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The Bedrock Geology of the Brewer Lake 7.5 ' Quadrangle, Maine

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INTRODUCTION

Rocks of the Brewer Lake 7.5' quadrangle include Late Precambrian(?) to Devonian(?) metasediments of the Passagassawakeag, Copeland, Vassalboro, and Bucksport Formations, the Rider Bluff member of the Copeland Formation, and the Mixer Pond member of the Passagassawakeag Formation; the Late Silurian to Early Devonian Stricklen Ridge granite; and the Devonian Lucerne pluton. The metasedimentary sequence was deformed by pre-Late Silurian isoclinal folding and subsequently intruded by the Stricklen Ridge granite and metamorphosed by an amphibolite facies event. A second folding event deformed this sequence prior to intrusion of the Lucerne pluton. Right-lateral strike-slip ductile shearing occurred along the Norumbega fault zone. High-angle, post-metamorphic brittle faults and fractures parallel the ductile shear zones.

The bedrock geology explained and illustrated in this report is the result of mapping by the author for his Masters research at Virginia Polytechnic Institute and State University and by Wones (unpublished data) during his research on the Lucerne pluton. Descriptions of units mapped only by Wones (Passagassawakeag Formation, Mixer Pond member, Vassalboro Formation, and Lucerne pluton) were compiled by the author as interpreted from Johnson and Wones (1984, 1985), Kaszuba and Wones (1985), Loiselle and Wones (1983), Stewart and Wones (1974), Wones (1974, 1976, 1978, 1980, and unpublished data), and Wones and Stewart (1976).

Editor's note: Field work for this project was completed in 1985 and the contract report was submitted in April 1986.

METASEDIMENTARY ROCKS

Passagassawakeag Formation

The Passagassawakeag Formation (Bickel, 1976) is a quartz-feldspar-biotite gneiss intercalated with layers and boudins of biotite schist. The type locality is at the headwaters of the Passagassawakeag River in the Belfast area (Bickel, 1976). The Passagassawakeag Formation crops out in the western portion of the Brewer Lake 7.5' quadrangle and extends from the Norumbega fault zone in the north to its contact with the Copeland Formation to the south. The Passagassawakeag Formation crops out in a ~10 km wide belt that extends ~5 km to the southwest into the Belfast area. The thickness of this unit is unknown, but in the Belfast area it is estimated to be ~300 m (Bickel, 1976).

Gneissic layers of the Passagassawakeag Formation are light-colored and predominantly composed of medium-grained quartz, plagioclase, K-feldspar, and biotite. Feldspar also occurs as coarse-grained augen. The presence of these augen is characteristic of the unit and prompts the nickname "popcorn gneiss." Schist layers and boudins are gray in color and less abundant than gneiss layers. The schist is mineralogically similar to the gneiss, but contains more biotite. Schist and gneiss layers are interlayered on a cm- to m-scale and often display pinch-and-swell structure. Sillimanite- and garnet-bearing metamorphic assemblages commonly occur, but it is not known if sillimanite is the product of reactions involving andalusite or muscovite + quartz. Numerous granitic and pegmatitic dikes and sills intrude these gneisses and are thought to be related to the Stricklen Ridge granite.

The age of the Passagassawakeag Formation is poorly constrained, but is thought to be Precambrian based on: (1) truncation by pegmatites related to the Late Silurian to Early Devonian Stricklen Ridge granite; and (2) lithologic similarity to other Precambrian rocks in New England (Stewart and Wones, 1974). Bickel (1976) interpreted the gneisses as metamorphosed feldspathic sedimentary and volcanic rocks on the basis of lithology.

Mixer Pond Member

The Mixer Pond member of the Passagassawakeag Formation (Bickel, 1976) is a fine-grained, light-colored, quartz-oligoclase-microcline gneiss. The type locality is at Mixer Pond in the Belfast area. The Mixer Pond member crops out in a < 1 km^2 area in the northwest portion of the Brewer Lake 7.5' quadrangle. The contact between it and the Passagassawakeag Formation is not exposed in the quadrangle, and its thickness is unknown. Wones (unpublished data) mapped it in the Bucksport 15' quadrangle as fault slivers within the Norumbega fault zone.

The Mixer Pond member is indistinctly layered on a scale of a few meters and is distinguished by its fine grain-size and feldspathic composition. It had been interpreted on the basis of lithology as a feldspathic metavolcanic unit interlayered with the Passagassawakeag Formation (Bickel, 1976). A 468 36 Ma age from Rb/Sr whole-rock data was assigned to it and interpreted as a metamorphic age (Gaudette, pers. commun., 1986).

Copeland Formation

The Copeland Formation (Trefethen, 1950; Wing, 1957) is composed of interlayered beds of bluish-gray pelitic schist and quartzite. The type locality is at Copeland Hill in the northwest portion of the Brewer Lake 7.5' quadrangle. The Copeland Formation crops out in an arcuate, belt-like pattern along the eastern margin of the Passagassawakeag Formation. It extends from the Norumbega fault zone in the northwest to the southwest corner of the study area where it pinches out. The width of the outcrop belt ranges from 3.5 km in the north to 2.5 km in the south. It also crops out in the northwest portion of the quadrangle in an area bounded by fault traces of the Norumbega fault zone. The contact between the Copeland and the Passagassawakeag Formations is not exposed in the quadrangle. It is not known whether the contact is conformable, unconformable (Stewart and Wones, 1974), or tectonic. The relative structural position between the two units is also unknown. The original thickness of the Copeland Formation in the quadrangle is unknown because its contacts are poorly constrained and multiple folding events have deformed it.

Pelites of the Copeland Formation are predominantly composed of medium-grained biotite, muscovite, and quartz. Accessory staurolite, andalusite, and sillimanite may also occur near stocks of Stricklen Ridge granite. Quartzites contain minor amounts of biotite and muscovite. Minor plagioclase (An_{21-28}), tourmaline, apatite, ilmenite, and garnet (average composition: 70% almandine, 20% spessartine, 8% pyrope, and 3% grossular) occur in both pelites and quartzites.

The pelites and quartzites are interlayered on a scale ranging from a few centimeters to tens of meters. Compositional grading of the layers from quartzite to pelite on individual outcrops and across the unit as a whole is interperted to represent bedding. Quartzites are predominant on Deer Hill and the southeast margin of Blood Mountain where they comprise 75-90% of the outcrop. Farther to the west, such as on Orcutt Mountain and the northwest margin of Blood Mountain, pelites comprise approximately 75% of the outcrop.

Veins, lenses, and centimeter-scale boudins of quartz that parallel bedding and foliation are prevalent in the pelites. Quartz and quartz + feldspar veins are especially common within 0.5 km of the contact with the Rider Bluff member. Green amphibolite layers concordant to the pelite and quartzite layering are typically 10 to 20 cm thick but cannot be traced along strike for more than a few meters. The lensoid character of the amphibolite layers suggests that they are boudins of originally more continuous mafic layers.

The Copeland Formation has been correlated on the basis of similar lithologies (Wones, 1976; Loiselle and Wones, 1983) with the Hogback Formation (Perkins and Smith, 1925) and Appleton Ridge Formation (Bickel, 1976) in the Belfast area and with the Cape Elizabeth Formation of the Casco Bay Group (Katz, 1917; Hussey, 1968, 1985) in the Casco Bay area. The Appleton Ridge Formation has been assigned a 455 25 Ma age from Rb/Sr whole-rock isochron data (Brookins, 1976). The Cape Elizabeth Formation has been assigned a 485 30 Ma age from Rb/Sr whole rock isochron data (Brookins and Hussey, 1978). Stratigraphic relationships suggest it is Late Precambrian to Ordovician in age (Hussey, 1968, 1985). These lithologic correlations are rather tenuous, and the assignment of a Precambrian to Ordovician age to the Copeland Formation is tentative.

Rider Bluff Member

The Rider Bluff member (informal usage by Stewart and Wones, 1974; Wones, 1976) of the Copeland Formation is a green, finely-laminated (millimeter-scale) pelitic siltstone. The type locality is on Rider Bluff in the northern portion of the quadrangle. The Rider Bluff member crops out as a sinuous, discontinuous belt along the eastern margin of the Copeland Formation. The width of the outcrop ranges from 2.0 km at Rider Bluff to 0.2-0.8 km further to the south. It is not known if this range in outcrop width is related to changes in bedding orientation, unit thickness, and/or deformation. The Rider Bluff member is assigned to the Copeland Formation (Wones, unpublished data) because it is lithologically more similar to the Copeland Formation than to any other unit. Kaszuba and Wones (1985) interpreted the Rider Bluff member as ductilely deformed Copeland Formation. Subsequent work revealed that the two

units are lithologically distinct where undeformed, but that ductilely deformed Rider Bluff member is almost indistinguishable from deformed Copeland Formation. No fossils have been found in the Rider Bluff member, and no radiometric dating has been attempted. The contact between the Rider Bluff member and the Copeland Formation to the west and the Bucksport Formation to the east is not exposed. The original thickness of the Rider Bluff member is unknown because its contacts are poorly constrained and because multiple folding events have deformed it.

In thin section, the Rider Bluff member is predominantly composed of chlorite, quartz, and plagioclase. The laminations are defined by alternating chlorite- and quartz-rich laminations. Minor epidote, muscovite, magnetite, garnet, tourmaline, and pyrite may also occur. Biotite, garnet, and albite occur as abundant porphyroblasts 1-3 mm across.

Bedding in the Rider Bluff member is difficult to recognize, but may be represented by magnetite- or granite-rich layers. Magnetite-rich layers contain 1-5% euhedral, 1-2 mm diameter magnetite octahedra. One anomalous outcrop on the southern tip of Long Lake contains 25% magnetite. Garnet-rich layers contain 5-10% euhedral, 3-5 mm diameter, amber-colored garnets (average core composition: 52% spessartine, 33% almandine, 12% grossular, 2% pyrope; average rim composition: 62% almandine, 26% spessartine, 5% grossular, 5% pyrope). The magnetite- and garnet-rich layers generally parallel the fine laminations, and contacts between these layers and the surrounding schist are diffuse. Ubiquitous quartz lenses and boudins are parallel to and folded with the laminations and comprise approximately 5% of any outcrop.

The presence of magnetite- and/or garnet-rich layers and biotite and albite porphyroblasts in the Rider Bluff member distinguishes it from the Copeland and Bucksport Formations. In the absence of these layers, Rider Bluff member is distinguished from the Bucksport Formation by the presence of abundant quartz lenses and boudins and the absence of carbonate, and is distinguished from the Copeland Formation by the presence of millimeter-scale laminations and the absence of interlayered pelitic schist and quartzite.

Magnetic anomaly maps of the area show a magnetic high of 300-500 nanoteslas. This anomaly displays a map pattern that generally coincides with the outcrop pattern of the Rider Bluff member (Zietz et al., 1980; Stewart et al., 1986). Magnetic anomalies over the Rider Bluff member in the northern portion of the study area (e.g. Rider Bluff) are as high as 700 nanoteslas. These anomalies are probably the result of the magnetite present in the Rider Bluff member.

