maine and New Brunswick. The area has a concentration of small earthquakes (Figure 3), most of which are below intensity IV or magnitude 3. Of the 48 seismic events plotted on Figure 3, the 26 that date between 1850 and 1977 are those with sufficient intensity to be recorded historically (Rand, 1977; Chiburis, 1981). The 22 events between 1977 and 1981 were recorded by the Northeast U. S. Seismic Network (Chiburis, 1981) and indicate an average of 4 earthquakes per year. The pattern of epicenters suggests a trend parallel to and in the general vicinity of the Oak Bay fault. The numerous small earthquakes imply that the crust in the Passamaquoddy Bay area is not strong enough to sustain much elastic strain.

The Bouguer gravity anomaly map (Figure 4) shows a northwest trending embayment of relatively flat gravity ranging from slightly positive to slightly negative beneath Passamaquoddy Bay and adjacent Maine. The embayment corresponds to the thick accumulation of the Silurian-Lower Devonian volcanic rocks and to the distribution of the Perry Formation. The granitic and gabbro-diorite plutons that underlie the gravity embayment south and southwest of Calais have little gravitational expression and hence are probably relatively thin. The large negative anomalies to the north and south of the gravity embayment coincide in part with surface exposures of granitic plutons, which presumably extend to considerable depth.

The steep gravity gradient, which becomes increasingly positive to the southeast and extends from Campobello Island southwestward beneath the Quoddy fault block, coincides with large masses of diabase and gabbro that intrude and presumably underlie the Quoddy Formation. This steep gradient continues 175 km to the southwest, diverging from the coastline. Southeast of Mt. Desert Island, it is 25 km offshore in the Gulf of Maine. Kane and others (1972) conclude that it marks a major boundary between two crustal blocks, one of comparatively dense Precambrian rock beneath the Gulf of Maine, the other of less dense Paleozoic rocks overlying the Precambrian basement in coastal Maine. Superimposed on this regional gravity gradient and within the crustal blocks are numerous large plutons of gabbroic and granitic rocks which show as large closed or partly closed positive or negative anomalies respectively. The large volume of gabbro and diabase intruding and probably underlying the Quoddy Formation may have been emplaced along this crustal boundary, thus dating the boundary as at least Early Silurian in age.

The magnetic anomaly map (Figure 5) shows a discontinuity between a linear pattern in New Brunswick, especially on Deer and Campobello Islands, and a flat pattern in Maine. The linearity corresponds to the distribution of the Precambrian Coldbrook Formation of volcanic rocks, either in outcrop on Campobello Island or presumably beneath the Letete Formation on Deer Island (McLeod, 1976). The linear pattern appears again on Grand Manan Island where Precambrian volcanic rocks, probably Coldbrook equivalents, crop out, and can be found farther to the southwest beneath

