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Title: Preliminary Geologic Survey of Potential Underground Oil Storage Sites in Maine

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Contents: 25 page report

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Preliminary Geologic Survey
of Potential Underground Oil Storage Sites in Maine

Purpose

This report contains a discussion of 12 general localities on the coast of Maine that are considered to be suitable, representative sites for the storage of strategic oil supplies in underground rock caverns. There are probably other sites on the Maine coast that are equal from a geotechnical point of view and may be superior in other respects. However, the discussion of the characteristics of the localities mentioned in this report should establish that suitable geological conditions for rock cavern storage can be found in Maine. This report concludes that there are a number of sites on the Maine coast with nearby port facilities or deep water anchorage that appear to be very satisfactory for the construction of large underground rock caverns with capacities of 1,000,000 to 20,000,000 barrels of oil.

Criteria

The localities discussed in this report were suggested by individual geologists that are mapping rock units in the respective areas. Experience in Finland (Johansson and Lahtinen, 1976) has shown that construction of rock caverns is more economical in acid granitic and high grade crystalline metamorphic rocks than in most other rock types. Support requirements and grouting are usually minimal in these rock types, provided they are relatively free of joints and fractures. These rocks generally transmit very little ground water flow below several hundred feet from the rock surface, thus oil losses are small and the chance of ground water contamination is low. The localities discussed in this report are representative of these more desirable rock types. The Maine geologists avoided choosing highly jointed or sheared rocks or low grade metamorphic, sedimentary, or volcano-clastic rocks. Sulfide bearing rock was also avoided.

The potentiometric ground water level must be higher than the elevation of the cavern roof so that a resultant hydrostatic pressure is maintained to contain oil within the cavern. The thickness of overburden should also be small to simplify shaft construction. Overburden thickness is very small in most of the Maine sites and in all cases less than 60 feet.

In addition to geotechnical considerations, a prime criterion for large oil storage facilities is proximity to oil terminal facilities or potential ocean tanker transfer sites. Most of the Maine sites are within several miles of 60 foot ocean depth.

This report does not deal with specific land parcels or the legal and environmental problems of rock cavern construction with ancillary oil transfer facilities. The report focuses mainly on the geotechnical characteristics of the suggested sites.

Generalized Geology of the Maine Coast

The Maine coast can be divided into three generalized regions based on topographic and geologic considerations: 1) the "southern sand plains" (Portsmouth to Portland), 2) the "central embayment" (Portland to Acadia), and 3) the "eastern headlands" (Acadia to Eastport).

The southern sand plains have little topographic relief which can be partially attributed to the moderately thick surficial cover of sandy glacial outwash that blankets much of the area. Most of the bedrock is phyllite, schist or quartzite derived from shale, sandstone, siltstone, and graywacke. Some marble and meta-volcanic rock is also present. In most cases the metamorphic grade is only low to moderate; the properties of the rocks have not changed greatly since they initially formed.

The bedrock in the southern sand plains also includes several large Devonian granitic plutons, and at least one complex of younger (Permian to Jurassic) intrusives.

The central embayment section of the coast is characterized by numerous long peninsulas separated by tidal estuaries. Although most of this part of the coast has low relief, a few areas such as Camden Hills and Acadia National Park have hills with elevations exceeding 1000 feet.

The central embayment is underlain by metamorphic and igneous rocks with the latter accounting for at least a third of the total area. The metamorphic rocks are derived from sedimentary and volcanic rocks and consist of mica schists and gneisses, quartzites, meta-volcanics, and some belts of marble. Some unmetamorphosed volcanic rocks are also present. The metamorphic rocks range from weakly metamorphic to very intensely recrystallized rock. The highly metamorphosed rocks underlie much of the southern half of the coastal embayment section, especially near the Bath and Boothbay regions. The physical properties of these rocks have been greatly changed from those of the original sedimentary rocks.

The igneous bodies are primarily various types of granite, however, some darker colored diorite and gabbro are also present.

The third segment of the coast, the eastern headlands, extends from Acadia in Frenchman Bay, northeasterly to the Canadian border at Eastport. Much of this part of the coast is underlain by igneous rock such as granite, granodiorite, and gabbro. The non-igneous rocks are largely volcanic in origin and some have not been metamorphosed. These consist of rocks that can be termed flows and volcano-clastics (tuffs, ashflows, agglomerates, etc.). Because few of the rocks in the eastern headlands are highly metamorphosed, they have properties similar to non-indurated sedimentary rocks.

Joints, Foliation, and Faults

Comprehensive information on bedrock jointing is not available for many of the sites discussed here. However, some of the sites have been studied in some detail by geologists and other sites lie near old quarries that were studied by Dale (1907). Foliation is not an important feature of the sites of this study since most sites are either massive plutons or are rocks with no weakness along the planes of foliation.

Table 1 shows that for those sites for which jointing information is available, sheet jointing is common in granite and there are generally several sets of nearly vertical joints with spacing of several feet to forty feet or more. Dale (1907) states that the greatest depth at which sheet jointing has been found in Maine was 175 feet below the rock surface. Many of the vertical joint patterns have strikes conforming to regional physiographic lineaments.

Slickensided joints were only specifically noted in the Agamenticus Pluton (Boston Edison, 1976). No mineralization of joint faces is noted for the sites presented here, however, it would not be unusual to find some calcite or pyrite in joints in granite near the rock surface. Weathering of Maine granite was cited by Dale (1907), however, it is often confined to near-surface zones--particularly between open sheet joints--where percolating ground water and frost have worked. Deep weathering should not be found at the sites discussed here.

Indirect data on the extent of jointing and fracturing is available from bedrock well records. Joints become tighter and fewer in number with depth in crystalline rocks such as granite. Clapp (1911a) found that the chances of drilling a successful well in Maine granite decrease with depth (see also Davis and Turk, 1969) and that very little ground water yield can be found below a 200 foot depth. (Clapp, 1911b, noted that wells drilled in slate may have greater yields at depths between 200 and 400 feet than wells in granite.)

Faults are a group of features that should be avoided in caverning because of the difficulties in construction and a potential for ground water contamination from stored oil leaking into highly permeable rock zones. High yield bedrock well zones and known faults were generally avoided in the selection of the sites since tunneling experience has shown (Davis and Turk, 1969) that highly permeable rock zones in crystalline rock are usually associated with faulting. Caswell (1974) has also inferred that high yield bedrock wells in Maine seem to occur in zones that coincide with known or inferred fault zones.

Seismicity and Unrelieved Stress

Although Maine can not be classified as aseismic, the coast has a relatively low earthquake intensity potential. Moderate earthquakes would do little damage to underground liquid-filled rock caverns, however, the caverns should obviously not be located across faults in "active" seismic areas since ground water contamination could occur.

In historical times, none of the sites has been subjected to an earthquake with an equivalent Modified Mercalli scale intensity of more than VI at the site. Using conservative empirical correlations relating intensity with ground acceleration, it is calculated that no more than 0.1 times the acceleration of gravity (g) has occurred in historical time at any of the sites. (Technology Review, 1977, reported that the expected 50-year recurrence interval earthquake-induced acceleration for the coast of Maine is about 0.1g.) The only sites lying near relatively "active" seismic zones are the Mt. Waldo and Lucerne Plutons and the Addison-Great Wass Island-Jonesboro region.

