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Volcanic Stratigraphy, Stratabound Sulfide Deposits, And Relative Age Relationships In The East Penobscot Bay Area, Maine

Bruce Albert Bouley

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VOLCANIC STRATIGRAPHY, STRATABOUND SULFIDE DEPOSITS, AND RELATIVE AGE RELATIONSHIPS IN THE EAST PENOBSCOT BAY AREA, MAINE

by

Bruce Albert Bouley

Department of Geology

Submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
January, 1978

COULEUR

Abstract

Volcanic rocks in southeast coastal Maine within the Castine and Blue Hill quadrangles have been mapped as the Castine Formation, a relatively undeformed sequence Silurian to Devonian in age. This sequence is cyclical with each cycle consisting of predominantly submarine mafic flows overlain by intermediate fragmental rocks, and these in turn by felsic fragmental rocks and rhyolite lava domes. Massive bodies of zinc and copper sulfide minerals, typified by the Penobscot mine, are stratabound within felsic, uppermost parts of volcanic cycles in coarse proximal volcanic lithofacies. The metal deposits are attributed to chemical sedimentation from metal-laden brines exhaled upon the seafloor. Such deposits closely resemble those of the Green Tuff region of Japan. Volcanic and volcaniclastic rocks more distant from centers of volcanism are finer-grained and include more sedimentary members. Sulfide deposits within these more distal rocks, typified by the Hercules mine, are more stratiform and have greater zinc and lead concentrations relative to copper.

The Ellsworth Formation flanks the Castine Formation and was mapped previously as a deformed sequence of Cambro-Ordovician fine-grained siliceous and pelitic clastic rocks and minor tuffs. It is demonstrably richer in volcanic component where adjacent to the Castine Formation. Metal sulfide deposits within the Ellsworth, typified by the Blue Hill mine, are stratiform and have greater concentrations of zinc

and lead relative to copper than deposits in the Castine Formation. The progressive change in metal content and deposit geometry from Castine Formation to Ellsworth Formation is viewed as a progression from proximal through distal volcanic environments.

Prior criteria for relative age distinction between the Castine and Ellsworth Formations have included differing degrees of deformation and the presence of fragmental rocks interpreted as basal conglomerates at erosional unconformities. However, comparison of structures in mechanically equivalent rocks in both formations during this study indicates that relative timing and style of deformation are identical. Detailed mapping and reinterpretation of the purported basal conglomerates indicate they are volcanic breccias, common throughout the Castine succession, and not representative of a major erosional interval.

Pb-Pb and Rb-Sr isotopic data suggest that volcaniclastic sedimentary rocks of the Ellsworth Formation were derived mainly from the Castine Formation, and that the two formations were deposited penecontemporaneously. The conclusion is that the Castine and Ellsworth Formations and their enveloped base metal deposits are proximal and distal manifestations of a single volcanic-tectonic episode.

Acknowledgements

I am indebted to Professors R. W. Hodder and R. W. Hutchinson for introducing me to this stimulating and worthwhile problem, and for their continual enthusiasm and encouragement. The generous financial support of the Western Exploration office of Phelps Dodge Corporation through Mr. R. W. Ludden, and of Phelps Dodge Exploration East, Inc., through Mr. R. B. Ludden, is gratefully acknowledged. Mr. F. M. Beck of Callahan Mining Corporation provided access to all information amassed during the exploration, development, and production of the Penobscot mine, as well as permission to map, study, and sample at the mine site. Similar assistance was extended by the staff of Kerr-American, Inc., especially by Mr. J. A. Pearson. The insights and abilities of Dr. R. Kerrich were essential in understanding the deformational history of the Ellsworth Formation. Laboratory support was efficiently and generously provided by Dr. S. A. Williams, director of geological research, Phelps Dodge Corporation, and his staff, especially Mr. B. S. Khin. Lead isotopic data were provided by Dr. B. R. Doe and the isotope Branch of the United States Geological Survey. Discussions in the field with Mr. T. E. LaTour were important in reaching an appreciation of the structures in the Ellsworth Formation. Able field assistance by Messrs. P. R. Baxter, and G. B. Margeson is appreciated. The graphics arts abilities of Mr. and Mrs. F. W. Graves, Mr. A. Noon, and Mr. R. Getty were indispensible in figure preparation and layout. Mr. J. Forth

prepared all of the polished surfaces, and Mrs. R. Ringsman kindly drafted two figures.