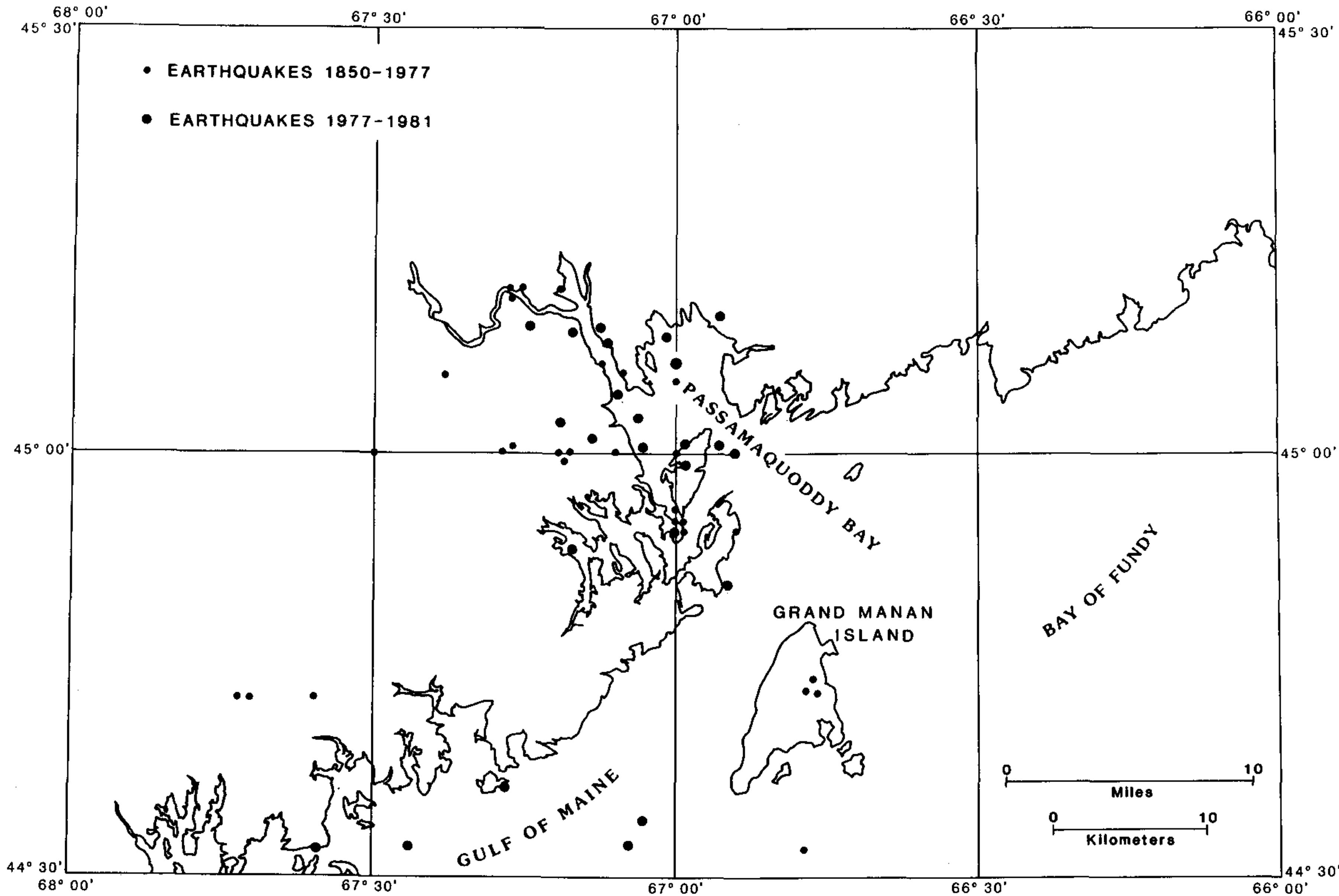

Figure 3. Epicenters of earthquakes from 1850 to 1981, Passamaquoddy Bay area, Maine and New Brunswick. (Compiled from Rand (1977), Chiburis (1981), and Lepage and Johnston (1982))