Unrelieved stress was reported in a quarry in the Mt. Waldo Pluton (Dale, 1907). During quarrying, vertical joints developed, trending north-northwest. (This trend is parallel to a fairly active seismic zone running from Orrington to Milo, Maine.) Some studies suggest that New England is under an overall compressive stress; some people believe the unrelieved stress that seems to be inherent in many plutonic bodies is only a surface phenomenon that rapidly diminishes with depth. Although some unrelieved stress can be expected at least near the surface of Maine granites, it is not expected to affect normal rock cavern construction.

Hydrogeology of Coastal Maine

Most of the hydrogeology of granites and other rocks in Maine must be inferred from records of bedrock wells. These records suggest that most Maine granites have a relatively high ground water table that can be utilized for containment of oil stored below the potentiometric surface.

Clapp (1911b) found that 86% of wells drilled more than 50 feet in granite were successful in striking a suitable quantity of water for domestic use. Prescott (1963) found that about 20% of Maine bedrock wells yielded more than 10 gallons per minute, but wells yielding more than 100 gallons per minute are rare and are probably in a fault zone or in limestone.

The potentiometric level of ground water as measured in bedrock wells in Maine, generally conforms to a subdued version of the bedrock surface topography. Potentiometric levels in Maine bedrock wells generally fluctuate less than 20 feet over the seasons. With the exception of Mt. Waldo in Prospect, all of the localities have a potentiometric ground water level that lies relatively close to the ground surface (less than 60 feet).

Overburden Character and Thickness

Many of the sites have little or no surficial cover. The Maine granites and gabbros are normally more resistant than the surrounding country rock. The plutonic bodies were usually left as topographic highs by the Wisconsinan glaciations. The glaciers rarely left more than 40 feet of drift on these topographic highs.

In most cases the bulk of the surficial cover at the sites consists of a dense lodgment till with a fine-grained matrix immediately overlying the bedrock. The till may be overlain in turn by several feet of silty sandy ablation till, silty marine-laid sediments, or sandy outwash deposits. Thus the depth and type of cover at most sites would not significantly increase cavern construction costs over a "bare rock" site.

Oil Transfer Capability

Although Maine is obviously not centrally located with respect to high population centers, it does offer potential for deep water tanker transfer which is not available elsewhere on the eastern seaboard. In many cases, natural 60 foot ocean depths lie within several miles of a suggested site. Fairly direct rail connections to the Boston area can also be made from most of the sites. Sites in the Portland area (or the Searsport-Bucksport area) could take advantage of existing oil transfer capabilities.

Summary of Individual Site Characteristics

Table 1 is a summary of the pertinent geologic and locational aspects of the sites selected for discussion. The individual sites were not examined in the field for this study. Literature references and the comments of the Maine Survey geologists were assembled in selection of the sites and description of site characteristics. As mentioned in the statement of purpose, these should only be considered representative sites. Given more time for a thorough study, localities with similar geology but better locational characteristics might be found.

The sites are discussed in the following pages in order from southwestern Maine, moving up the coast to eastern Maine. No relative ranking of the sites is attempted. The Westbrook Pluton, Clark Island granite, Mt. Waldo Pluton, and Sedgwick Pluton would be favored sites, however, because of their combination of geologic and locational factors.

Agamenticus Pluton - 1

This pluton consists of a core of binary granite and a formation of alkali syenite on the northeastern side of the pluton, both of which would be suitable for cavern construction. Several strong sets of physiographic lineaments and some slickensided joints are found in the southwestern portion of the pluton. There are no nearby port facilities, but deep water lies 3 miles to the east of the site.

Webhannet Granite - 2

Although there is little detailed information on the site, it appears to be excellent from a geologic point of view. Overburden thickness may be greater (up to 60 feet) than average for the Maine sites. There are no nearby port facilities, however, deep water lies 5 miles to the east and the Boston and Maine Railroad passes near the site.

Westbrook Pluton - 3

This foliated biotite granite does have locally closely spaced joints and scattered high yield bedrock within the pluton. However, surficial cover is minimal and the well-developed Portland Harbor oil terminal lies only 7 miles away. Maine Central Railroad also runs nearby.

High Grade Metamorphics of the Cape Elizabeth Formation - 4

Lying just southeast of Bath in a region of many peninsulas bordered by deep ocean channels, these rocks consist of high grade quartzose metapelites. The nearly vertically dipping foliation is not a plane of weakness; joints are widely spaced. Surficial cover is generally minimal. Subsite 3 has a relatively deep potentiometric surface (100 feet below ground) and has a regional fault just to the east. Oil transfer to the sites in this rock formation would probably be made by barge.

Clark Island Granite (St. George Pluton) - 5

This biotite-muscovite granitic body has many excellent geologic and locational attributes. There are no significant faults or seismicity sources in close proximity. Other than sheet jointing, only one set of widely spaced vertical joints has been reported. Overburden is thin or non-existent and the ground water table is within 30 feet of the ground surface. Excellent deep ocean water tanker access is within 2 miles and the Maine Central Railroad is within 5 miles.

Mt. Waldo Pluton - 6

This very high strength granite rises steeply to over 1000 feet above adjacent sea level. To get below the water table, one would probably tunnel down into the mountain from somewhere near the base. A northwestly trending zone of active seismicity begins just to the northeast of the pluton. Although only widely spaced vertical joints are reported, vertical north-northwest fissures developed during quarry operations here indicating unrelieved stress in the rock. The Bangor and Aroostook Railroad lies adjacent to the site; a 20 foot navigable channel lies 2 miles to the east in the Penobscot River. Oil handling facilities are present in Bucksport, 4 miles to the southeast, and in Searsport, 9 miles to the south. A U.S. Air Force pipeline running from Searsport to Limestone also runs nearby.

Lucerne Pluton - 7

This large granitic body is at the southeast end of an active, northwesterly trending seismic zone. Strong northwest physiographic lineaments run through the Lucerne. Some moderately high bedrock well yields are reported throughout the pluton and the potentiometric ground water surface is 50 to 60 feet below ground surface in the vicinity of the site. The best oil transfer point would be in Blue Hill Bay, 6 miles to the southeast where 60 foot water depths are found.

Sedgwick Pluton - 8

This biotite granite has four separate vertical joint sets, but each set has wide spacing. There is a northeasterly trending fault zone inferred to run along the southeastern contact of the pluton which correlates with a zone of high yield bedrock wells in that area. Surficial cover is less than 20 feet. Deepwater tanker access is possible 2 miles away in Eggemoggin Reach and is also possible through Blue Hill Bay.

Tunk Lake Pluton - 9

The Tunk Lake Pluton is a granite with Tunk Lake lying over most of the core. Not much information is available on jointing, however, the core is reported to be relatively massive. There is an east-northeastly trending fault along the south-southeast edge of the intrusion. Surficial cover may be relatively thick in the core area (40 to 60 feet) but is minimal on the flanks. Although Maine Central Railroad runs through the southern end of the pluton, it is 8 miles to deep water at Sorrento.

Gabbro South-southeast of Addison - 10

There is little information available on this gabbro. Surficial cover may be relatively thick (up to 60 feet). Strong northwest physiographic lineaments cut through the terrain in this area. Deep water access is possible in Western Bay, 2½ miles away. Maine Central Railroad lies 7 miles to the north.

Great Wass Island Granite - 11

This biotite granite has two sets of widely spaced vertical joints, in addition to sheet joints. An instrumental MM Intensity V earthquake was recorded 2-1/3 miles to the north (a zone of moderately high yield bedrock wells are also found in the vicinity of the epicenter). The northeasterly trending Fundy Fault is inferred to lie one mile south of the site. There is no existing road transportation to the mainland, however, it is less than one mile to 120 foot ocean depths.