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Chapter One

Introduction

The area of this study includes major parts of the Castine and Blue Hill fifteen minute quadrangles, Hancock County, southeast coastal Maine, between north latitudes 44°15' and 44°30', and west longitudes 68°35' and 68°55' (Figure 1). U. S. highway #1 and state route 15 lead from Bangor to Bucksport, and there connect with state routes #166, #172, #175, #176, and #199, providing access to all parts of both quadrangles. Numerous old town roads, logging roads, fire breaks, and jeep trails provide ready foot access to most wooded and swampy areas. Small islands in Penobscot Bay can be reached by private boat; larger islands have ferry service. Approximately 5% of the area is exposed bedrock, generally along the coastline, with infrequent inland exposures due to extensive glacial debris, forest, and swamp cover.

Over 183 occurrences of base and precious metals are known in Hancock County (Rand, 1957), and although most have no recorded production,they attracted interest during the world-wide metal mining boom of the 1880's. Interest is periodically rejuvenated by upsurges in metal prices. Significant production came from American Smelting and Refining Company operations near Blue Hill, where, between 1917 and 1918 copper ore was produced from the Douglas Mine and processed in a 125 ton-per-day mill at the site. Mining activity in the region was then dormant until Callahan Mining Corporation began producing from its copper-zinc Penobscot