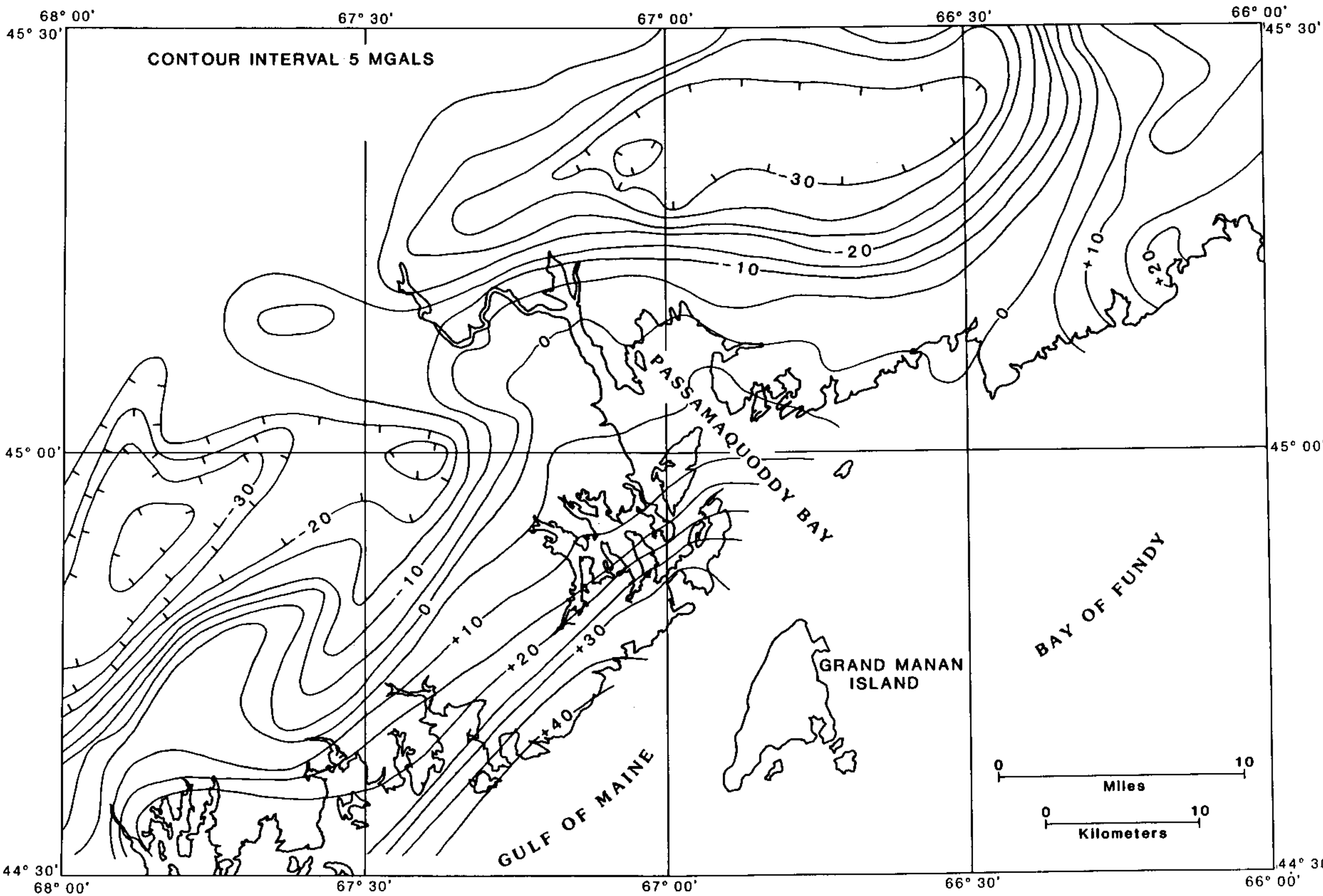

Figure 4. Bouguer gravity anomaly map of coastal Maine and New Brunswick adjacent to Passamaquoddy Bay. (Compiled from Kane and others (1972) and Weng (1981))