Vassalboro Formation

The Vassalboro Formation (Perkins and Smith, 1925; Osberg, 1968) is a calcareous quartz wacke. Its type locality is in the town of Vassalboro west of Penobscot Bay. It crops out in a small slice within the Norumbega fault zone in the northeast corner of the Brewer Lake 7.5' quadrangle.

The calcareous quartz wackes of the Vassalboro Formation contain white mica, chlorite, calcite, and quartz and weather to a gray to green color. Compositional layering is probably related to original bedding and includes thin beds (several cm's to m's thick) of gray quartz-mica schist. Schist beds are ubiquitous but distinctly less abundant than the wacke and contain sulfides that commonly weather to a rusty color. Quartz veins are abundant.

The Vassalboro Formation was interpreted as part of a turbidite sequence (Osberg, 1968, 1979) now metamorphosed to greenschist facies (Stewart and Wones, 1974). A single graptolite locality west of Penobscot Bay suggests a Llandoverian to Ludlovian age (Pankiwskyj et al., 1976).

Bucksport Formation

The Bucksport Formation (Trefethen, 1950; Wing, 1957) is a greenschist facies calcareous siltstone. The unit is named for exposures in the Silver Lake area in the Bucksport 15' quadrangle (~ 4 km north of the town of Bucksport). It crops out in the Brewer Lake 7.5' quadrangle as an irregularly-shaped belt (0.6-3.5 km wide) east of the Rider Bluff member and west of the Lucerne pluton and directly adjacent to the Copeland Formation in the southwest portion of the quadrangle. The original thickness of the unit in the quadrangle is unknown because it is not well exposed and its contacts are poorly constrained.

The siltstones of the Bucksport Formation contain finely-laminated (1-2 mm thick) carbonate-bearing beds (0.5 to several meters thick). The laminations are defined by the alternation of quartz- and mica-rich siltstone containing fine- to very fine-grained quartz, white mica, chlorite, calcite, ilmenite, and plagioclase. Accessory biotite, calcic amphibole, tourmaline, titanite, and epidote may also occur. Interlayered with the calcareous siltstones (which comprise approximately 95% of any outcrop) are suflide-bearing pelitic siltstone beds (several centimeters to 0.5 km thick) which weather to a rusty color. The pelites are compositionally and texturally similar to the calcite-bearing beds but are coarser-grained, contain less quartz and more phyllosilicate, and contain no sphene or amphibole and little or no carbonate.

In the northern portion of the quadrangle, quartz veins commonly occur as lenses and boudins parallel to the laminations, although cross-cutting veins do occur. Occasional composite quartz + calcite veins also occur. Quartz veins are far less common in the southern portion of the quadrangle. This distribution of quartz veins within the Bucksport Formation may be related to proximity to the Norumbega fault zone.

The Bucksport Formation is lithologically similar to the Silurian Vassalboro Formation and has been correlated with it (Stewart and Wones, 1974; Wones, 1976, 1980; Osberg, 1980; Loiselle and Wones, 1983; Gates et al., 1984; Hussey, 1984). No fossils are found within the Bucksport Formation, and nowhere can it be traced directly into the Vassalboro Formation. Age cor-

relations are based strictly on lithologic similarities across the Norumbega fault zone. Loiselle and Wones (1983) suggested that slices of rock mapped within the Norumbega fault zone may be either Vassalboro or Bucksport Formation. The two units are often difficult to distinguish where deformed. The Late Silurian to Early Devonian Flume Ridge Formation (Ruitenberg, 1967; Ruitenberg and Ludman, 1978), part of the Fredericton trough, has also been correlated with the Bucksport Formation based on lithologic similarities (Wones, 1980; Ludman, 1981). The Bucksport Formation as mapped by Bickel (1976) in the Belfast area was distinguished by Wones (unpublished data) as a different unit from Bucksport Formation as defined by Wing (1957) in the type locality north of the town of Bucksport.

IGNEOUS ROCKS

Stricklen Ridge Granite

The extent of Stricklen Ridge granite (informal usage by Wones, 1974, 1976; Stewart and Wones, 1974) outlines the occurrence of a two-mica, garnet-bearing leucogranite that intruded the Copeland and Passagassawakeag Formations and Rider Bluff member as dikes, sills, and very small stocks. The regional stratigraphy is traceable through the granite terrane. Overall the granite comprises less than one-eighth of the total map area outlined as Stricklen Ridge granite. Within the Copeland Formation, two areas of 1-2 km^2 extent have been delineated where Stricklen Ridge granite comprises greater than 50% of the exposure (Fig. 1). Within these stocks there are only a few places where granite comprises greater than 90% of the exposure. The granite was named by Wones (unpublished data) for exposures of one of these stocks on Stricklen Ridge. Dikes of Stricklen Ridge granite have been assigned a 412 14 Ma age based on concordant U-Pb data from zircons (Zartman and Gallego, 1979).

The Stricklen Ridge granite is a compositionally restricted (Pitcher, 1979) monzogranite in the IUGS classification system (Streckeisen, 1973)(Fig. 2). Biotite-rich tonalite (Figs. 2, 3) dikes sometimes occur in small amounts (Fig. 1) in Stricklen Ridge granite outcrops. These tonalite dikes cut Stricklen Ridge granite and are intruded by pegmatite. No tonalite is reported in the Penobscot Bay area. The same field relationships are described for the Winterport granite (Trefethen, 1944), which occurs in the Bucksport 15' quadrangle. However, it is described as a mafic-rich granodiorite (Stewart and Wones, 1974; Wones, 1976, unpublished data; Loiselle and Wones, 1983).

Feldspars and quartz range in size up to ~5 mm in diameter (i.e. seriate texture, Wones, 1980). K-feldspar is usually subhedral to anhedral, perthitic microcline (Or_{90-95}, Ab_{5-10}), but sometimes it occurs as orthoclase. Plagioclase is subhedral and uniform in composition (An_{10-17}). Compositional zoning in plagioclase is prevalent, but no systematic zoning pattern is observed. K-feldspar sometimes surrounds and replaces plagioclase as anhedral grains. This replacement may be related to fluid/rock interaction during late-stage crystallization of the granite or to one of the post-granite deformations. The granite displays variations in kinds and abundance of accessory minerals (Figs. 2, 3) and texture. Aplites, tourmaline-bearing pegmatites, and miarolitic cavities are common, suggesting vapor saturation of the melt (Jahns and Tuttle, 1963; Jahns and Burnham, 1969; Krauskopf, 1979).

Gravity data collected from the Penobscot Bay area (Kane and Bromery, 1966; Sweeney, 1974, 1976) indicates a north-south-trending, elongate anomaly trough over the quadrangle. Three-dimensional models of this data (Sweeney, 1974, 1976) suggest that the Stricklen Ridge granite is a north-south-trending, discrete body ~3.0 km thick, 1.5 to 3.0 km wide, and more than 11 km long with a total volume of approximately 100 km^3. Contacts on the east side are subvertical while those on the west side dip inward (east) towards the body. In Sweeney's (1974, 1976) gravity models, a difference of approximately 0.01 g/cm^3 between granite and background densities results in a thickness change of approximately 1 km for the subsurface granite bodies, but the models depend on density data from only two samples (Sweeney, 1976). While the exact dimensions depicted in Sweeney's (1976) models may be debatable, the data strongly suggest that the Stricklen Ridge granite occurs as a discrete body just below the surface of the quadrangle. The abundance of aplites, tourmaline-bearing pegmatites,

coarse-grained granite	54.5%	71.0%
fine-grained granite	2.5%	3.0%
tonalite	3.5%	4.5%
Copeland Formation	16.5%	21.5%
not exposed	23.0%	—
total	100.0%	100.0%

Figure 1. Estimated modal percentage by area of different rock types exposed in a representative outcrop mapped as a stricklen Ridge granite stock. Outcrop is located at UTM grid coordinates: 4943.0N, 521.55E. Mode was determined by a 1 m grid spacing of a horizontal pavement approximately 200 m^2 in area. First data column includes the percentage of outcrop not exposed, the second column excludes this area from the totals. Modal analyses (volume percent) of the three granite varieties are listed in Figure 2.

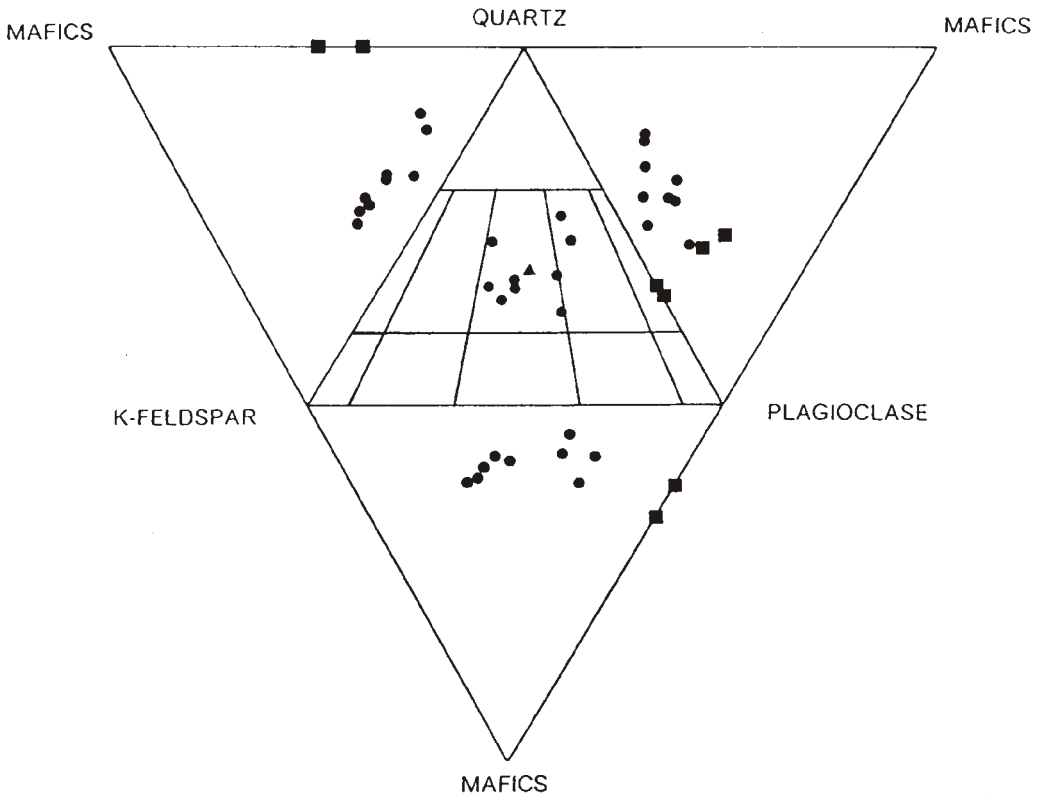

Figure 2. Modal analyses of Stricklen Ridge granite. Solid circle, granite; solid square, tonalite; solid triangle, sample of Carl et al. (1984).