Jonesboro Granite Pluton - 12

The northeastern portion of the pluton is reported to have 3 sets of vertical joints, but there is no information on joints in the southwestern part of the intrusion. The ground water table may be fairly deep (about 60 feet) in the vicinity of the site but a surficial cover of lodgment till should be less than 20 feet thick. The Maine Central Railroad passes 3½ miles to the north. Chandler Bay has 60 foot depths within 5 miles of the site and 30 foot depths within 2½ miles.

Summary

Geologists mapping in Maine have selected 12 localities on the coast of Maine that they consider suitable for the storage of strategic oil supplies in large underground rock caverns. Ten of the sites are located in granite, one in gabbro, and one in high grade metamorphic rock. These sites are characterized as generally having a relatively massive structure with few joint sets, relatively low seismicity potential (Modified Mercalli Intensity VI or less), a high ground water table, and relatively thin surficial cover. Oil transfer to these sites can usually be made by deep draft ocean tankers within several miles of the sites. Railroad connections are also usually possible.

The combination of deep draft tanker transfer potential and suitable geologic conditions makes the Maine coast worthy of consideration for rock cavern storage of petroleum reserves.

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TABLE 1
Summary of Site Characteristics

Preliminary Geologic Survey of Potential Underground Oil Storage Sites in Maine
8 July 1977

Site, Rock Type & Age	Joints & Foliation	Seismicity & Faults	Hydrogeology	Overburden Thickness & Type	Distance to Oil Transfer Points
Agamenticus Pluton; binary granite, alkali syenite; 225 MY	Sheet joints; widely spaced vert. N20E, N40W joints, some slickensides; N10E, N45W lineaments in SW portion; no major joints in alkali syenite	Historical MM VIII 30 miles to SSE	Potentiometric level 60' below ground; moderately high well yields to SW & SE	Up to 40' fine-grained lodgment till	2½ miles to 60' ocean depth; Boston & Maine RR 5 miles to W; no nearby port facilities
Webhannet Granite; granite; Devonian	Generally massive; no detailed information on joints; reported to be locally free of closely spaced joints	Historical MM VIII 35 to 40 miles to SSE	Potentiometric level 10' or less below ground; no high yield wells in vicinity	20' to 60' of fine-grained lodgment till, sandy outwash	5 miles to 60' ocean depth; Boston & Maine RR runs near site; no nearby port facilities
Westbrook Pluton; biotite granite; Devonian	Sheet joints ½' to 2½' apart at surface; locally closely spaced N10E joints dipping 55W; granite often foliated	Historical MM VI 15 miles to N; instrumental MM VI 25 miles to SE; inferred regional faults trending NE run along SE and NW contact with country rock	Potentiometric level 50' below ground; high yield wells around contact with country rock; several moderately high yield wells within pluton	Generally less than 5' of lodgment and ablation till	7 miles to Portland oil port facilities; Maine Central RR runs nearby
Cape Elizabeth formation (high grade metamorphics); high grade quartzose metapelites; Ordovician-Silurian	nearly vert. bedding & foliation striking N5E with no parting on foliation; nearly horizontal joints several feet apart; widely spaced nearly vert. N75W joints	Historical MM IV 4 mi. to W; historical MM VI 25 miles to N; historical MM VI 20 miles to NW; instrumental MM VI 20 miles to S; NNE trending regional fault just east of subsite 3	Subsite 1--potent. level 20' to 40' below ground; mod. high well yields to S & W Subsite 2--potent. level 60' below ground; high yield wells to N, E, and S Subsite 3--potent. level 100' below ground; high yield wells to E	Generally less than 10' of till and silty marine-laid sediments	Subsite 1--2½ miles to 60' ocean depth in New Meadows River Subsite 2--1½ miles to 30' depth in Kennebec R. Subsite 3--2½ miles to 60' ocean depth; 0.3 miles to 30' ocean depth
Clark Island granite (St. George Pluton); biotite-muscovite granite, fine to med. even-grained texture; 367 MY; crushing strength 13,000 to 15,000 psi	sheet joints 2' to 10' apart at surface; vert. N65W joints at 10' to 20' spacing	No significant seismicity or faults nearby	Potentiometric level 30' below ground; one high yield well to NE	Generally less than 5' ablation till	2 miles to 60' ocean depth; Maine Central RR 5 miles to N
Mt. Waldo Pluton; fine even-grained biotite granite; 325 MY; ult. comp. strength 30,000 psi	sheet joints 8" to 8' at surface; vert. N85W & N60W at 20'-40' spacing; NNW vert. joints developed in quarrying	3 Hist. & 1 instr. MM V 15 mi. to NE; NE trending Norumbega Fault 5 miles to NW	Potent. level 100' below ground at el. 200'; high yield wells around northern contact	Generally less than 5' ablation till	2 miles to 20' ocean depth in Penobscot R.; Bangor & Aroostook RR adjacent to site; oil port 4 miles to SE

TABLE 1
Summary of Site Characteristics

Preliminary Geologic Survey of Potential Underground Oil Storage Sites in Maine
8 July 1977

Site, Rock Type & Age	Joints & Foliation	Seismicity & Faults	Hydrogeology	Overburden Thickness & Type	Distance to Oil Transfer Points
Lucerne Pluton; coarse-grained granite 356 MY	No detailed information on joints; strong N35W physiographic lineaments	3 Hist. & 1 instr. MM V 20 miles to NE; inferred fault along NW contact; at SE end of N35W trending seismic zone	Potentiometric level 50' to 60' below ground; some mod. high yield wells within pluton	Generally less than 20' lodgment till	6 miles to 60' ocean depth in Blue Hill Bay; Bucksport oil facilities 11½ miles to NW
Sedgwick Pluton; coarse to medium-textured biotite granite; 395 MY	Sheet joints 2'-8' apart at surface; vert. N40W, N50E, N67E, N67W joints at 15'+ spacing	No significant seismicity in area; NE trending fault along SE contact	Potentiometric level 40' below ground; high yield wells to the S	Generally less than 20' lodgment till	2 miles to 60' ocean depth in Eggmoggin Reach; ship transfer also possible in Blue Hill Bay
Tunk Lake Pluton; granite; Devonian	No detailed information on joints; reported to be relatively unjointed in the core	No significant seismicity in area; ENE trending fault along SSE edge of pluton	Potent. level less than 20' in core, but deeper in rock around core; no reported high yield wells in pluton	40' to 60' till & lacustrine deposits over core, but less than 10' till on rock around core	8 miles to 60' ocean depth at Sorrento; Maine Central RR just to S
Gabbro SSE of Addison; gabbro; Devonian	No detailed information on joints; strong NW physiographic lineaments	Instrumental MM V 5 miles to SE; NE trending Fundy Fault 8 miles to SE	Potentiometric level 40' below ground; mod. high well yields to E	Up to 60' of lodgment till	2½ miles to 60' ocean depth in Western Bay; Maine Central RR 7 miles to N
Great Wass Island granite; coarse-grained biotite granite; Devonian	Sheet joints 5'-15' apart at surface; vert. N10E joints at 5'-10' spacing; vert. N90W joints at 20'+ spacing	Instrumental MM V 2-1/3 miles to N; NE trending Fundy Fault 1 mile to S	Potentiometric level 20' below ground; mod. high yield wells to N	Less than 40' lodgment till and silty marine-laid sediments	1 mile to 120' ocean depth; no highway to mainland
Jonesboro Granite Pluton; medium-textured biotite granite; Devonian	Sheet joints ½'-5' apart at surface; vert. joints in NE part of pluton striking N60E, N50W, & N70W	Instrumental MM V 10 miles to S; NE trending Fundy Fault 12 miles to SE	Potentiometric level 60' below ground; high yield wells to NW within pluton	Less than 20' of lodgment till	5 miles to 60' ocean depth in Chandler Bay, 2½ miles to 30' depth; Maine Central RR 3½ miles to N