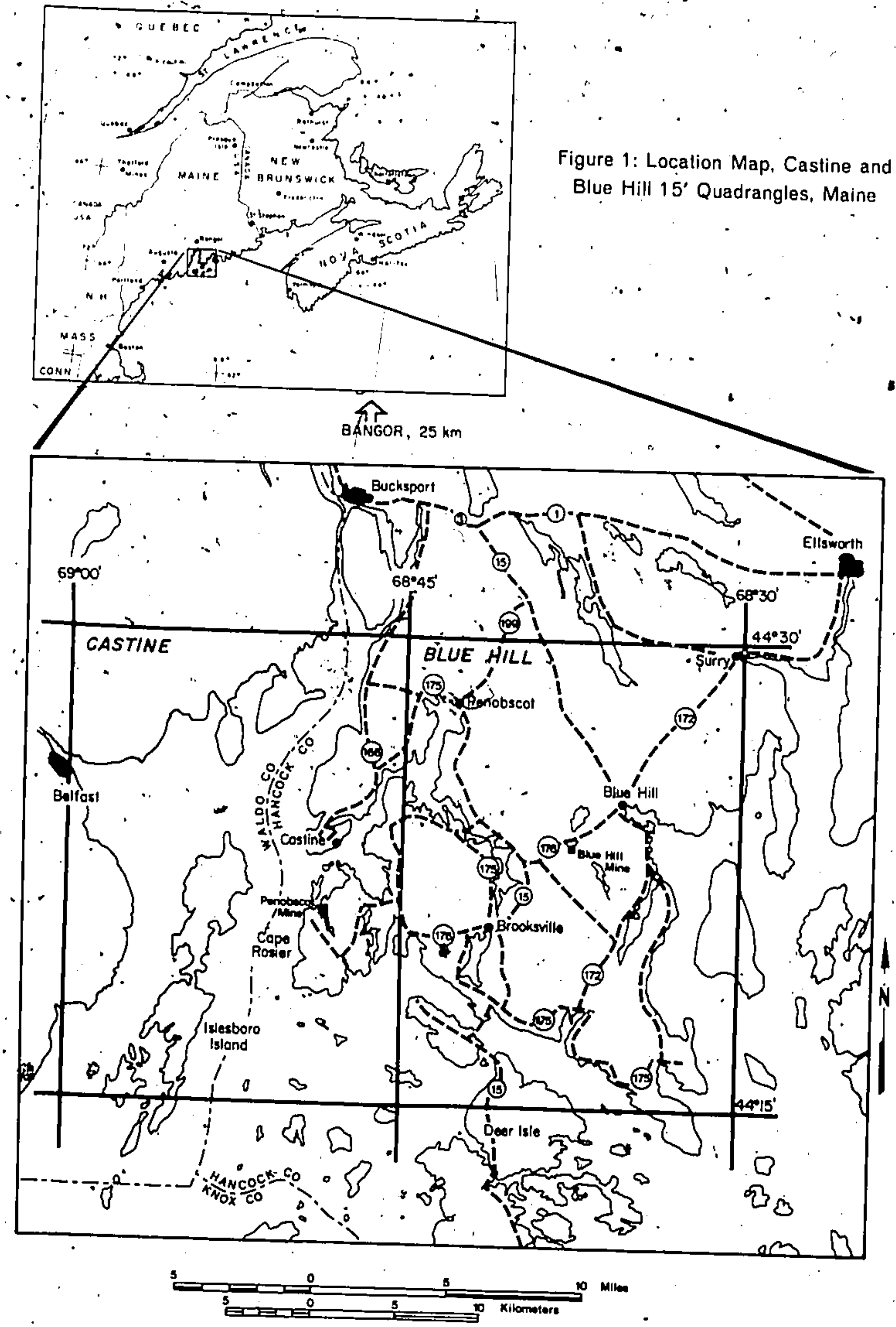


Figure 1: Location Map, Castine and Blue Hill 15' Quadrangles, Maine

Unit at Harborside, where nearly 1 million tons of 1% copper and 6% zinc were extracted between 1966 and 1972. Kerr-American, Inc. began production in 1971 from the Blue Hill Mine, a zinc-copper deposit on the south shore of, and beneath Second Pond. This is virtually contiguous with the old Douglas mine.

Statement of Problem

This study deals with the spatial and temporal relationships among several of the metal sulfide occurrences and their enclosing rocks in the Castine and Blue Hill areas, southeast coastal Maine. The problem is essentially to document and explain the relationships between:

1. The form and metal contents of sulfide mineral occurrences in rocks accumulated at volcanic centers of the Castine Formation, as typified by the Penobscot mine.

2. The form and metal contents of sulfide mineral occurrences in sedimentary rocks of the Ellsworth Formation flanking the afore-mentioned volcanic centers, as typified by the Blue Hill mine.

The Castine and Blue Hill areas were selected because, despite differing prior interpretations of the geological relationships, there appeared to be a continuum of changing form and metal content of metal deposits from an apparent proximal volcanic setting to a distal sedimentary setting. These relationships are important because they can be used to resolve controversy about age relationships, extent of deformation, and stratigraphic relationships of the proximal volcanic rocks and distal sedimentary rocks. For these purposes five particular geological aspects have been emphasized:

1. The distribution and nature of volcanic rocks within the Castine Formation, shown on most recently published maps as relatively undeformed volcanic rocks of Silurian to Devonian age.

2. The lithologic and stratigraphic setting, and interpreted genesis of the Penobscot base metal sulfide deposit within the Castine Formation.

3. The distribution and nature of volcanic-derived sedimentary rocks within the Ellsworth Formation, shown on most recently published maps as relatively deformed sedimentary rocks of Upper Cambrian to Lower Ordovician age.

4. The lithologic and stratigraphic setting, and interpreted genesis of the Blue Hill base metal sulfide deposit within the Ellsworth Formation.

5. The comparison of the Castine and Ellsworth Formations as to distribution, composition, style of deformation, and enclosed base metal occurrences, and interpretation of their age relationships.

Methods of Investigation

Over four months were spent in the field, much of the time traversing well-exposed and nearly uninterrupted coastline outcrops. These exposures permit detailed description of the nature and cyclicity in volcanic products, and of the relationships between volcanic and sedimentary rocks. Detailed information on virtually all aspects of the Penobscot mine was provided by Callahan Mining Corporation, and similar data were provided by Kerramerican, Incorporated for the Blue Hill mine. In addition, all old prospects, showings and mines were visited and samples collected for study. Two areas of shoreline considered critical to understanding the spatial distribution of rock types were mapped by transit and plane table at one inch equals ten feet, and several hundred mesoscopic fold axes were measured. Petrographic data were gathered from thin sections and polished sections, and combined with over 600 field descriptions, 50 whole rock chemical analyses, and 250 analyses of sulfide-bearing samples. X-ray diffraction studies aided in identification of fine-grained rocks and unusual mineral species. Lead isotopic ratios for galena separated from three mines were determined by the Branch of Isotope Geology of the United States Geological Survey.