	1	2	3	4	5	6	7
Quartz	40.3	40.6	24.4	42.2	34.0	28.9	26.1
K-feldspar	29.1	30.1	np	13.9	21.7	34.9	35.5
Plagioclase	18.6	16.8	52.4	35.8	39.2	24.0	27.9
Biotite	1.5	0.3	21.4	np	0.2	1.8	5.5
Muscovite	9.2	9.5	np	7.2	2.6	5.7	0.7
Garnet	np	np	np	np	0.8	4.2	np
Apatite	tr	0.3	0.3	tr	tr	tr	0.4
Chlorite	1.1	1.5	0.5	np	0.6	0.5	2.0
Hematite & Ilmenite	0.2	tr	0.1	np	tr	tr	0.1
Epidote	np	np	np	np	np	np	0.1
Secondary Muscovite	tr	0.9	0.9	0.9	0.8	tr	1.6
Total	100.0	100.0	100.0	100.0	99.9	100.0	99.9

1. Coarse-grained granite of Fig. 1.
2. Fine-grained granite of Fig. 1.
3. Tonalite of Fig. 1.
4, 5, 6. Granite near stock on Stricklen Ridge (UTM grid no. 4949.2N, 523.3E).
7. Granite near shear zone (UTM grid no. 4946.1N, 523.6E).

Figure 3. Modal data (by volume) of representative samples of Stricklen Ridge granite. Minimum 1000 points counted per thin section. Chlorite, hematite, ilmenite, and epidote are secondary minerals associated with the recrystallization of biotite. Secondary muscovite associated with the recrystallization of muscovite and plagioclase. Abbreviations: tr, trace amounts (less than detected by point count grid); np, not present.

and miarolitic cavities; the variation in texture; and the occurrence of sills, dikes, and very small stocks rather than one homogeneous expanse of granite are consistent with it being the roof zone of a granitic pluton.

Lucerne Pluton

The Lucerne Pluton is 672 km^2 in area and is one of the 10 largest plutons in New England (Wones, 1980). The type locality is at Lucerne in the northeast portion of the Orland 15' quadrangle. The Lucerne pluton crops out in the southeast portion of the Brewer Lake 7.5' quadrangle where it intrudes the Bucksport Formation. It has been assigned a 380 4 Ma age based on Pb/Pb data from zircons (Zartman and Gallego, 1979). Whole rock and mineral chemistry suggest magma emplacement and crystallization at 650-700 C and 1-2 kb total pressure (Wones, 1980).

The Lucerne pluton is a coarse-grained, two-feldspar, biotite granite. Approximately 5% of all alkali feldspar phenocrysts are ovoidal in shape and are rimmed by plagioclase (i.e. rapakivi texture). Seriate and porphyritic facies have been recognized, but only the former crop out in the qudrangle. A strong foliation, defined by alignment of K-feldspar phenocrysts and ductilely deformed biotite and quartz, parallels the contact with the Bucksport Formation. Dikes of Lucerne granite in Bucksport Formation are uncommon and extend only a few meters from the contact. Large, rotated enclaves of Bucksport Formation several meters across occur in the pluton, but only within a few meters of the contact. Well-developed schlieren are uncommon. Aplite dikes are uncommon and tend to occur in swarms. Only one occurrence of pegmatite was observed, ~800 m north of Moosehorn Stream along the contact with the Bucksport Formation.

Thermal effects of the Lucerne pluton on the Bucksport Formation extend ~1 km from the contact (Novak, 1979). Quartz-calcite-muscovite-chlorite assemblages are recrystallized to hornfelsic plagioclase-biotite assemblages. Pelitic layers react to form andalusite- and corundum-bearing assemblages. The pronounced rise along the Bucksport/Lucerne contact reflects the relative resistance of the Lucerne pluton and its contact aureole contrasted to lower grade Bucksport Formation.

Mafic Rock

One outcrop of a fine-grained, porphyritic mafic rock occurs in the quadrangle (roadcut at UTM grid coordinate 4941.75N, 522.0E). No contacts are exposed between it and the country rock, and it is massive except for brittle fractures and faults.

In thin section, the rock is composed of 60% euhedral bytownite and 40% anhedral, interstitial orthopyrozene which displays a subophitic texture. The rock is a norite in the IUSG classification system (Streckeisen, 1973). Bytownite occurs as 0.5-2.5 mm long lathes (aspect ratio ~4:1) that are randomly oriented. Larger lathes display normal, continuous zoning from ~An_{90} cores to An_{80} rims. Fibrous green amphibole, brown biotite, and magnetite occur as alteration products of orthopyroxene and what is interpreted as matrix. Matrix is completely altered, but orthopyroxene is relatively pristine.

The porphyritic texture, composition, and lack of metamorphism and ductile deformation suggest the norite intruded the country rock as a dike or sill after ductile deformation. Mesozoic mafic dike swarms are common in the Casco Bay area (Hussey, 1985) and this rock probably represents one such dike.

STRUCTURAL GEOLOGY

The contact between the Passagassawakeag Formation/Copeland Formation/Rider Bluff member and the Bucks-port Formation has been interpreted as a normal or reverse fault (Stewart and Wones, 1974), an unconformity (Wones, 1976), and a thrust fault (Kaszuba and Wones, 1985; Osberg et al., 1985). To the southwest in the Casco Bay area, rocks of the Casco Bay Group were interpreted to structurally overlie the Bucksport Formation along a pre-metamorphic thrust fault (Hussey, 1985). The contact is not exposed in the Brewer Lake 7.5' quadrangle, and no observed strain gradient or structural or metamorphic discontinuity coincides with it.

The structural history outlined below is based on detailed work in a small area (the author's mapping). Temporal relationships among different small-scale structures were established in outcrop using overprinting relationships. Sets of structures were correlated on the basis of orientation, style, and position within temporal sequences. Microstructural characteristics of the various fabrics and relationship of these fabrics to metamorphic mineral growth were determined in thin section. Using these methods, four major groups of structures (D_1, D_2, D_3, and D_4) were distinguished (Table 1). D_1 produced folds and axial plane foliations, whereas D_2 produced folds and hinge-parallel mineral elongation lineations. D_3 strike-slip ductile shear zones and D_4 folds followed. A separate event of granitic plutonism and thermal metamorphism (M_{1-2}) is recognized and interpreted to have occurred between D_1 and D_2. Late brittle joints and faults cut all ductile structures.

The structural sequence described below is probably true for those portions of the Copeland and Bucksport Formations in the quadrangle not mapped by the author. However, its relevance to the Passagassawakeag Formation and Mixer Pond member is uncertain. The following discussion applies with certainty only to the area mapped by the author.

Deformation Phase One

The earliest recognizable deformation phase (D_1)(Table 1) produced F_1 folds (Table 2) and a strong axial plane foliation (S_1) defined by a uniform compositional layering. F_1 folds (Table 2) occur in all metasedimentary units, but are prevalent in the Cope-

Feature \ Event	D_1	M_{1-2}	D_2	D_3	D_4	Brittle
Structures	-F_1 folds -S_1 axial plane foliation -rare L_1 mineral lineation	-porphyroblasts overgrow S_1	-F_2 folds -L_2 mineral lineation and crenulation -weak S_2 axial plane foliation	-ductile shear zones -L_3 stretching lineation -S_3 mylonitic foliation and compositional layering	-F_4 folds -weak L_4 mineral lineation and crenulation -weak S_4 axial plane foliation	-brittle joints and faults -slickensides -veins filled with quartz ± hematite
Metamorphic Conditions	greenschist (?)	amphibolite	upper greenschist to lower amphibolite	upper greenschist to lower amphibolite	greenschist	sub-greenschist
Relative Timing	pre-Stricklen Ridge granite intrusion	between D_1 & D_2, syn-granite (?) intrusion	post-granite intrusion	post-L_2	post-mylonite	after all ductile deformation
Orogeny	pre-412 ± 14 Ma, early Acadian (?), possibly Taconic (?)	Acadian (?), ~412 ± 14 Ma	Acadian	post-Lucerne (380 ± 4 Ma), syn-NFZ, Alleghenian	post-D_3 shear zones syn-NFZ, Alleghenian	

Table 1. Characteristics of deformational and metamorphic events. NFZ, Norumbega fault zone; $L_{2,4}$ crenulation, hinge line of $F_{2,4}$ microfolds.

land Formation in the southern part of the quadrangle. They deform bedding (S_0) and are cut by dikes of Stricklen Ridge granite in the Copeland Formation. Style and geometry of folds vary among the metasedimentary units. F_1 folds in the Copeland Formation (Table 2) are steeply-reclined to vertical (classification of Fleuty, 1964) and tight to isoclinal. Axial planes strike predominantly east-west (Fig. 4a) and fold hinges plunge steeply to the east (Fig. 4b). In the Rider Bluff member, F_1 folds (Table 2) are recumbent isoclines that deform quartz veins. In the Bucksport Formation, F_1 folds (Table 2) are tight and inclined with hinges that plunge moderately to the northeast. Preliminary work by Kaszuba and Wones (1985) did not recognize F_1 folds in the Bucksport Formation.

Foliations measured in outcrops where fold closures are not observed strike predominantly north-northeast and dip steeply to the west (Fig. 4c) in contrast to the F_1 axial plane data measured within fold noses (Fig. 4a). These foliations may either be a bedding-parallel foliation which is common to the area or the S_1 axial plane foliation. The data plotted in Fig. 4c probably represents a combination of both.

S_1 compositional layering in the Copeland Formation is defined by alternating quartz- and mica-rich layers up to 5 mm thick. In the Rider Bluff member, it is defined by millimeter-scale quartz- (90% quartz) and chlorite-rich (50% quartz, 50% chlorite) laminae. Quartz veins within both units are locally flattened within S_1 and extended parallel to an L_1 lineation. They sometimes contain quartz rods that define an L_1 mineral lineation. The character of S1 in the Bucksport Formation varies with the different lithologies and grain sizes of that unit. In siltstone containing little to no carbonate, S_1 is a continuous to disjunctive cleavage (classification of Powell, 1979). A continuous, slaty cleavage occurs in very fine-grained siltstone, whereas coarser-grained siltstone displays a 0.1 mm-scale disjunctive cleavage that ranges from smooth to rough to anastomosing. A mm-scale compositional layering defined by alternating quartz- and phyllosilicate-rich layers parallels this cleavage. S_1 in carbonate-rich Bucksport Formation is a compositional layering up to 1 cm thick defined by a range of phyllosilicate, calcite, quartz, and plagioclase amounts present. Quartz veins alternate with this compositional layering. S_1 is refracted across bedding planes between the two Bucksport Formation lithologies probably because of the competency contrasts between them (Hobbs et al., 1976).