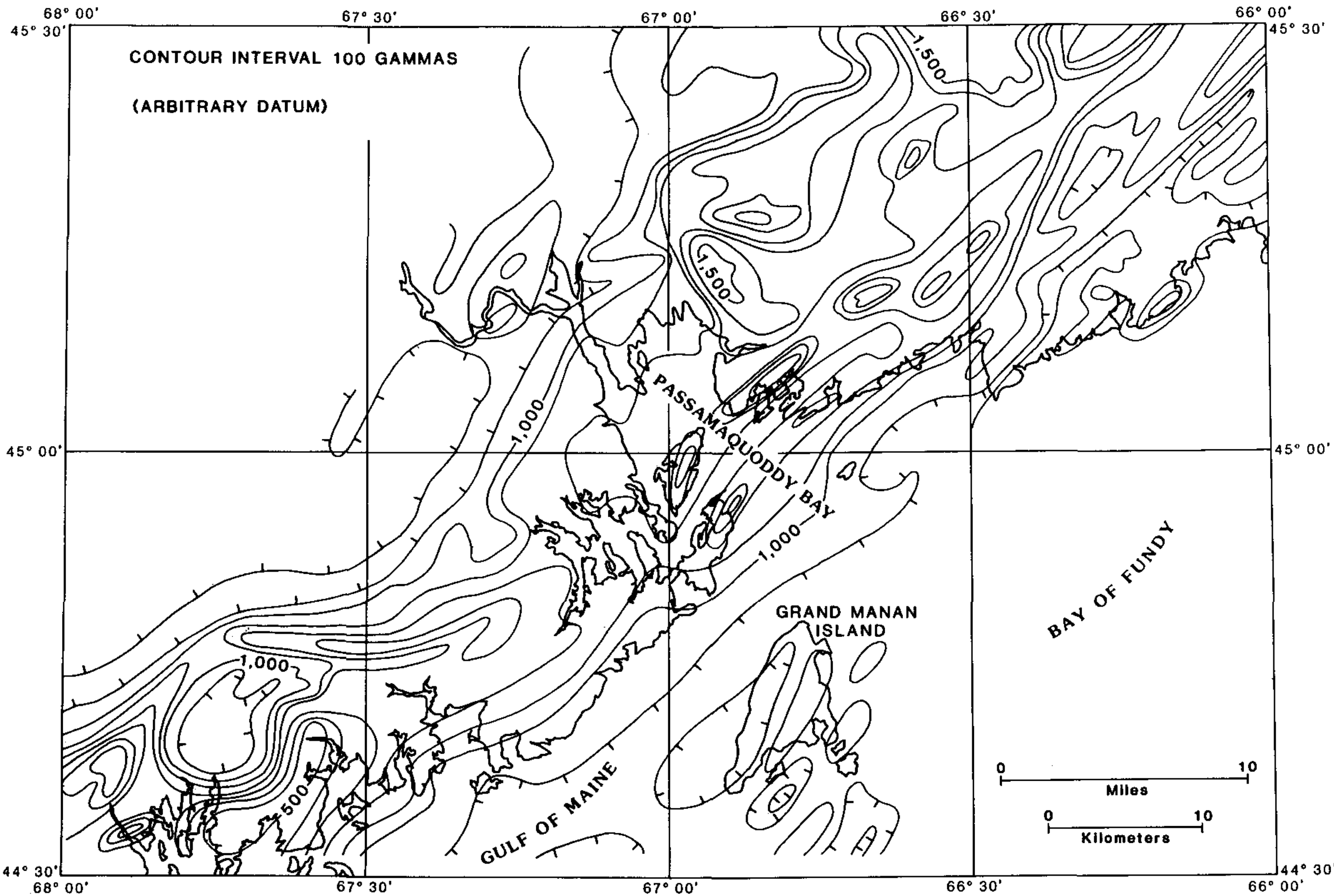

Figure 5. Aeromagnetic anomaly map of coastal Maine and New Brunswick adjacent to Passamaquoddy Bay. (Adapted from Kane and others (1972))

the Gulf of Maine. Kane and others (1972) tentatively identify this linear pattern beneath the Gulf of Maine as the magnetic signature of the Precambrian rocks that show the same linearity in New Brunswick.

The 25 km left lateral offset of this linear pattern between Campobello Island and Grand Manan Island and the similar but less pronounced offset of the large negative gravity anomalies suggest that there is a left lateral offset of the crust trending northwesterly through the Passamaquoddy Bay area. The 25 km of supposed left lateral displacement far exceeds that of the Oak Bay fault and cannot be the result of movement on that fault. On the other hand, the location and strike of the Oak Bay fault may have been influenced by the presumed crustal discontinuity.

Evidence for a large left lateral offset is not apparent in the Ordovician to Middle Devonian rocks. The maps of Amos (1963) and Ruitenberg and Ludman (1978) show no corresponding offset in the Acadian plutonic rocks or in the pelitic rocks of Ordovician, Silurian, and Lower Devonian age along the strike of the supposed offset in the vicinity of and inland from Calais. This suggests that apparent offset of the large gravity anomalies marking Middle Devonian granitic plutons is fortuitous. A cautious conclusion is that if the linear magnetic anomalies mark Precambrian volcanic rocks, the Coldbrook Formation, and if the offset of the magnetic patterns indicate a similar offset in the crust, then the movement must have been of late Precambrian to Cambrian age.