Previous Work

Jackson (1838) undertook the first geologic reconnaissance of the Maine coastal volcanic belt, followed by Smith and others (1907), whose comprehensive regional mapping at 1:100,000 has been the basis for all subsequent work. These early workers defined the Castine Formation as a succession of volcanic rocks of Cambrian age, resting unconformably upon schists of the Ellsworth Formation of Precambrian age. More recently, Castine Formation has been assigned a Siluro-Devonian age because of Niagaran through Geddinian fauna in Castine correlative rocks (Brookins and others, 1973; Brook-

-ins, in Wones, 1974; Brookins, 1976.) Rubidium-strontium data and paleontologic correlation have suggested an Upper Cambrian to Lower Ordovician age for Ellsworth Formation (Brookins, 1976).

Relative age relationships and the position and nature of contacts between these two formations have been and still are controversial. Stewart (1956) considered Ellsworth Formation to be pre-Middle Silurian, and Castine Formation Late Silurian through Early Devonian. Doyle (1967) considered Ellsworth Formation to be of Ordovician age, and Castine Formation Silurian to Devonian. Areas mapped previously as Castine Formation by Smith and others (1907) were redefined as Ellsworth Formation by Stewart (1956), and Wingard (1961) further diminished the extent of the Castine Formation by assigning rocks on Deer Isle and Little Deer Isle to the Ellsworth Formation. Correlations between Castine, Ellsworth, and adjacent formations have been attempted by Chapman and Wingard (1958), Wingard (1958, 1961), Osberg (1968, 1974), Gates (1969), and Brookins and others (1973). Recent compilation and correlation papers by Stewart and Wones (1974) and by Brookins (1976) present the current consensus regarding relative ages of formations in the Penobscot Bay area.