Deformation Phase Two

The second deformation phase (D_2)(Table 1) produced F_2 folds (Table 2) that deform S_1 in metasedimentary units and fold

	F_1			F_2			F_4		
	Copeland Formation	Rider Bluff member	Bucksport Formation	Copeland Formation	Rider Bluff member	Bucksport Formation	Copeland Formation	Rider Bluff member	Bucksport Formation
Style	steeply reclined to vertical; tight to isoclinal	recumbent to gently reclined isoclines	inclined; tight	upright to inclined; open to tight			steeply reclined to vertical; open to tight		
wave-length	rarely > 0.5m	rarely > 10cm	—	6cm to 6m			6cm to 1.5m		
amplitude: wavelength	4:1 to 8:1	4:1 to 8:1	—	1:1 to 2:1			1:9 to 1:2		
relative abundance	abundant	rare	rare	common			abundant	rare	common
structures it deforms	S_0	quartz veins	S_0	S_1	S_1, L_1	S_0, S_1	S_0, S_1, F_1, S_3	S_1	S_1, F_2

Table 2. Characteristics of fold generations. Fold classification of Fleuty (1964).

dikes of Stricklen Ridge granite in the Copeland Formation. F_2 folds (Table 2) are open to tight, upright to inclined folds. Axial plane and hinge line orientations are grouped into two geographic domains. In the northern half of the quadrangle, axial planes are subvertical and strike northeastward (Fig. 5a); hinge lines plunge gently to the northeast (Fig. 5b). In the southern half of the quadrangle, axial planes strike north-south and range in dip (Fig. 5c). Hinge lines plunge at moderate angles to the north-northeast and south-southwest.

A strong mineral location (L_2) parallels F_2 fold hinges throughout the quadrangle (compare Figs. 5b and 5e), but is best developed in the north. The L_2 mineral lineation is defined by a strong grain-shape preferred orientation of elongate quartz grains in quartz veins and quartz-rich layers, and by elongate micas and feldspar in pelitic layers. In the Stricklen Ridge granite, L_2 is defined by quartz rods and by stretched and reoriented feldspars and micas. In outcrop, F_2 microfolds often appear as a crenulation. Their fold hinges were measured as L_2 and are included in the data plotted in Fig. 5e.

Asymmetric F_2 microfolds deform S_1 in the Copeland Formation. Biotite and muscovite are recrystallized into an S_2 foliation which is axial planar to F_2 microfolds. S_2 is not as pronounced as S_1 because the mica foliation is not as pervasive and no new compositional layering is developed. In the Rider Bluff member, a variable, mm-scale zonal crenulation cleavage (classification of Powell, 1979)(S_2) deforms S1. White mica and chlorite in cleavage zones (<1 mm thick) are recrystallized parallel to S_2. D_2 structures in the Bucksport Formation vary with lithology. Siltstone develops a discrete to zonal crenulation cleavage (S_2) which deforms S_1. Matrix biotite, white mica, chlorite, and elongate quartz are recrystallized parallel to S_2. S_2 in carbonate-rich lithologies is a zonal crenulation cleavage that deforms S_1 compositional layering and is subparallel to the axial planes of F_2 microfolds.

Shear Zones

The Norumbega fault zone is a major right-lateral strike-slip fault which stikes ~060 and crops out in the northwest corner of the quadrangle. Ductile shear zones are ubiquitous in the study area. They occur at both outcrop and map scales

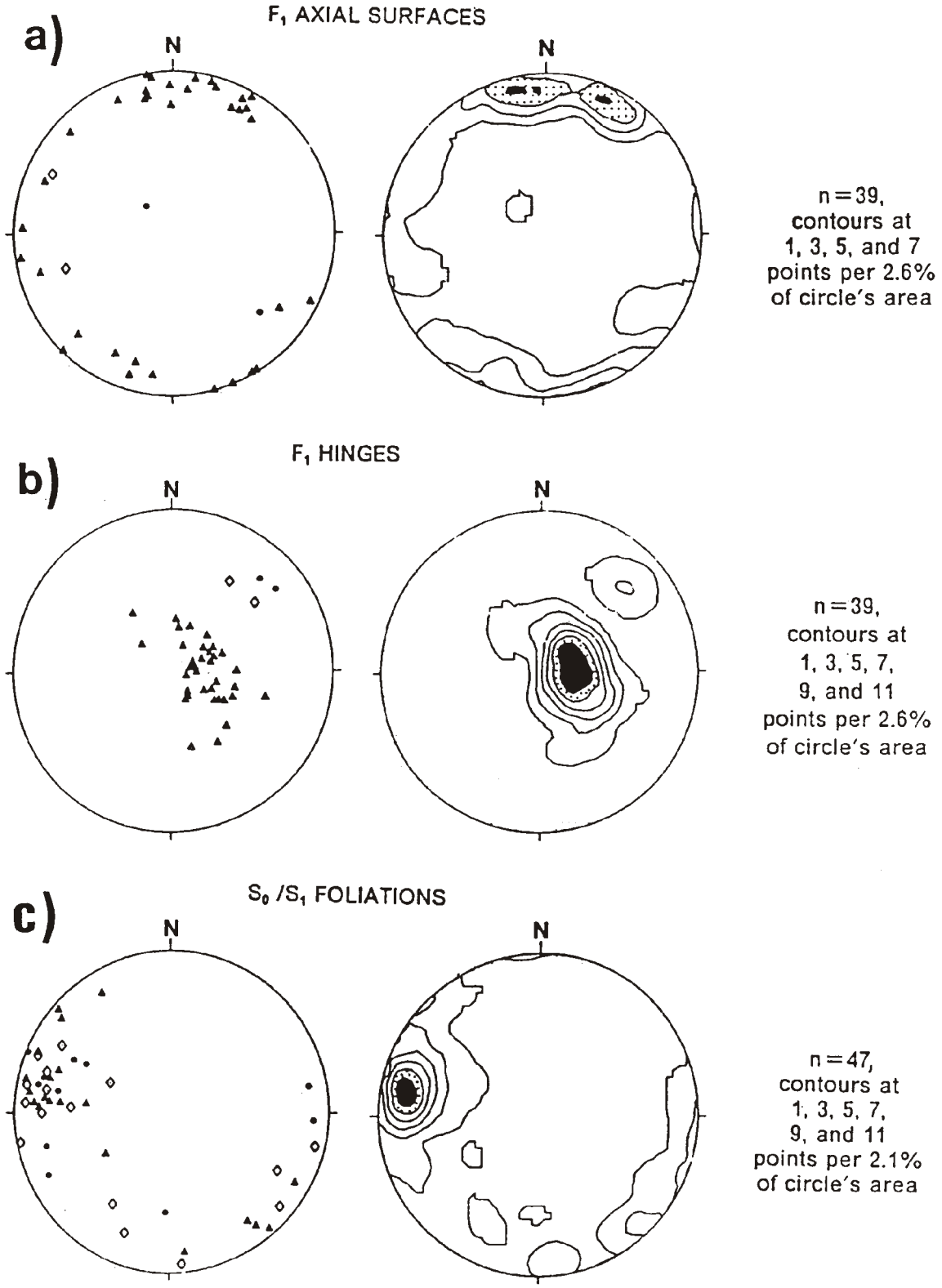

Figure 4. Lower hemisphere, equal area stereographic projections of D_1 field data. For all projections, original orientation data is plotted on left and contoured on right. Solid triangle, Copeland Formation; solid circle, Rider Bluff member; open diamond, Bucksport Formation. For all contoured projections, highest density contour interval is shaded , second highest is stippled. (a) Poles to axial surfaces of F_1 folds. Data measured where fold closures occur. (b) F_1 fold hinges. (c) Poles to S_0 and S_1 foliations. Data measured where fold closures not observed.

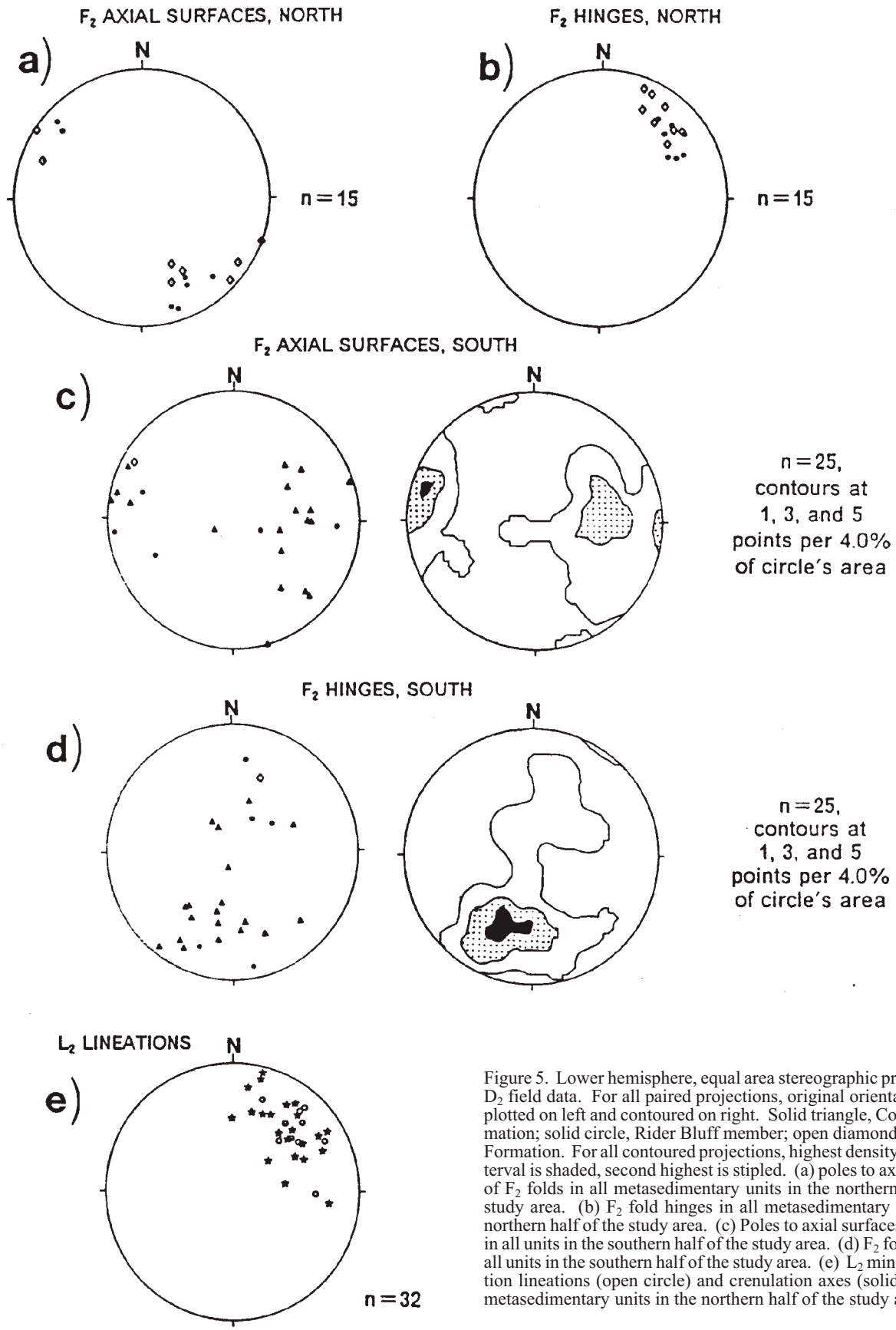

Figure 5. Lower hemisphere, equal area stereographic projections of D_2 field data. For all paired projections, original orientation data is plotted on left and contoured on right. Solid triangle, Copeland Formation; solid circle, Rider Bluff member; open diamond, Bucksport Formation. For all contoured projections, highest density contour interval is shaded, second highest is stipled. (a) poles to axial survaces of F_2 folds in all metasedimentary units in the northern half of the study area. (b) F_2 fold hinges in all metasedimentary units in the northern half of the study area. (c) Poles to axial surfaces of F_2 folds in all units in the southern half of the study area. (d) F_2 fold hinges in all units in the southern half of the study area. (e) L_2 mineral elongation lineations (open circle) and crenulation axes (solid star) in all metasedimentary units in the northern half of the study area.

and offset contacts and juxtapose units within their boundaries. The shear zones deform Stricklen Ridge granites and L_2 and are deformed by later folds (F_4, see below), therefore they are labeled D_3 (Table 1). The majority of shear zones are subparallel to the Norumbega fault zone and display right-lateral movements as determined by shear banding in metasediments (Platt and Vissers, 1980) and S (schistosité) and C (cisaillement, shear) foliations in granites (Berthé et al., 1979; Simpson and Schmid, 1983). Other shear zones are orthogonal to the Norumbega fault zone and display left-lateral movements.