CONCLUSIONS

Tyler and Ladd (1980), using data from repeated first-order leveling surveys furnished by the National Geodetic Survey, have determined that the regional ground surface between Bangor and Eastport is downwarping at a rate that increases eastward, with the maximum of 0.9 cm/year located in the Passamaquoddy Bay area. Thompson and others (1983) have compiled an isobase map derived from measurements of the elevations of glaciomarine shoreline features, primarily deltas, which shows the amount of postglacial rebound in coastal Maine. The isobases generally parallel the northeast trend of the retreating late Wisconsinan ice margin, except in the Passamaquoddy Bay area where a northwest-oriented reentrant indicates that the net apparent uplift since the marine transgression that accompanied ice retreat is up to 24 meters less than in the adjacent coastal region to the southwest. Whether the 24 meter difference in amount of post-glacial rebound results from a lag in uplift going back through 10,000 years of post-glacial rebound or is a relatively short term subsidence imposed on the normal regional rebound is an unanswered question. If the 24 meters is a lag in rebound over the last 10,000 years the rate is .24 cm/year, much less than the current rate of subsidence. On the other hand, the current rate of .9 cm/year would require only about 2600-2700 years to produce the 24 meter difference in isobases. Anderson and others (1984) using the tide gauge and levelling data of Brown (1978), suggest a very short term fluctuation in rate of subsidence, that of 1942 to 1966 being 3.4 times that of the average for the period 1927-1966. They note that this increase in subsidence corresponds with an increase in local seismicity beginning about 1940. The 1942 date is that of a releveling and hence need not be the date of an increase in the rate of subsidence.

The current subsidence of the Passamaquoddy Bay region is not an isolated event in the history of crustal warping in New England and the Maritimes. Studies of changes in sea level along the New England coast (summarized by Anderson and Borns, 1983) indicated that there have been fluctuating rates and amounts of sea-level rise along different parts of the coastline going back at least 4,000 years. Vanicek (1976), using tide-gauge data combined with data from repeated leveling surveys, has found a wave-like warping in New Brunswick and Nova Scotia that includes a northwest-trending trough having a current subsidence rate of 40 cm/century near the head of the Bay of Fundy and of 30 cm/century in southern New Brunswick. The current subsidence of the Passamaquoddy Bay area is thus part of a regional warping pattern spread over eastern coastal Maine and the adjacent Maritime provinces.

It is beyond the scope of this paper to discuss possible geological mechanisms responsible for past and present regional warping in New England and the Maritimes. The most recent major crustal deformation in coastal Maine is the large (173m) and rapid (1,000 years) crustal rebound that was an isostatic response to unloading of the lithosphere as the last continental ice sheet withdrew (Stuiver and Borns, 1975). Kane and others (1972), citing the data of Yelling (1968), conclude that the slightly positive free-air gravity anomaly over coastal Maine and the Gulf of Maine indicates that the crustal blocks of differing density beneath these two regions are now in isostatic equilibrium. The postglacial isostatic rebound appears to have run its course.

However, some strain is present in the crust of the Eastport area. The strain-relief overcoring technique has shown that there is a maximum principal horizontal compressive stress oriented east-northeast and a minimum principal horizontal stress oriented northwest-southeast (Anderson and others, 1984). Whether this stress pattern and its resulting strain are residual or represent current tectonic events is not known. The vertical velocity surfaces of the present subsidence in the Eastport area strike approximately 70 degrees from the least stress axis and thus do not fit the pattern expected for subsidence due to extension.

The length of time the Eastport region has been subsiding relative to the surrounding region, variations over that time in the rate of subsidence, the amount of prehistoric seismicity, and the origin and duration of the present anisotropic stress in the local crust are all unknown. Without a more complete Holocene tectonic record, it seems pointless to speculate about the regional tectonic regime in eastern Maine and southern New Brunswick causing subsidence. However, geologic history, the local fault density, current seismicity, and geophysics suggest that the most rapid subsidence, whatever its cause, is located in the Eastport area because the underlying crust is weak relative to the strength of the crust in the surrounding region.