Chapter Two

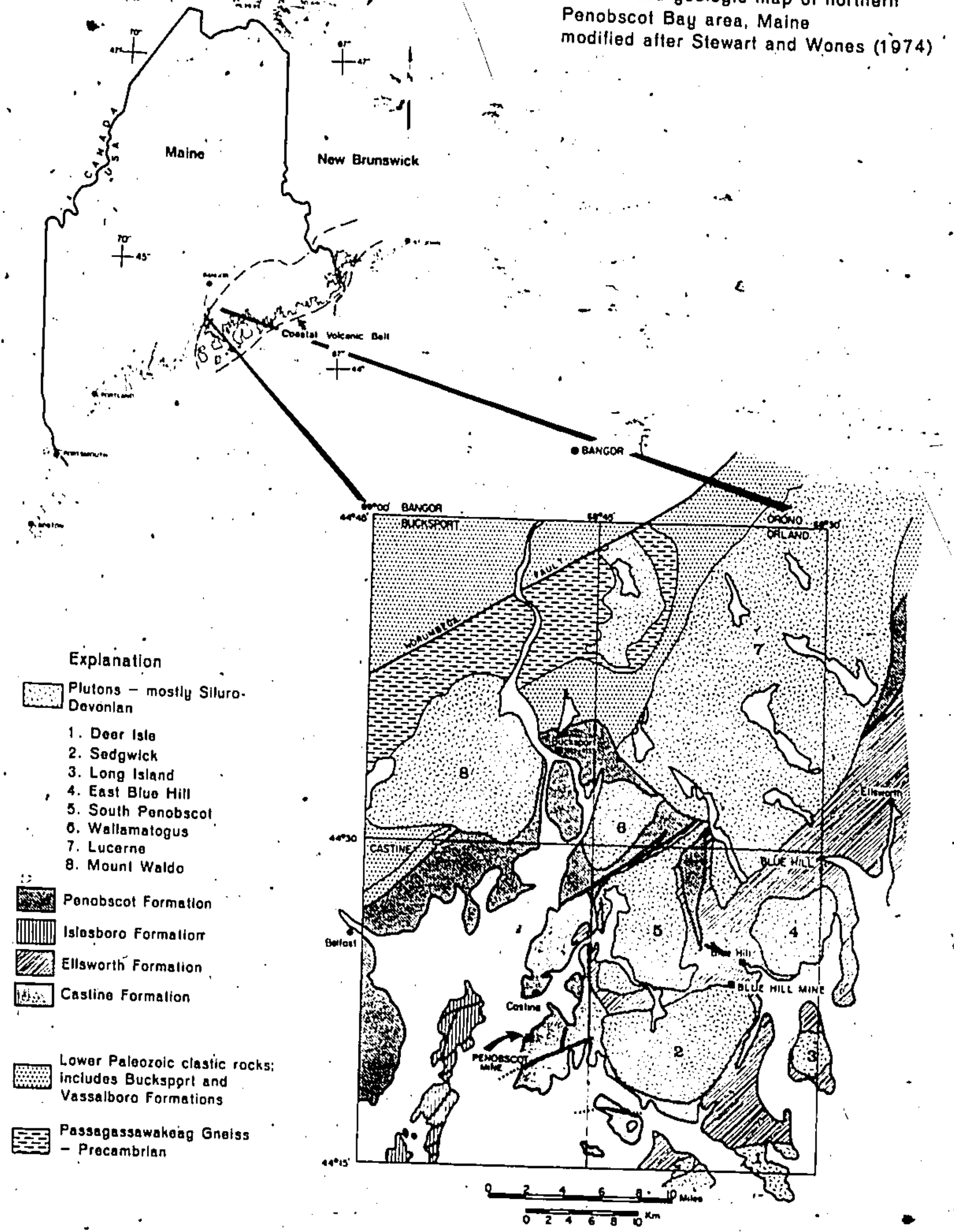
Regional Geology

General Geology and Rock Units

Late Silurian through Early Devonian volcanic and related sedimentary rocks extend from the Penobscot Bay region of Hancock, Waldo, and Knox Counties, Maine, northeastward into New Brunswick (Figs. 1 and 2). This layered sequence is intruded by granitic plutons, some of which are considered comagmatic with the extrusive rocks (Brookins and others, 1973). The volcanic rocks in the east Penobscot Bay region are mapped as the Castine Formation (Smith and others, 1907), a differentiated sequence of mafic, intermediate, and felsic rocks, consisting of flows, pyroclastic rocks, and lava domes. Intermediate and felsic rocks predominate on Cape Rosier and the Castine peninsula, but are subordinate to mafic rocks on islands in Penobscot Bay. The rocks are in the greenschist facies of regional metamorphism, but the prefix meta- is not used because of complete preservation of original volcanic textures, partial preservation of original mineralogy, and absence of metamorphic fabric.

The Ellsworth Formation flanks the Castine Formation to the east, and is thin-banded quartzitic, quartzofeldspathic, sericitic, and chloritic metasediment, intercalated with fine-grained beds of volcanic debris, infrequent tuffs and tuffaceous wackes, and thin mafic flows, suggesting volcanic provenance for the formation as a whole. The Ellsworth Formation also is in the greenschist facies of regional meta-

Figure 2: Generalized geologic map of northern Penobscot Bay area, Maine modified after Stewart and Wones (1974)



-morphism. Within the study area, the Penobscot Formation is the only other rock unit of formational status. Although named for the excellent exposures on the west side of Penobscot Bay, it also occurs west of the Castine Formation in Brooksville and Castine Townships (Fig. 1). It is similar to the Ellsworth Formation inasmuch as it is thin-bedded and contains clay minerals which define a foliation parallel to compositional banding. It is generally graphitic, and locally pyritic, and is in the greenschist facies of regional metamorphism.

Well-defined and broad contact metamorphic aureoles containing cordierite, anthophyllite, garnet, diopside, biotite, andalusite, or sillimanite are superimposed upon the regional greenschist facies assemblages near the Sedgwick, South Penobscot, East Blue Hill, Wallamatogus, and other plutonic bodies. These thermal effects are most pronounced in the pelitic Ellsworth and Penobscot Formations, but less so in the more massive and siliceous rocks of the Castine Formation.

Regional Tectonic Relationships

Recent ideas concerning igneous petrogenesis of Silurian and Devonian rocks in coastal Maine and adjacent parts of New England and New Brunswick have postulated subduction with related island arc development during closure of a proto-Atlantic in the lower Paleozoic, and eventual Siluro-Devonian collision of the North American and European plates (Gates, 1969). Later, Mesozoic rifting did not parallel precisely this plate junction, and left a European plate fragment at-

-tached to North America, part of which is perhaps the coastal volcanic belt of Maine. Crustal blocks, defined by consistency of lithology and structural style, and bounded by postulated major faults, are the inferred remnants of these large-scale compressional and extensional tectonic events (Osberg, 1974)(Table 1). The Castine and Ellsworth Formations form the Castine-Ellsworth block, and are fault-bounded on the west.