In ductile shear zones developed in Stricklen Ridge granites, quartz shows ribbon structure. Fine-grained, recrystallized tails of mica fish (asymmetric mica porphyroclasts that have fine-grained, recrystallized tails, e.g. Lister and Snoke, 1984) and wrapping of micas around rigid porphyroclasts indicate ductile deformation of micas. Large porphyroclasts (~1.0-2.0 mm in diamter, although ~1 cm diameter and larger porphyroclasts occur in deformed pegmatites) of plagioclase (An_{10-15}), microcline, and orthoclase display brittle fractures, undulatory extinction, and dynamically recrystallized tails. Garnet, tourmaline, and apatite are brittlely fractured and extended into the subhorizontal stretching direction (L_3) and contain recrystallized phyllosilicates quartz within their pressure shadows and fractures. Ductile shear zones in the Copeland Formation display a mm- to m-scale compositional layering defined by alternating quartz- and mica-rich (usually muscovite) layers and quartz ribbons. Discontinuous lenses composed of fine-grained, brittlely fractured plagioclase or tourmaline are interspersed with the quartz and mica compositional layers. Asymmetic porphyroclasts of 0.2-2.0 mm diameter garnet, muscovite, oligoclase, and tourmaline are dispersed throughout the matrix. Ductile shear zones in the Rider Bluff member and the Bucksport Formation are superimposed on rocks that were originally fine-grained and consist of a foliated matrix of fine-grained phyllosilicates and quartz. Albite and amphibole porphyroclasts are often concentrated in mm-scale discontinuous lenses that parallel the matrix foliation. Within these lenses, these minerals display primarily brittle behavior in contrast to the ductile behavior of the surrounding matrix.

Shear bands are developed in the metasedimentary units outside of shear zone boundaries. They range in thickness (up to 0.5 mm thick) and spacing (up to 5 mm and larger), and contain recrystallized phyllosilicates and quartz and concentrations of magnetite, ilmenite, and pyrite. Pre-existing foliations are asymptotically deflected into the shear bands, and rigid mineral grains (e.g. albite porphyroclasts) are truncated across them.

Microstructural criteria for movement direction in the shear zones are internally consistent and support the field observations. These criteria include asymmetric feldspar, tourmaline, and garnet porphyroclasts; antithetic and synthetic offset along microfractures in tourmaline and garnet and along microfractures and cleavages in feldspars; elongate, dynamically recrystallized quartz grains (Simpson and Schmid, 1983); mica fish (Lister and Snoke, 1984); asymmetric microfolds, C/S bands in granites (Berthé et al., 1979; Simpson and Schmid, 1983); and shear bands in metasediments (Platt and Vissers, 1980).

Deformation Phase Four

The youngest observed deformation phase (D_4) (Table 1) produced F_4 folds (Table 2) that occur in all metasedimentary units, but are prevalent in the Copeland Formation in the southern portion of the quadrangle. They deform S_0 and D_1, D_2, and D_3 structures. F_4 folds (Table 2) are open to tight, steeply-reclined to vertical folds (classification of Fleuty, 1964). Axial planes strike predominantly north-south (Fig. 6a) and hinge lines are steeply plunging (Fig. 6b). F_4 microfold hinges were measured in outcrop as a lineation (L_4). An L_4 mineral lineation defined by elongate micas and quartz rods occurs parallel to these fold hinges, but it is not as pervasive as the L_2 mineral lineation.

F_4 microfolds in the Copeland Formation occur as crenulations of S_1 compositional layers and F_2 fold limbs, especially in pelitic layers. An S_4 foliation, defined by a preferred orientation of recrystallized micas, occurs parallel to F_4 axial planes, but it is not well-developed and is not as penetrative as S_1 or S_2. In Bucksport Formation siltstones, symmetrical microfolding of S_1 produces a zonal crenulation cleavage (classification of Powell, 1979). Cleavage zones and microlithons are evenly-spaced (~0.5 mm) and have diffuse boundaries. F_4 folds deform the mylonitic foliation (S_3), compositional layers, and mica fish present in the D_3 shear zones.

Brittle Deformation

Brittle faults and joints (Table 1) are ubiquitous to the quadrangle. They truncate all ductile fabrics (D_1, D_2, D_3, and D_4) and are often filled with quartz and/or hematite. In thin section, quartz which fills the fractures occurs as polygonal grains that display no crystallographic or grain-shape preferred orientation. The orientation and sense of motion of the brittle faults and associated joints parallels the D_3 ductile shear zones.

INTERDEFORMATIONAL METAMORPHISM

The porphyroblasts listed in Table 3 occur in all metasedimentary units and share the following textural relationships: except for fibrolitic sillimanite, they are euhedral to subhedral and large (up to several millimeters in diameter) compared to other minerals in the thin section which crystallized or recrystallized during D_1, D_2, D_3 or D_4; they overgrow S_1 and often contain an internal foliation (S_1) oriented subparallel to and often continuous with S_1; porphyroblasts containing S_1 lack synmetamorphic rotational textures (e.g. Spry, 1969); and grain-shape preferred orientations of porphyroblasts parallel D_2, D_3, or D_4 structures. These textural relationships suggest that the

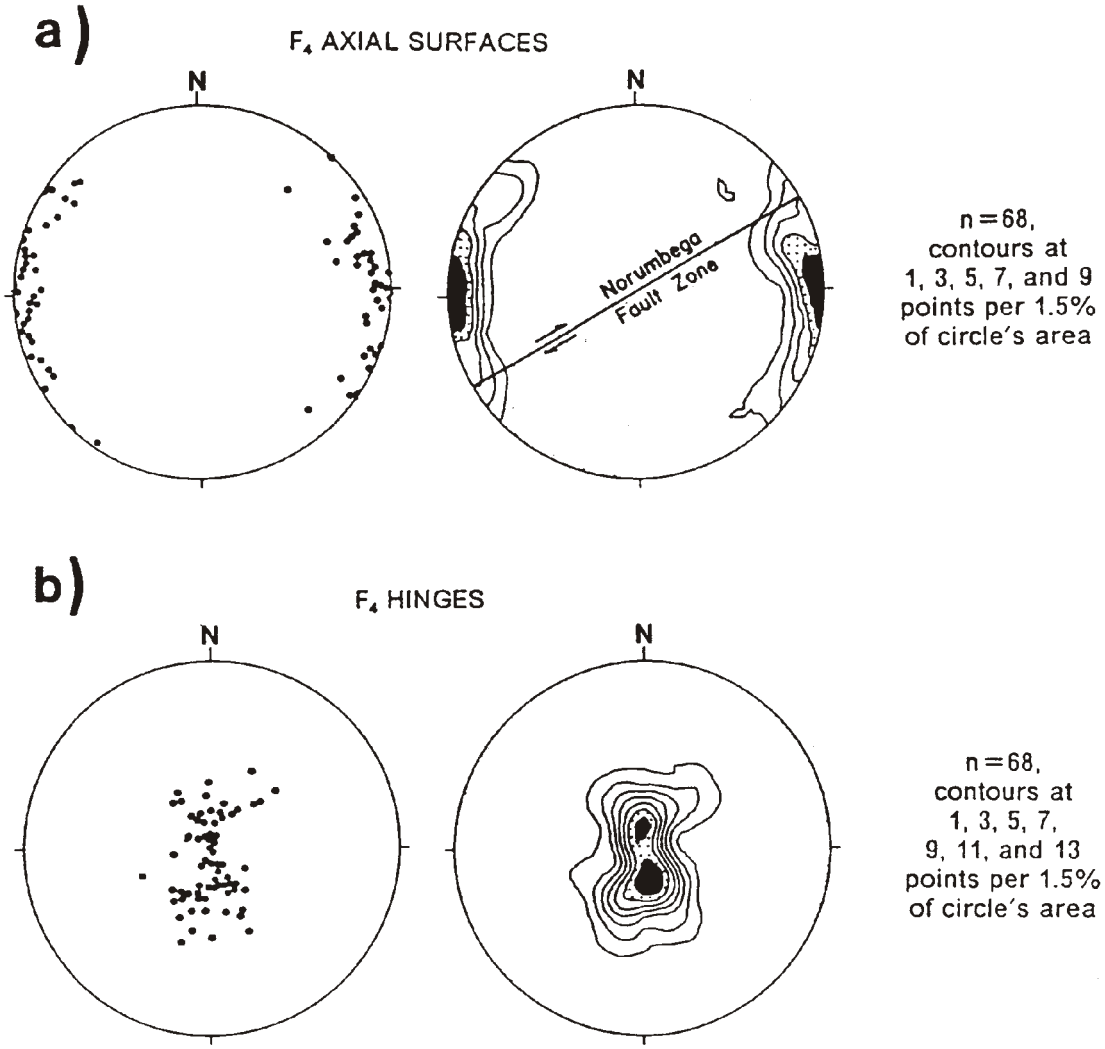

Figure 6. Lower hemisphere, equal area stereographic projections of D_4 field data in all units throughout the study area. For all projections, original orientation data is plotted on left and contoured on right. For all contoured projections, highest density contour interval is shaded, second highest is stippled. (a) Poles to axial surfaces of F_4 folds. Data measured where fold closures occur. Trace and sense of movement of the Norumbega fault zone also plotted. (b) F_4 fold hinges.

porphyroblasts crystallized between D_1 and D_2, therefore they are labeled $M_{1\text{-}2}$.