Part of the evidence for a locally weak crust is historical, beginning perhaps with the vaguely perceived northwest-trending late Precambrian to Cambrian crustal discontinuity that the magnetic pattern hints at. The thickness of the Silurian-Lower Devonian volcanic pile is greater than elsewhere in the Coastal Volcanic Belt, implying greater local subsidence. The development of the Upper Devonian Perry fault basin and its subsequent survival after deposition suggest a continued local tendency towards subsidence. The concentration of faults of many ages and the anomalous orientation of the Oak Bay fault zone further suggest a locally weak crust. The local concentration of current small earthquakes indicates the crust of the Passamaquoddy Bay area is not sufficiently strong to sustain much elastic strain.

A second contributing factor unique to the Passamaquoddy Bay area may be the proximity of the steep coastal gravity gradient which underlies the Gulf of Maine for most of its length but intersects the coast in the Bay area. If this gradient marks the contact between two crustal blocks as proposed by Kane and others (1972), it may also represent a lineament of crustal weakness. Furthermore, the steep gravity gradient indicates a steep gradient in the masses of the adjoining crustal blocks. Perhaps the regional subsidence produces slight differential isostatic adjustments which set up small strains in the local crust.

In summary, it is proposed that the Passamaquoddy Bay area is subsiding at a higher rate than the surrounding region of eastern coastal Maine and New Brunswick because a weaker crust (and presumably upper mantle) presents less elastic strength to the stresses reponsible for the broad regional subsidence.

The hypothesis presented here that the rapid local subsidence stems primarily from local crustal weakness might be tested by a detailed study of erosion and deposition just prior to, during, and immediately after the post-glacial rebound. The magnitude and rate of vertical displacement and the departure from isostatic equilibrium at that time were much greater than during the present regional warping. Consequently, the local response of a weak crust and a steep gravity gradient should have been much greater as well. The history of the Passamaquoddy Bay area during the time isostatic equilibrium was being restored after withdrawal of the continental ice sheets should be perceptibly different from that of the surrounding region if the hypothesis proposed here is correct. Continuous seismic profiling of the topography and postgacial deposits beneath Passamaquoddy Bay and detailed mapping of subaerial glacial deposits and erosion might provide the necessary evidence.