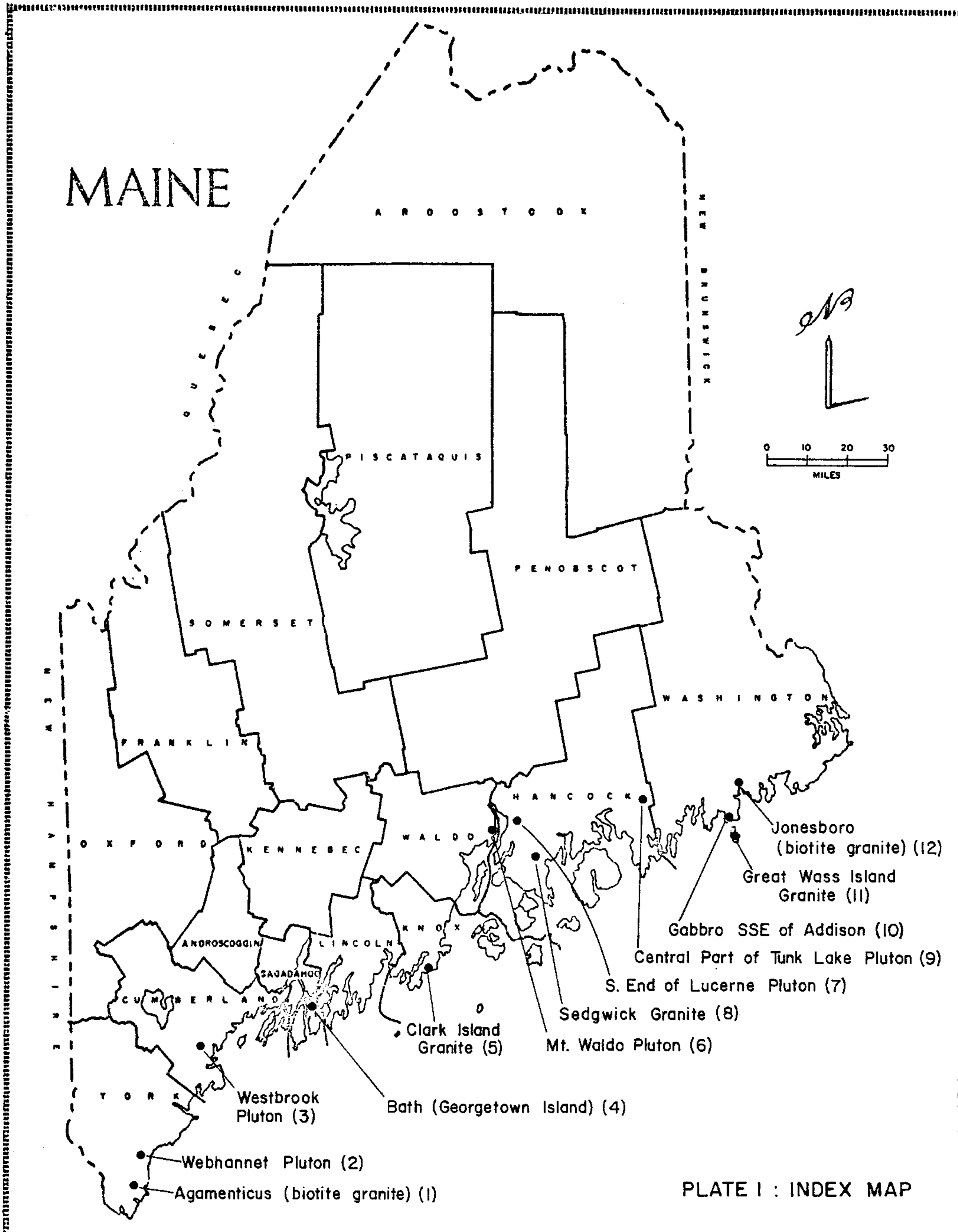
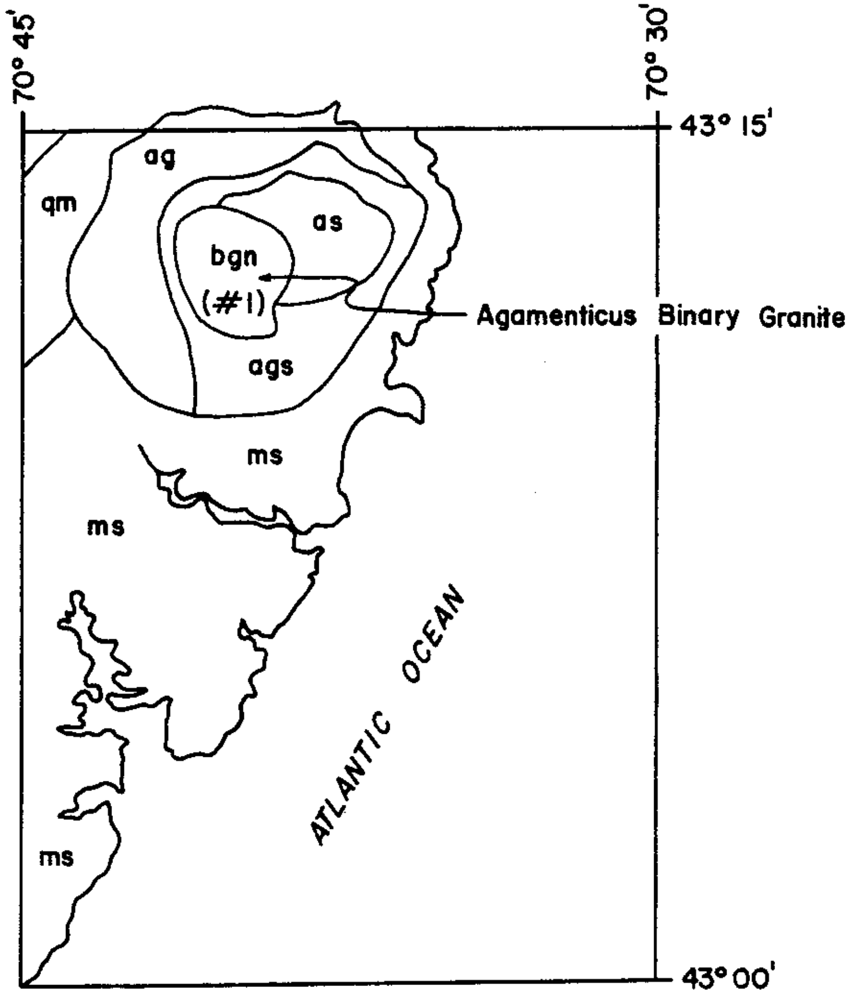