Sillimanite-bearing assemblages (Table 3) occur in the Copeland Formation within ~0.6 km of Stricklen Ridge granite stocks, and lower grade assemblages are stable with increasing distance from these stocks, suggesting that $M_{1\text{-}2}$ metamorphism is related to the intrusion of Stricklen Ridge granite. Occurrence of staurolite as embayed grains mantled by optically continuous andalusite in the Copeland Formation suggest the reaction: (1) staurolite + muscovite + quartz = biotite + aluminum silicate + garnet + H_2O. Muscovite, quartz, and sillimanite are abundant in the Copeland Formation near the Stricklen Ridge granites, but K-feldspar is absent, suggesting that the reaction: (2) muscovite + quartz = K-feldpsar + aluminum silicate+ H_2O has not occurred. Andalusite and sillimanite are mantled by massive, felty intergrowths of very fine-grained white mica and fibrolitic sillimanite. These andalusite/sillimanite textures and the absence of kyanite suggest that sillimanite crystallized by the reaction (3) andalusite = sillimanite. Metamorphic reactions (1), (2), and (3) bracket the pressure-temperature space where peak metamorphic conditions occurred (Fig. 7). These brackets depend on the choice of aluminum silicate triple point data. Triple point data by Richardson et al. (1969) and Holdaway (1971) are the two generally accepted data sets, although Holdaway's (1971) data bracket peak $M_{1\text{-}2}$ metamorphic conditions at 1 to 2.5 kb and 490 to 165 C (Fig. 7). For comparison, data by Richardson et al. (1969) data bracket pressure-temperature conditions at 1 to 5 kb and 490 to 680 C (Fig. 7). Both pressure-temperature brackets suggest amphibolite facies metamorphic conditions (Winkler, 1979).

EVENT / UNIT	D_1	M_{1-2}	D_2	D_4
COPELAND FORMATION	-musc + bt + qtz ± olig ± mag ± ilm	-sill + bt ± gt ± tour -and + bt ± gt -staur -bt + gt ± tour	-bt + musc + qtz	-bt + musc + qtz ± chl ± ilm ± hem
RIDER BLUFF MEMBER	-qtz + chl + white mica + plag + mag ± pyr	-bt + gt + ab	-qtz + white mica + chl + bt	-chl + qtz
BUCKSPORT FORMATION	-qtz + white mica + chl + Cc + plag ± mag ± ilm ± pyr	-Ca-amph + ab + ti -bt + chl + ti + ep -bt + chl ± tour	-bt + Cc + qtz -qtz + white mica + chl + bt + Cc ± ilm ± mag ± pyr	-chl + white mica + qtz -bt + Cc + qtz

Table 3. Inferred stable mineral assemblages in metasediments. M_{1-2} assemblages are listed in order of decreasing metamorphic grade. All M_{1-2} assemblages in the Copeland Formation include muscovite + quartz. Abbreviations: musc, muscovite; bt, biotite; qtz, quartz; olig, oligoclase (An_{21-28}), plagioclase; mag, magnetite; ilm, ilmenite; chl, chlorite; plag, plagioclase; pyr, pyrite; Cc, calcite; sill, sillimanite; gt, garnet; tour, tourmaline; and, andalusite; staur, staurolite; ab, albite; Ca-amph, calcic amphibole; ti, titanite; ep, epidote.

Minimum pressure of crystallization of granitic magmas may be estimated by comparison of rock composition to experimental work in the quartz-orthoclase-albite-anorthite-H_2O system. This approach assumes the granitic magma was H_2O-saturated and a minimum melt. The abundance of aplites, tourmaline-bearing pegmatites, and miarolitic cavities in Stricklen Ridge granite suggests H_2O saturation. Normative compositions of two samples of Stricklen Ridge granite are plotted in the quartz-albite-orthoclase ternary diagram in Fig. 8. Normative data from Carl et al. (1984) is plotted because their model data compare well with the data of this study (Fig. 2). The normative composition of a typical granite sample in this study was calculated from modal and mineral chemical data. Also plotted in Fig. 8 are compositions of minimum granite liquids as a function of Ab/An ratio and pressure. This data was compiled by Anderson and Cullers (1978) from the experimental data of Winkler and Von Platen (1957, 1958, 1960, 1961), Von Platen (1965), Von Platen and Höller (1966), James and Hamilton (1969), and Brown and Fyfe (1970). Normative compositions of Stricklen Ridge granite plot near minimum compositions for granitic liquids at <1 kb (Fig. 8), suggesting that the Stricklen Ridge granite represents a minimum melt that crystallized at or near this pressure. This pressure is consistent with that independently derived for crystallization of M_{1-2} porphyroblasts (1-2.5 kb), suggesting that both events occurred at approximately the same depth.

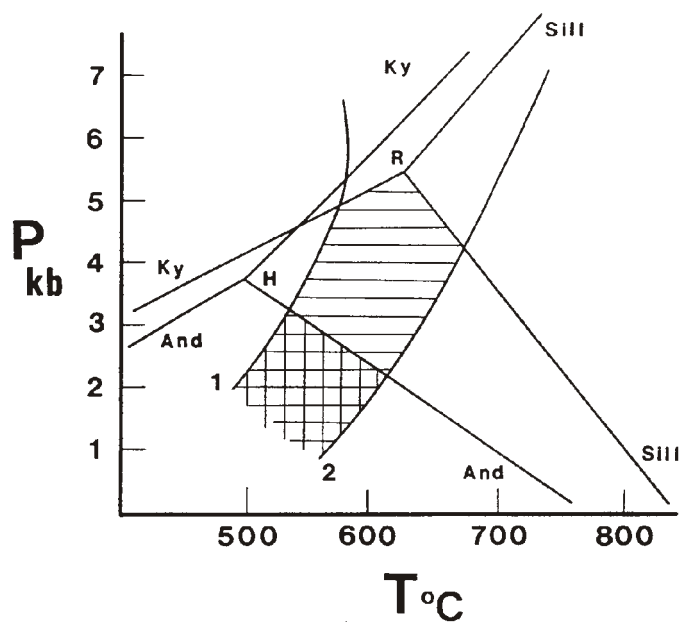

Figure 7. Selected reactions bracketing pressure-temperature conditions of M_{1-2} porphyroblasts. Aluminum silicate data: R, Richardson et al. (1969); H, Holdaway (1971). Reaction (1), staurolite + muscovite + quartz = biotite + garnet + aluminum silicate + H_2O (Carmichael, 1978; Archibald et al., 1983). Reaction (2), muscovite + quartz = aluminum silicate + K-feldspar + H_2O (Chatterjee and Johannes, 1974). H_2O on high-temperature side of all reactions. Pressure-temperature space bracketing peak conditions: horizontal ruling, assumes Richardson et al. (1969) data; vertical ruling, assumes Holdaway's (1971) data.

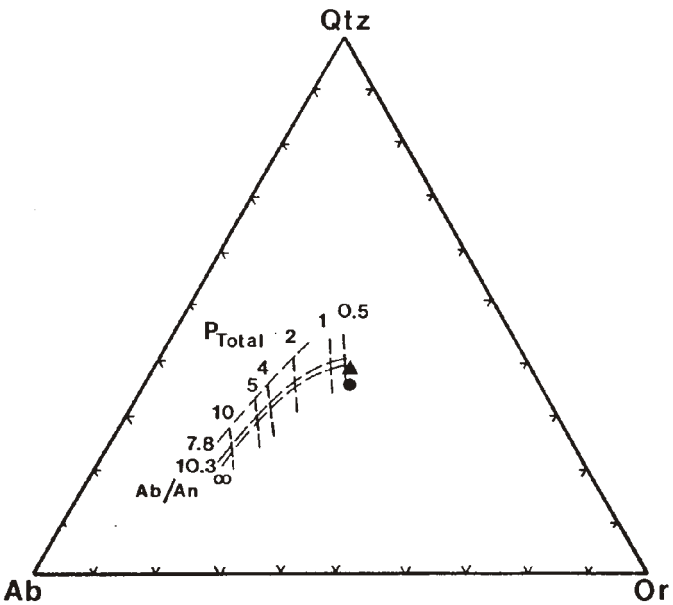

Figure 8. Normative compositions of Stricklen Ridge granite in terms of quartz (Qtz), albite (Ab), and orthoclase (Or) and comparison to experimental work in the granite system. Minimum melt compositions plotted as a function of Ab/An ratio and pressure. Solid circle, calculated normative composition of representative granite sample from this study; solid triangle, normative data of Carl et al. (1984). Minimum melt experimental grid compiled by Anderson and Cullers (1978) from the experimental data of Winkler and Von Platen (1957, 1958, 1960, 1961), Von Platen (1965), Von Platen and Höller (1966), James and Hamilton (1969), and Brown and Fyfe (1970).

RELATIONSHIP BETWEEN STRUCTURE AND METAMORPHISM

Folds defined by contacts between metasedimentary units display a closed geometry and refolded pattern characteristic of F_1. S_1 parallels the axial trace of these folds, and geometric relationships between S_0 and S_1 and the closures of these folds (i.e. cleavage/bedding relationship, Ramsay, 1967) are consistent with F_1 folding. These contacts are therefore interpreted as being deformed by F_1. S_0 and S_2 compositional layering are distinguished from each other in F_1 fold noses where S_0 is transposed into S_1. F_1 and F_4 fold hinges are subparallel (Figs. 4b, 6b), suggesting that the range of F_1 axial plane orientations (Fig. 4b) may be partly the result of refolding about the F_4 fold axis.

The domainal distribution of F_2 fold orientations may be controlled by the superposition of F_2 on F_1 or by refolding of F_2 by F_4. However, the change in strike of F_2 axial planes from north-south (Fig. 5c) to northeast-southwest (Fig. 5a) and in F_2 fold hinge orientations from moderate north-northeast and south-southwest plunges (Fig. 5d) to gentle northeast plunges (Fig. 5b) occurs with closer proximity to the Norumbega fault zone, suggesting that right-lateral strike-slip movement on the Norumbega fault zone reoriented F_2 structures in the northern portion of the study area.

The Norumbega fault zone is a major strike-slip fault zone with a long history of Paleozoic ductile and Late Paleozoic and Mesozoic brittle deformation (Wones and Stewart, 1976; Wones, 1978; Loiselle and Wones, 1983; Johnson and Wones, 1984). The majority of D_3 shear zones are subparallel to and display the same movement sense as the Norumbega fault zone, suggesting that they are related to the same deformation event. The orientation and sense of motion of deformation zones oblique to the Norumbega fault zone trend suggest that they may be second-order shears similar to those discussed by Chinnery (1966a, 1966b). Conjugate sets of vertical northeast-trending dextral and north- to northwest-trending sinistral ductile shear zones and brittle faults and fractures occur along the entire extent of the Norumbega fault zone (Wones, 1978; Loiselle and Wones, 1983; Johnson and Wones, 1984).

The northeast-trending shear zone and nearby brittle structures that parallel it coincide with the Penobscot Lineament of O'Leary et al. (1978), a 0.8 km wide zone that trends ~05 from eastern Penobscot Bay for at least 64 km to north of the Lucerne pluton. It is represented topographically by aligned streams and elongate lakes and hills, and geologically by right-lateral ductile shear zones and brittle faults (O'Leary et al., 1978).