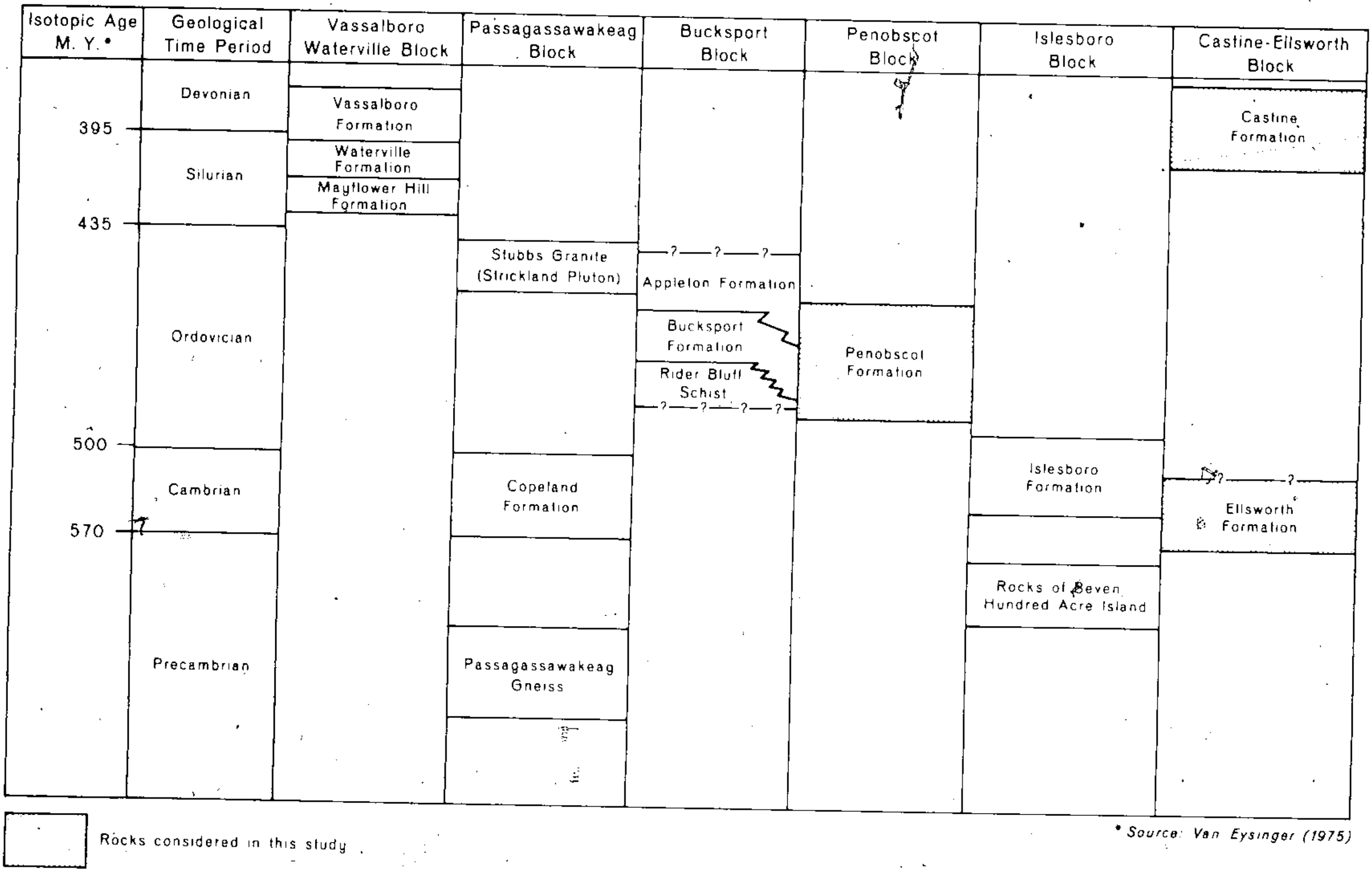
On the northwest an abrupt lithologic change across Penobscot Bay is interpreted by Stewart and Wones (1974) as the trace of the ancient suture line. The east and southeast parts of the coastal volcanic rocks are beneath Penobscot Bay and the Atlantic Ocean, and are thus unknown, although large faults in the Gulf of Maine break Triassic and older formations, and appear to truncate coastal volcanic rocks (Kane and others, 1974).