PLATE I : INDEX MAP



LOCALITY # 1: Agamenticus Binary Granite

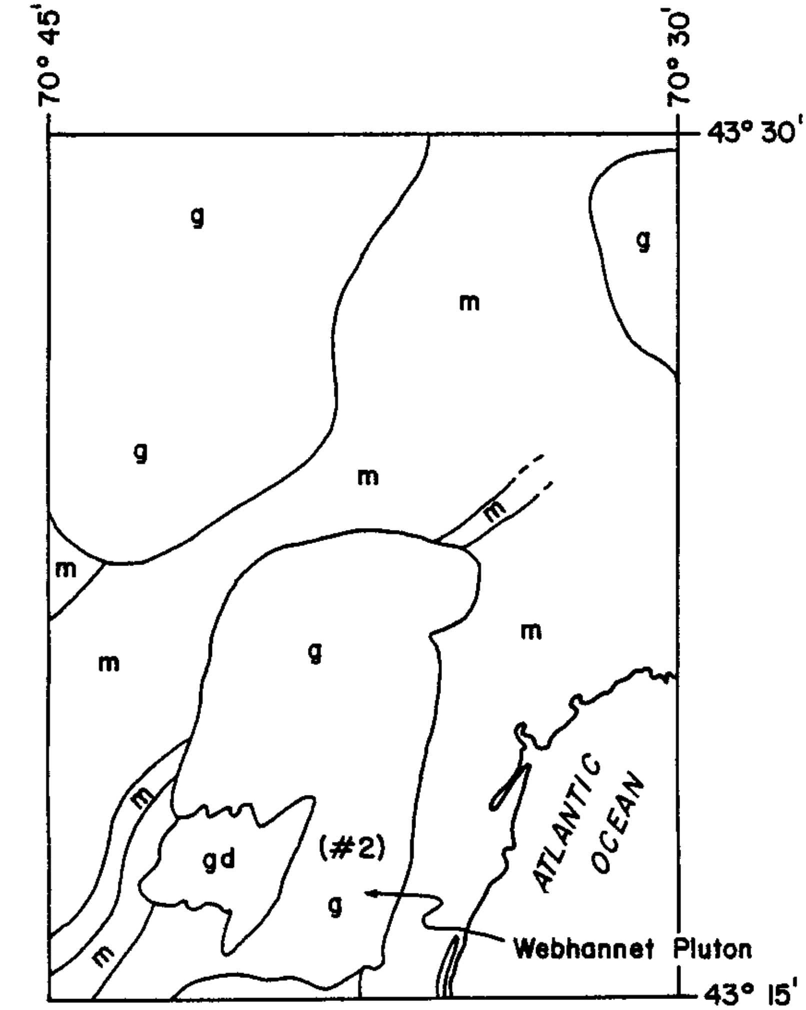
ms - metamorphic rocks
qm - quartz monzonite
as - alkaline syenite
ag - alkaline granite
ags - alkaline quartz syenite

Scale 1:250,000

N

FIGURE 1

MGS 1977



LOCALITY #2: Webhannet Granite

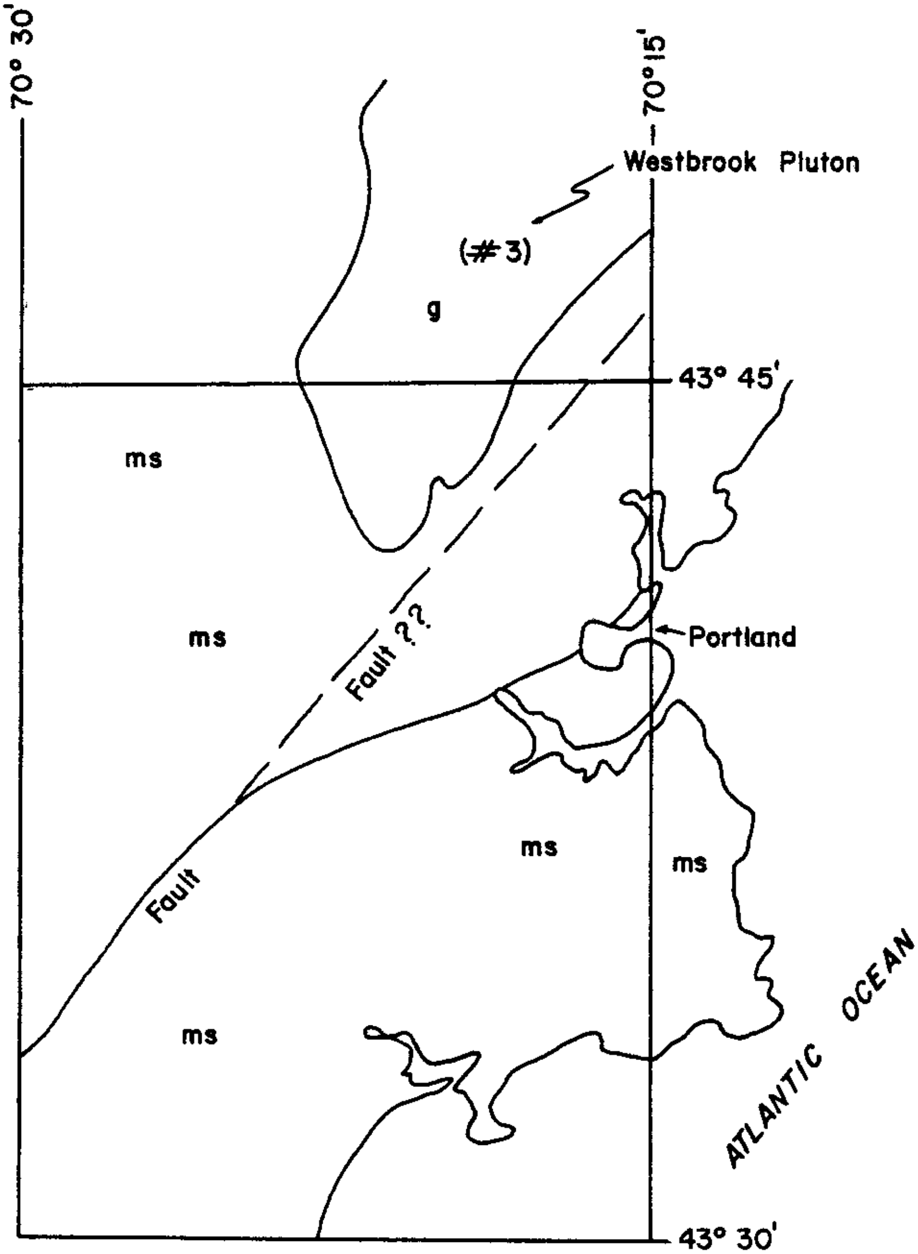
m - metamorphic rocks
g - granite
gd - granodiorite