Index minerals that uniquely define a metamorphic facies are absent from tectonic fabrics formed during each ductile deformation event. Metamorphic conditions for each ductile event are bracketed based on the mineral assemblages that are present to define each fabric, micro-structures displayed by these minerals, and textural relationships among minerals of different tectonic fabrics.

The mineral assemblages interpreted to be stable in S1 and in the S_1 of $M_{1\text{-}2}$ porphyroblasts are listed in Table 3. The presence of quartz pressure shadows containing fibrous minerals, the truncation of quartz grains along S_1 cleavage zones, and the concentration of phyllosilicates and sulfide minerals within these zones in siltstones of the Bucksport Formation suggest that pressure solution (Rutter, 1976) was an important deformation mechanism in this lithology during D_1.

$M_{1\text{-}2}$ mineral assemblages (Table 3) and textures suggest $M_{1\text{-}2}$ metamorphism occurred at 490 -575 C and 1-2.5 kb (Fig. 7)(amphibolite facies conditions). $M_{1\text{-}2}$ porphyroblasts overgrow S_1 and are deformed by D_2, D_3, and D_4 structures, suggesting that $M_{1\text{-}2}$ occurred between D_1 and D_2. However, $M_{1\text{-}2}$ may have been part of a continuum of events at the end of D_1 or the beginning of D_2. Stricklen Ridge granite intrusion occurred between D_1 and D_2 at a minimum pressure of crystallization of <1.0 kb (3.8 km). Sillimanite-bearing $M_{1\text{-}2}$ mineral assemblages occur in Copeland Formation pelites next to and within Stricklen Ridge granite stocks, and progressively lower-grade $M_{1\text{-}2}$ assemblages occur with increasing distance from these stocks. These relationships suggest that $M_{1\text{-}2}$ metamorphism may have occurred in a contact aureole in association with the intrusion of Stricklen Ridge granite.

The mineral assemblages interperted to be stable in S_2 and L_2 are listed in Table 3. These assemblages commonly occur as retrograde products of M_{1-2} porphyroblasts and suggest D_2 deformation occurred under greenschist facies metamorphic conditions. Ductile microstructures in albite and calcic amphibole are interpreted as having formed under upper greenschist to lower amphibolite facies metamorphic conditions. The presence of quartz pressure shadows containing fibrous minerals and the trunction of quartz grains along and the concentration of sulfide minerals with S_2 cleavage zones in siltstones of the Bucksport Formation suggest that pressure solution (Rutter, 1976) was an important S_2-forming mechanism in that lithology.

Phyllosilicates are stable in the mylonitic foliation (S_3), suggesting the presence of water and consequently the reduction of the metamorphic conditions under which feldspar begins to deform ductilely (Tullis and Yund, 1980). The lack of upper amphibolite to granulite facies mineral assemblages and the presence of water during deformation suggest that feldspar porphyroclast textures formed under upper greenschist to lower amphibolite facies metamorphic conditions in D_3 shear zones. Ductile microstructures in feldspar, quartz, and micas reported for shear zones in the Norumbega fault zone (Johnson and Wones, 1985) are similar to those in D_3 shear zones, suggesting that both structures formed under similar deformation conditions, probably during the same deformation event. However, metamorphic condition estimates based on feldspar microstructures are probably imprecise because the ductile response of feldspar is controlled by strain rate, fluid pressure and composition, and confining pressure as well as temperature and the presence of water.

The mineral assemblages interpreted to be stable in S_4 (Table 3) suggest D_4 deformation occurred under greenschist facies metamorphic conditions. The prevalence of mineral assemblages consistent with greenschist facies metamorphism in all three fold events (Table 3) seems a bit fortuitous. Greenschist facies assemblages clearly define L_2, S_2, and S_4 and are probably representative of the conditions prevalent during D_2 and D_4. However, it is possible that D_1 contained different metamorphic assemblages which have not survived M_{1-2} metamorphism or subsequent deformation. Greenschist facies conditions for D_1 are therefore only best estimates.

TECTONIC SIGNIFICANCE

D_1 is characterized by tight to isoclinal folding and the formation of a strong S_1 axial plane. The Stricklen Ridge granite cuts D_1 structures and has been assigned a 412 14 Ma age (Zartman and Gallego, 1979), therefore D_1 must be pre-Late Silurian to Early Devonian in age. Since F_1 folds occur within, and deform contacts between, all three metasedimentary units, these units must have been in contact and have shared a common structural and metamorphic history by the time of D_1 at the latest. Emplacement of the Copeland Formation as a thrust sheet over the Bucksport Formation could not have taken place between 390 and 410 Ma as suggested by the preliminary work of Kaszuba and Wones (1985). These interpretations are consistent with Ludman's (1981, 1985) suggestion that the terranes of coastal Maine were not exotic to each other by Early Devonian at the latest. Ludman (1981, 1985) based his interpretation on the lack of stratigraphic and metamorphic discontinuities between, and the structural and radiometric age continuity across, the terranes of northeast Maine (i.e. Fredericton trough area).

Several authors have grouped the Bucksport, Vassalboro, and Flume Ridge Formations into one terrane (the Silurian-Early Devonian central Maine turbidite belt) based on lithologic and age similarities (Hussey, 1978; Osberg, 1980; Gates et al., 1984). If this correlation of the Bucksport Formation with the Silurian- to Devonian-age Vassalboro and Flume Ridge Formations is valid, then D_1 must be no older than Silurian. Late Precambrian (?) to Early Ordovician (?) rocks of the Passagassawakeag and Copeland Formations are interpreted to structurally overlie units of the central Maine turbidite belt along a pre-metamorphic thrust fault because of the apparent age disparity between these units (Osberg, 1980; Gates et al., 1984; Hussey, 1985). The occurrence of a pre-metamorphic thrust fault between the Copeland and Bucksport Formations is neither proven nor disproven by this study. However, any pre-metamorphic thrust fault separating the Copeland and Bucksport Formations could be no older than the Silurian. D_1 and pre-metamorphic thrusting would therefore be Acadian events. If the correlation of Vassalboro and Bucksport Formations is not correct, however, and the Bucksport Formation is pre-Silurian in age, then D_1, and pre-metamorphic thrusting if present, could be Taconic events. Pre-Acadian (Taconic?) isoclinal folding has been recognized in northeast Maine both north and east of the Fredericton trough (Ludman, 1981, 1985)(Fig. 1b). Most other first-recognized folds in coastal Maine are recumbent isoclines assigned to the Acadian orogeny (Bickel, 1976; Ludman, 1981; Hussey, 1985), and structural features of undoubted Taconic age are exposed only in western Maine (Osberg, 1978).

Correlation of the Bucksport Formation with the Vassalboro and Flume Ridge Formations and separation of the Copeland and Bucksport Formations by an Acadian pre-metamorphic thrust fault are based on extensive mapping and stratigraphic analysis (Hussey, 1978, 1985; Osberg, 1980; Gates et al., 1984; Osberg et al., 1985). No existing evidence contradicts these interpretations, and D_1 is therefore interpreted as an Acadian event. Quartz veins are abundant in the Copeland Formation and Rider Bluff member near the PGW/Bucksport terrane boundary and are deformed by the entire structural sequence. Extensive quartz veining may reflect the presence of large amounts of fluid associated with faulting (e.g. Etheridge et al., 1983) and may mark the trace of the pre-metamorphic thrust fault.

The M_{1-2} event is a static metamorphism which occurred under amphibolite facies conditions between two ductile deformation events (D_1 and D_2). M_{1-2} metamorphism may have been a discrete event or part of a continuum of events at the end of D_1 or

at the beginning of D_2. Instrusion of Stricklen Ridge granite and growth of M_{1-2} porphyroblasts at similar pressure-temperature conditions between D_1 and D_2 and prevalence of sillimanite-bearing M_{1-2} mineral assemblages with closer proximity to Stricklen Ridge granite stocks suggest that M_{1-2} metamorphism may have occurred in a contact aureole in association with the intrusion of Stricklen Ridge granite. Narrow, sillimanite-bearing thermal aureoles around granitic intrusions have also been reported from a number of other localities in New England (Naylor, 1971). M_{1-2} metamorphism is probably not related to instrusion of the nearby Lucerne pluton. The Lucerne pluton is probably younger than deformation that affects M_{1-2} porphyroblasts, and its contact aureole is only ~1 km wide (Novak, 1979). Sillimanite-bearing mineral assemblages and pervasive granitic intrustions occur throughout the Passagassawakeag Formation to the west of the study area (Stewart and Wones, 1974; Guidotti, 1985), and their presence may be the result of regional, high-grade metamorphism. Granitic plutons may have been convectors of heat that produced local hotspots where they intruded.

D_2 is characterized by open, upright folding and the formation of a strong, hinge-parallel mineral lineation under upper greenschist to lower amphibolite facies metamorphic conditions. D_2 structures deform the 412 14 Ma Stricklen Ridge granite, but reportedly do not affect the 385 4 Ma Lucerne pluton (Kaszuba and Wones, 1985). D_2 is therefore assumed to have occurred during the Acadian orogeny when upright folding occurred throughout New England (Osberg, 1978; Ludman, 1981; Hussey, 1985).

The Norumbega fault zone is a major structure in the quadrangle. The orientation, sense of motion, and inferred deformation conditions (upper greenschist to lower amphibolite) for D_3 shear zones in the study area suggest that they are related to the same deformation event. The coincidence of the Penobscot Lineament with D_3 shear zones and brittle structures suggests it is a second-order shear of the Norumbega fault zone and not a major, continuous zone of faulting and shearing as suggested by O'Leary et al. (1978). D_4 is characterized by open, reclined folding under greenschist facies metamorphic conditions. The relationship between the orientation of F_4 folds and the Norumbega fault zone (Fig. 6) suggests that the stress field which produced right-lateral strike-slip movement on the Norumbega fault zone could also have caused F_4 folding. Eusden et al. (1986) suggest a similar relationship between folding and strike-slip faulting in southwestern Maine along a continuation of the Norumbega fault zone. D_4 may therefore represent a later, lower temperature episode of the same stress event which produced the Norumbega fault zone. Alternatively, D_4 could represent a discrete ductile event unrelated to the one that produced the Norumbega fault zone, but no such event is recognized elsewhere in coastal Maine (Hussey and Newberg, 1978; Hussey, 1985). D_3 shear zones and D_4 folds do not represent deformation associated with intrusion of Stricklen Ridge granite or the Lucerne pluton. D_3 deforms Stricklen Ridge granite, and shear zones similar to D_3 shear zones occur within and deform the Lucerne pluton (Wones, 1980). Furthermore, D_3 shear zones are probably related to the same deformation event as the Norumbega fault zone, and the Norumbega fault zone truncates the Lucerne pluton.

Brittle fracturing and faulting is common along the entire Norumbega fault zone (Hussey, 1978, 1985; Hussey and Newberg, 1978; Wones, 1978; Ludman, 1981; Johnson and Wones, 1984). Brittle joints and faults cut all ductile structures observed in the study area and may be related to the same stress field which initially produced the Norumbega fault zone, or to a later brittle event which exploited the Norumbega fault zone as a pre-existing zone of weakness.