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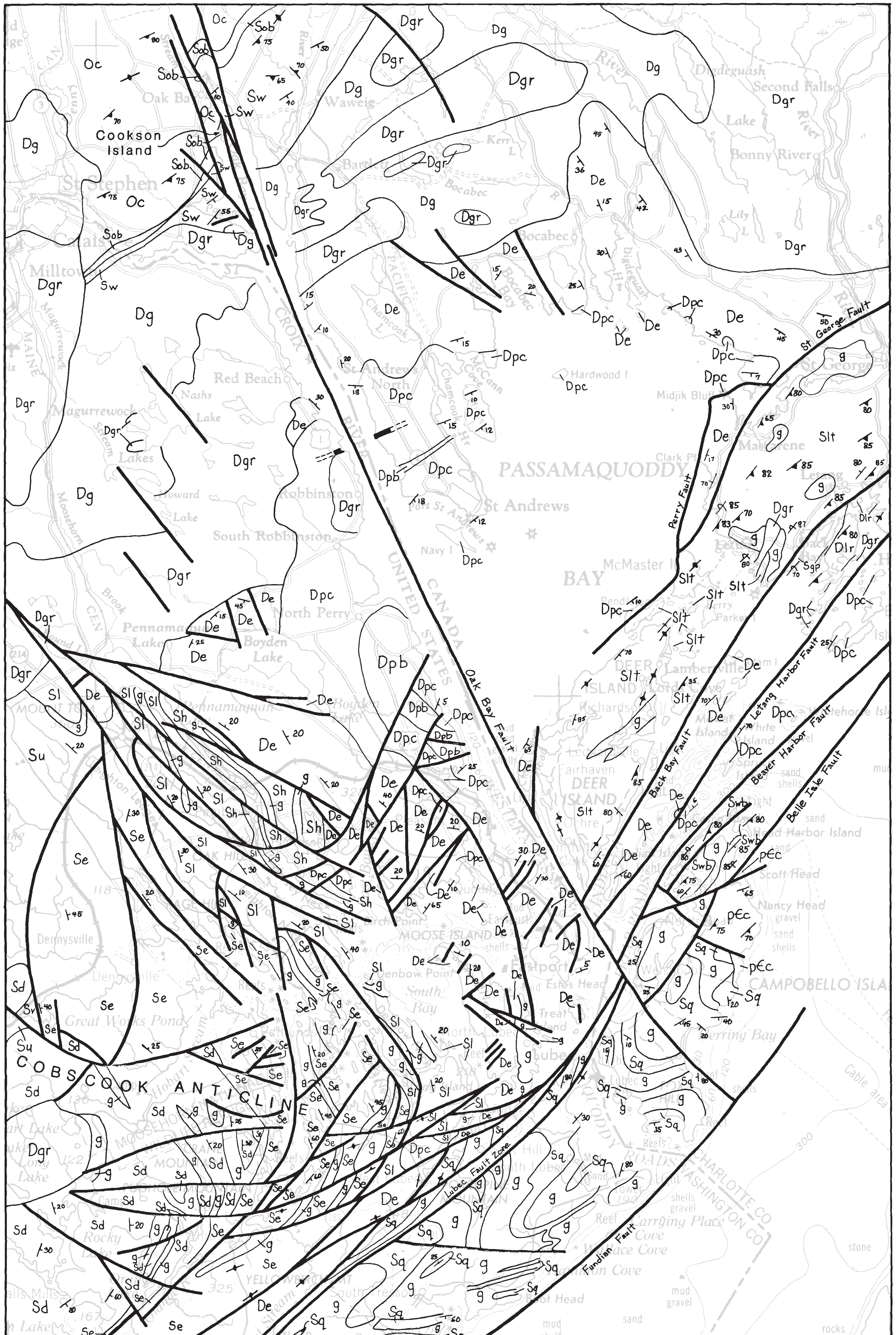

PLATE 1
OPEN-FILE NO. 84-10

GEOLOGIC MAP OF THE PASSAMAQUODDY BAY AREA
MAINE AND NEW BRUNSWICK

by
Olcott Gates

Maine Geological Survey
DEPARTMENT OF CONSERVATION
Walter A. Anderson, State Geologist

1984

3 0 3 MILES
5 0 5 KILOMETERS

EXPLANATION

TRIASSIC?

Diabase dike

UPPER DEVONIAN

Dpc / Dpb — Perry Fm.
Dpc - Conglomerate
Dpb - Basalt flows

------Unconformity------

LOWER-MIDDLE DEVONIAN

Dg — Gabbro and diorite plutons
Dgr — Granitic plutons

------Intrusive contact------

Maine	New Brunswick — Coastal	New Brunswick — Inland
LOWER DEVONIAN		
De — Eastport Fm.	De — Eastport Fm.; Dlr — Letang Ryholite	
SILURIAN		
Sh — Hersey Fm.		
Sl — Leighton Fm.	Slt — Letete Fm.; Swb — Wilsons Beach Fm.	Sw — Waweig Fm.
Se — Edmunds Fm.	Sgp — Gross Point Fm.	Sob — Oak Bay Fm.
Sd — Dennys Fm.		
Sq — Quoddy Fm.	Sq — Quoddy Fm.	
Su — Undifferentiated		

g — Diabase dike, sills

----?----?----Unconformity----

ORDOVICIAN

Oc — Cookson Fm.

----?----?----Unconformity----?----?----

PRECAMBRIAN

p€c — Coldbrook Fm.

SYMBOLS

Contact
Fault
Attitude of bedding
Attitude of overturned bedding
Attitude of cleavage

Sources: Amos 1963; Ruitenburg 1967,1968; Gates 1975; Pajari 1976; McLeod 1976; Donohoe 1978; Burke and Stringer 1981; Ludman 1978

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