Scale 1:250,000

N

FIGURE 2

MGS 1977

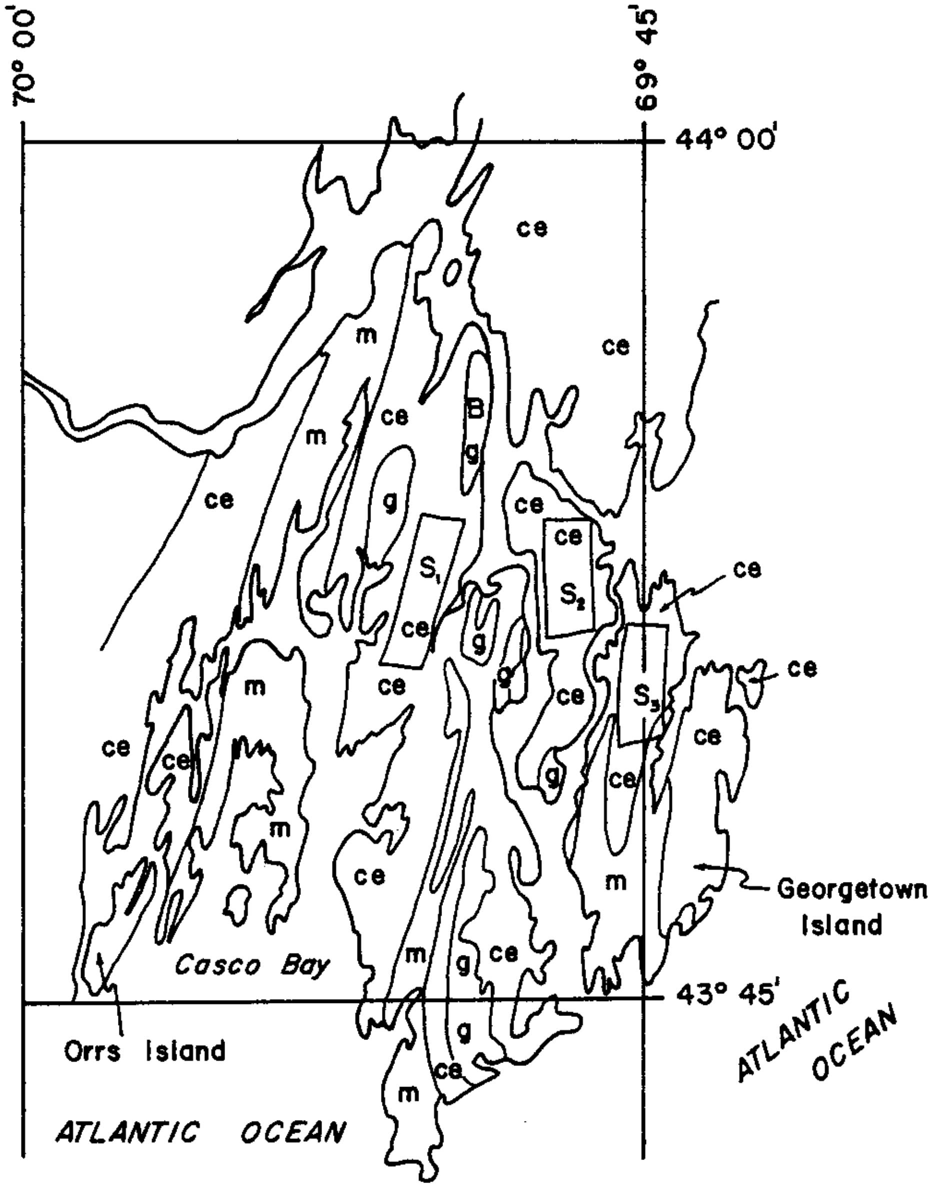


LOCALITY #3: Westbrook Pluton
ms - metamorphic rocks
g - granite

Scale 1:250,000

FIGURE 3

MGS 1977



LOCALITY # 4: Highgrade Metamorphic Rocks Near Bath (shown by B)

Sites 1,2,3 in the Cape Elizabeth Fm

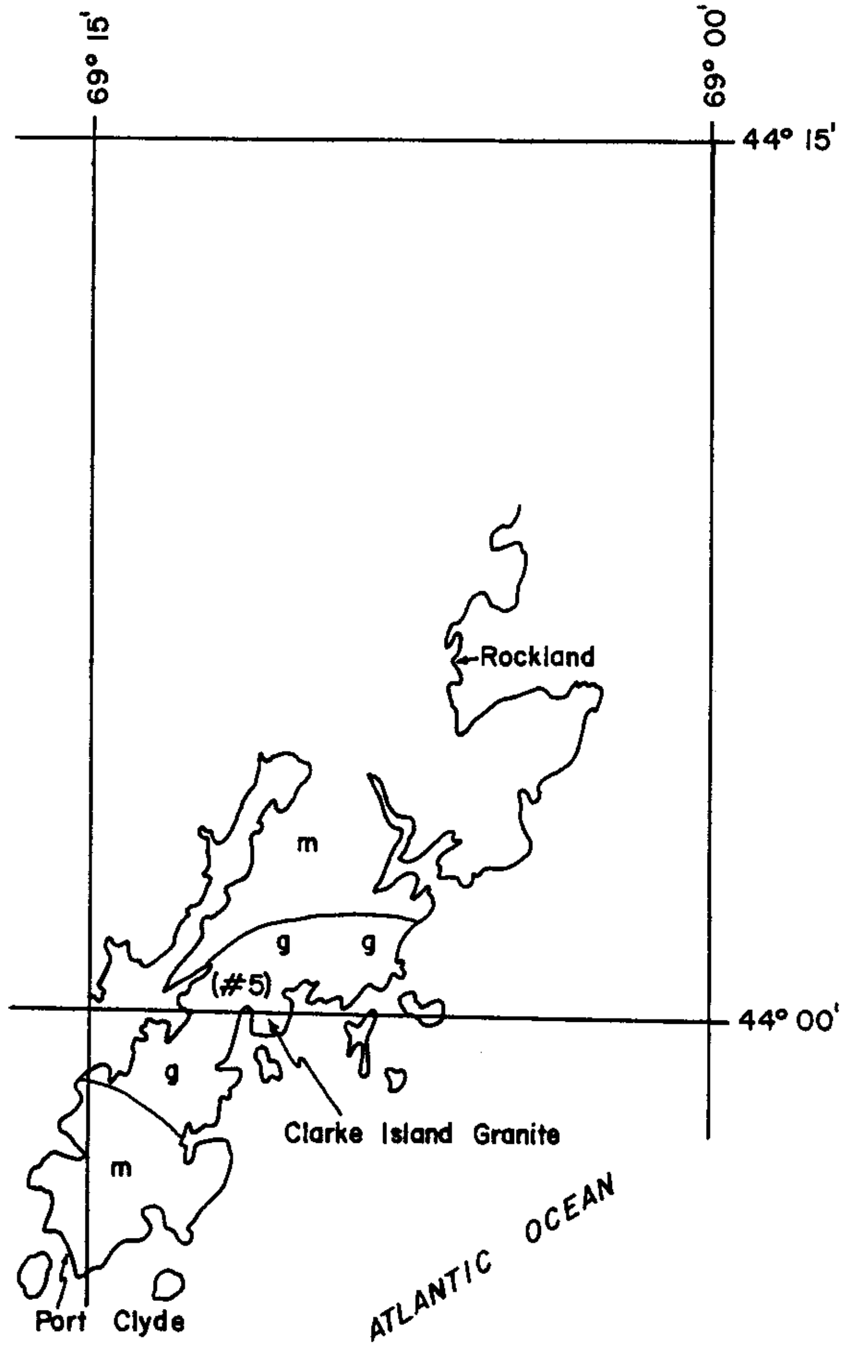
g - granite
m - other metamorphic rocks
ce - Cape Elizabeth migmatites