GEOLOGIC HISTORY

In the Brewer Lake 7.5' quadrangle, metasediments of the Copeland Formation, Rider Bluff member, and Bucksport Formation experienced four phases of ductile deformation (D_1, D_2, D_3, and D_4) and an interdeformational event (M_{1-2}) of metamorphism and granitic plutonism. The earliest recognizable deformation phase (D_1) produced F_1 folds and a strong axial plane foliation (S_1) defined by a uniform compositional layering. Since D_1 structures occur within and deform contacts between all metasedimentary units, these units must have been in contact and shared a common history by the time of D_1 (Early Acadian?) at the latest. To the southwest of the study area, units equivalent to the Copeland and Bucksport Formations are bound by a pre-metamorphic thrust fault (Hussey, 1985). No structural or metamorphic discontinuity coincides with the boundary between these two units in the quadrangle, and the occurrence of a pre-metamorphic thrust fault is neither proven nor disproven by this study. A static thermal event (M_{1-2}) of shallow-level (~3.8 km) granitic plutonism (412 14 Ma Stricklen Ridge granite) and porphyroblast growth at 490 -575 C and 1-2.5 kb (amphibolite facies metamorphism) occurred between D_1 and D_2. It may have been a discrete event or a part of a continuum at the end of D_1 or the beginning of D_2. The occurrence of sillimanite-bearing M_{1-2} mineral assemblages with closer proximity to stocks of Stricklen Ridge granite suggest that this metamorphism may have occurred in a contact aureole in association with the intrusion of Stricklen Ridge granite. The second ductile deformation event (D_2, Acadian) produced open, upright folds and a strong, hinge-parallel mineral elongation lineation under upper greenschist to lower amphibolite facies metamorphic conditions. The orientation, sense of motion, and inferred deformation conditions (upper greenschist to lower amphibolite) for D_3 shear zones suggests they are related to the same stress system that produced right-lateral strike-slip movement on the Norumbega fault zone (Alleghanian). The orientation of open, reclined F_4 folds that formed under greenschist facies conditions suggests D_4 may represent a later, lower-temperature episode related to the same stress system. Brittle structures truncate all ductile structures, and their orientation and sense of movement

suggests that they are either related to the same stress field which initially produced D_3 and D_4 ductile structures, or to a later brittle event which exploited D_3 shear zones and the Norumbega fault zone as pre-existing zones of weakness.

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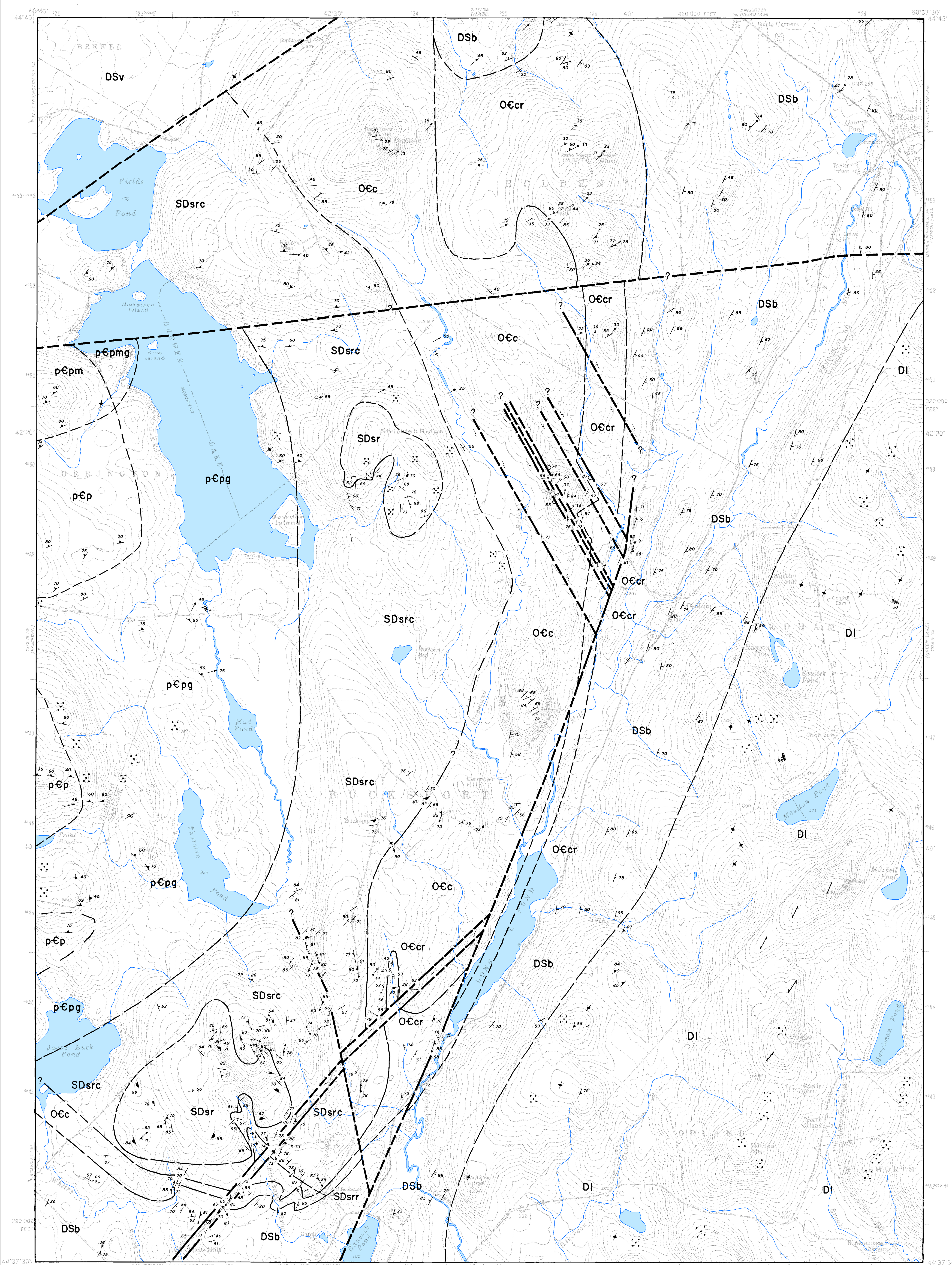


EXPLANATION

Plutonic Rocks

Dl	Lucerne Pluton (Wones, 1980). White-weathering, coarse-grained, seriate granite. Two feldspars, biotite-bearing. Rare aplites and quartz-tourmaline veins. Zircon Pb/Pb age of 380 ± 4 Ma (Zartman and Gallego, 1979).
SDsr	Stricklen Ridge granite stock (Wones, unpublished data). Garnet-bearing, two-mica granite, pegmatite, and aplite that comprise 50%-90% of outcrop. Concordant U/Pb zircon age of 412 ± 14 Ma (Zartman and Gallego, 1979).
SDsrc SDsrr	Extent of Stricklen Ridge granite. Copeland Formation (SDsrc) and Rider Bluff member (SDsrr) intruded by dikes and sills of Stricklen Ridge granite. Granite comprises <50% of outcrop.

Metasedimentary Rocks

DSb	Bucksport Formation (Trefethen, 1950; Wing, 1957). Silurian (?) to Devonian (?). Grey- to green-weathering calcareous siltstone. Intercalated beds of sulfidic pelite common.
DSv	Vassalboro Formation (Perkins and Smith, 1925; Osberg, 1960). Silurian (?) to Devonian (?). Grey- to green-weathering calcareous siltstone. Correlative with the Bucksport Formation.
OЄc OЄcr	Copeland Formation (Trefethen, 1950; Wing, 1957). Precambrian (?) to Ordovician (?). OCc, grey-weathering, interlayered pelite and quartzite. OCcr, Rider Bluff member. Thinly-laminated, pelitic, chlorite-rich siltstone. Contains garnet and magnetite in alternating layers.
pЄp	Passagassawakeag Formation (Bickel, 1976). Precambrian (?). Quartz-feldspar-biotite gneiss intercalated with biotite schist. Commonly contains sillimanite and garnet.
pЄpm	Mixer Pond member. Fine-grained, light-colored quartz-oligoclase-microcline gneiss.
pЄps pЄpmg	Areas of Passagassawakeag Formation and Mixer Pond member. Intruded and injected by Stricklen Ridge granite.

Symbols for areas mapped by Kaszuba

- strike and dip of inclined, vertical bedding
- strike and dip of inclined axial surface and bearing and plunge of associated inclined hinge of small-scale F_1 fold
- strike and dip of inclined S_1 foliation
- strike and dip of inclined axial surface and bearing and plunge of associated inclined hinge of small-scale F_2 fold
- bearing and plunge of inclined L_2 mineral lineation and crenulation axis
- strike and dip of inclined, vertical S_3 mylonitic foliation in metasedimentary rock
- strike and dip of inclined S_3 mylonitic foliation in plutonic rock
- strike and dip of inclined, vertical axial surface and bearing and plunge of associated inclined hinge of small-scale F_4 fold
- bearing and plunge of inclined L_4 mineral lineation and crenulation axis
- strike and dip of inclined brittle joint in metasedimentary rock
- strike and dip of inclined brittle joint in plutonic rock
- massive plutonic rock (no fabric observed)

Symbols for areas mapped by Wones

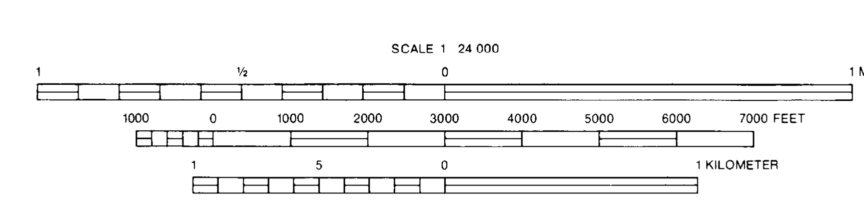
- strike and dip of inclined, vertical compositional layering
- strike and dip of inclined, vertical foliation (where lacking bearing and plunge)
- strike and dip of cleavage
- bearing and plunge of fold hinges of parasitic folds
- strike of sub-vertical shear zone
- strike and dip of Aplite
- massive rock, no observed fabric

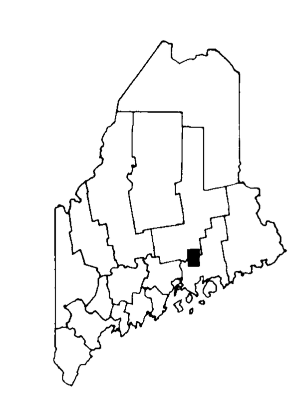
Contacts

- known
- approximate
- very approximate

Faults

- brittle
- ductile, dextral
- ductile, sinistral





Quadrangle Location

RECONNAISSANCE
BEDROCK GEOLOGY OF THE BREWER LAKE QUADRANGLE, MAINE

BY
JOHN P. KASZUBA

1992
Maine Geological Survey
DEPARTMENT OF CONSERVATION
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