Scale 1:250,000

N

FIGURE 4

MGS 1977

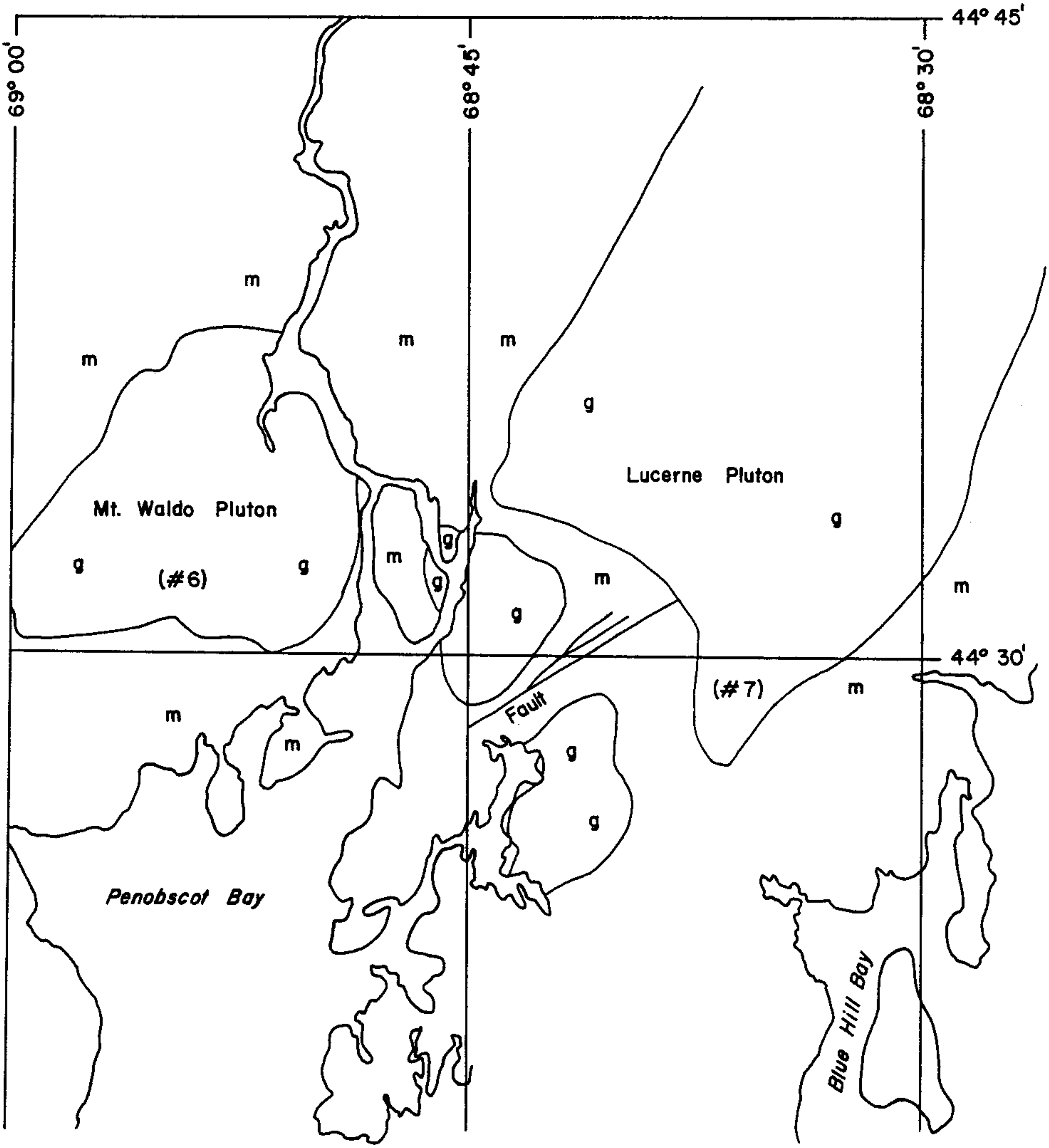


LOCALITY #5: Clark Island Granite
m - metamorphic rocks
g - granite

Scale 1:250,000

FIGURE 5

MGS 1977



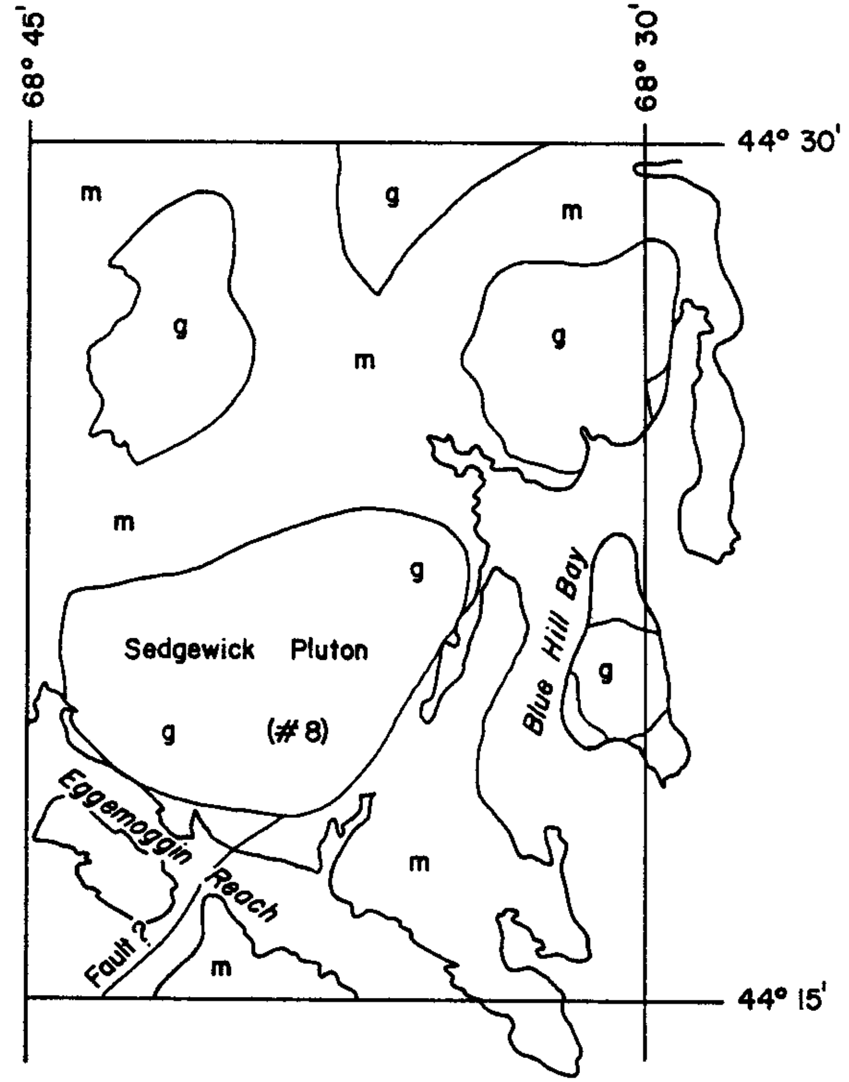
LOCALITY #6: Mt. Waldo Pluton
#7: South End of the Lucerne Pluton
m - metamorphic rocks
g - granite

Scale 1: 250,000

N

FIGURE 6

MGS 1977



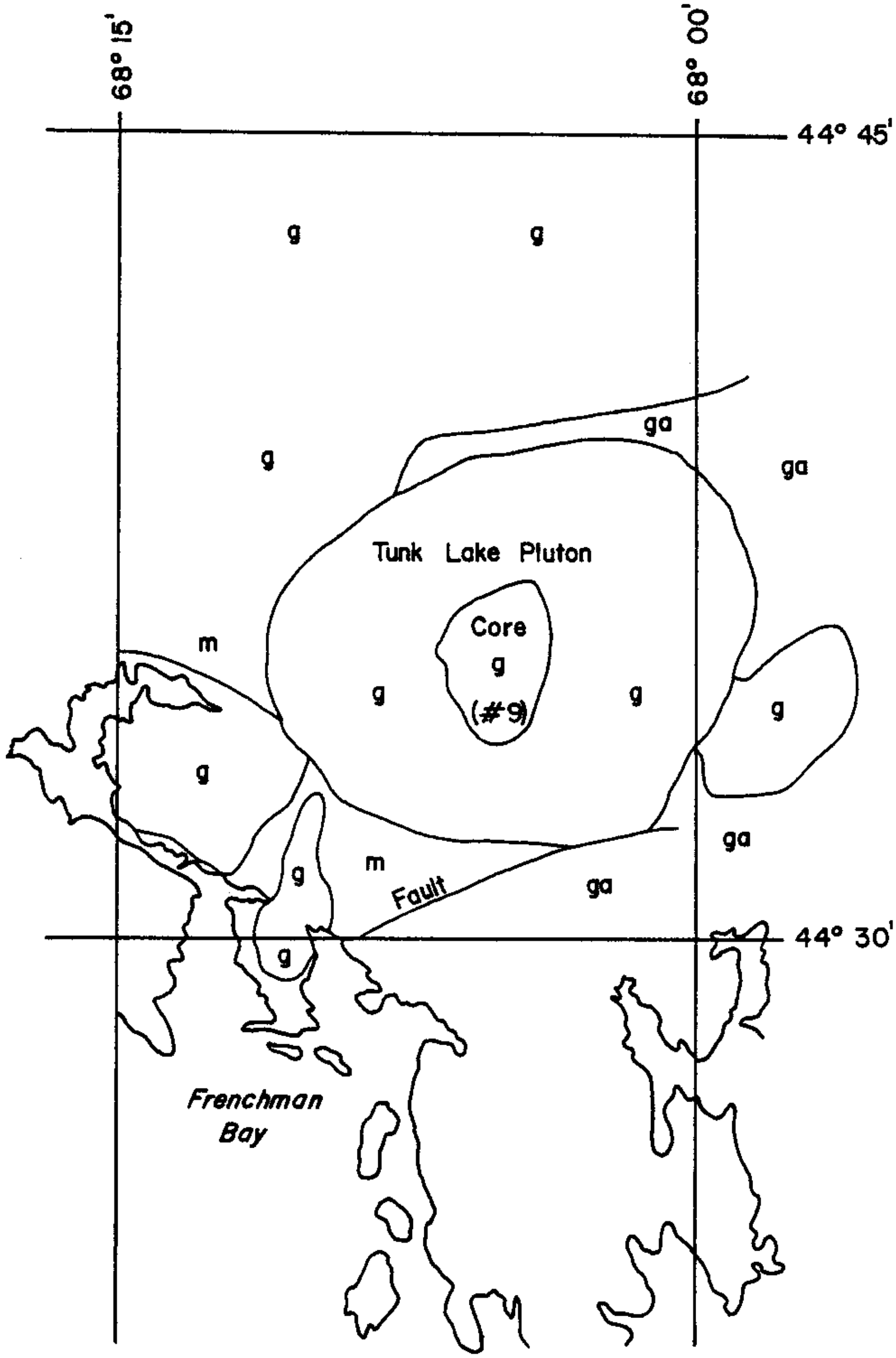
LOCALITY #8: Sedgwick Granite
m - metamorphic rocks
g - granite

Scale 1:250,000

N

FIGURE 7

MGS 1977



LOCALITY #9: Central Part of Tunk Lake Pluton

m - metamorphic rocks

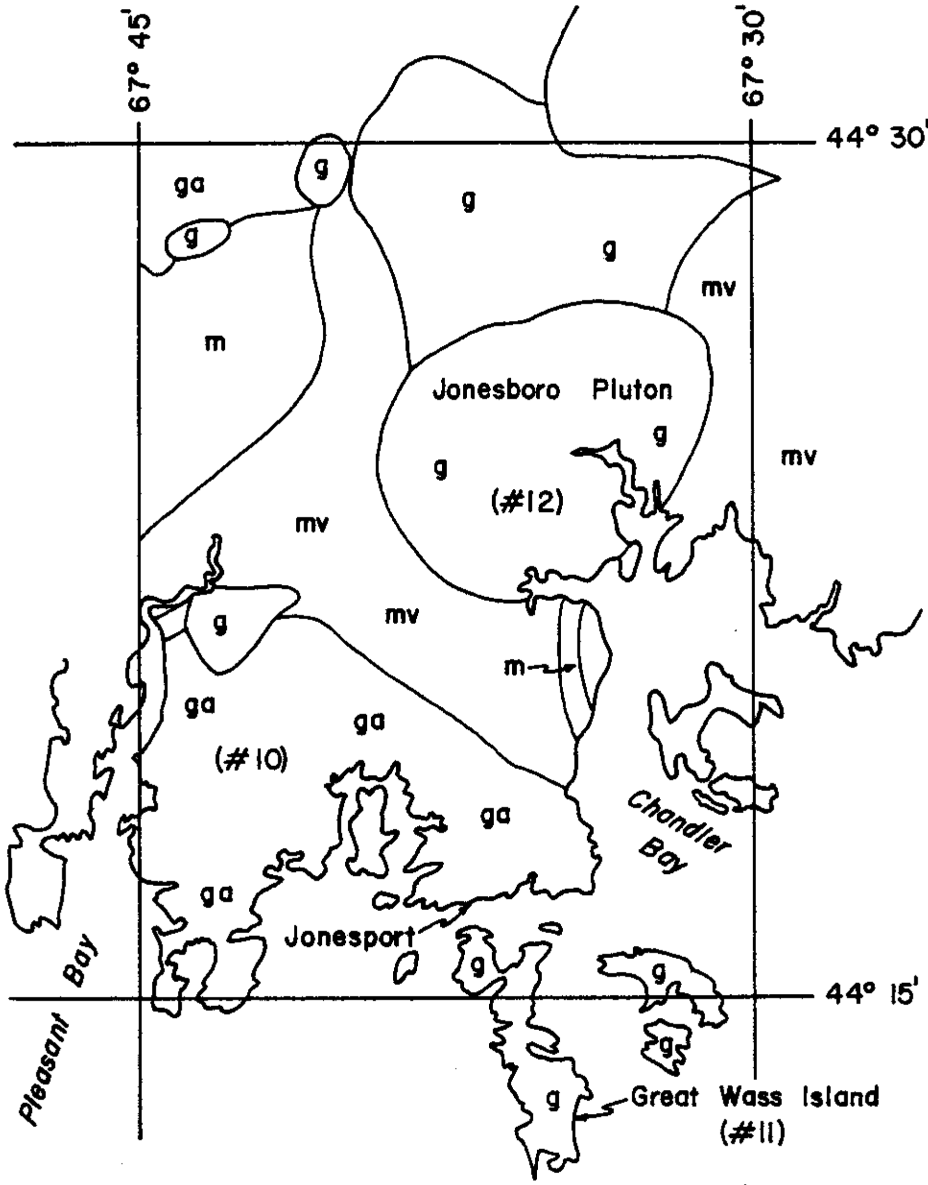
g - granite

ga - gabbro

Scale 1:250,000

FIGURE 8

MGS 1977



LOCALITY # 10: Gabbro to SSE of Addison
11: Granite on Great Wass Island
12: Jonesboro Granite Pluton

ga - gabbro
g - granite
mv - weakly metamorphosed volcanic rocks
m - weakly metamorphosed shales

Scale 1:250,000

N

FIGURE 9

MGS 1977