The Precambrian Passagassawakeag Gneiss is considered basement to the coastal volcanic rocks (Bickel, 1971; Stewart and Wones, 1974), although only exposed north of the coastal volcanic rocks and not in contact with them. It is overlain by Bucksport Formation, considered Middle to Late Ordovician (Stewart and Wones, 1974). Geophysical ~~studies~~ in south Penobscot Bay suggest a rock of high density and high magnetic susceptibility juxtaposed against and possibly underlying volcanic rocks of the Castine Formation (Kane and Bromery, 1964).

TABLE 1

Rock units and tentative age assignments, Penobscot Bay region

After Stewart and Wones (1974)



* Source: Van Eysinger (1975)

Chapter Three

The Castine Formation

Definition and General Features

Smith and others (1907, p. 5) defined the Castine Formation as,

> ". . . light colored altered lavas and pyroclastics, including rhyolites, dacites, and andesites. These rocks are typically developed on the Castine peninsula, some of the best exposures occurring in the vicinity of the town of that name."

Although named for the exposures near Castine, the best and most complete sections are exposed on Cape Rosier, and on islands in Penobscot Bay. Thorofare Andesite and Vinalhaven Rhyolite on North Haven and Vinalhaven Islands, volcanic rocks on many smaller islands in Penobscot Bay, volcanic rocks designated North Haven Greenstone or equivalent in some localities, and similar appearing rocks tens of kilometers south and east, are probably broadly coeval and correlative with the Castine Formation (Brookins and others, 1973).

Volcanic rocks of the Castine Formation are a differentiated sequence ranging from basalt and andesite, through dacite, trachyte, and latite, to rhyodacite and rhyolite, with approximately equal volumes of these mafic, intermediate, and felsic products. Pillow lavas, lapilli tuffs, tephra deposits, and bomb agglomerates recur throughout the succession, and are typical of mafic and intermediate sections. Felsic rocks occur as lava domes and coarse silicic breccias.

Basaltic through rhyolitic rocks were extruded cyclically.

Basalts are overlain by successively less mafic and more fragmental rocks, culminating in rhyolitic pyroclastic types with synvolcanic intrusion of associated rhyodacite and rhyolite domes. Five such cycles of volcanism are recognized on Cape Rosier (Fig. 3), and can be extrapolated to nearby islands in Penobscot Bay. Chemical sedimentary rocks, and fine-grained tuffaceous mudstones associated with siliceous pyroclastic rocks and rhyolite domes define contacts between volcanic cycles. These rocks occur only in stratigraphically uppermost parts of any cycle, and are overlain directly by basaltic to andesitic rocks representing the mafic base of a succeeding cycle of volcanism. These intercycle rocks are well-layered, and have the greatest areal extent of any rocks in the Castine Formation.

Rapid lateral lithofacies changes and great variability in volcanic products characterize the Castine Formation, and minor intercalated sedimentary rocks are rich in volcanic component. Conglomerate, volcanic breccia, unconformable successions, and steep initial dips are typical, and such heterogeneity has led Stewart and Wones (1974, p. 239) to conclude that,

> ". . . it has not been possible to establish a reliable stratigraphic column for the Castine volcanics, and the impression gathered is that beds and even sequences of beds are of short lateral extent. This suggests several nearby sources and possibly some topographic influence."

Such phenomena in volcanic terranes seriously complicate regional correlations based on type sections and conventional

Explanation to accompany
Lithologic Map (Fig. 3).

1 Volcanic Rocks

1a Basalt and andesite; flows, breccias, tuffs

1b Quartz andesite, dacite, trachyte, and intermediate rocks; dominantly fragmental, minor flows

1c Rhyolite and rhyodacite, lava domes, breccias, and minor flows; occur in upper parts of volcanic cycles
$1C_{1,2\ldots}$ described in text

1d Rhyolite, lava domes which cross-cut volcanic stratigraphy; younger than rhyolite of 1C

1e Undifferentiated thin mafic to felsic tuffs and flows

4 Plutonic Rocks

4a Sedgwick pluton, granite

4b South Penobscot pluton, granite

4c Deer Isle pluton, granite

4d Long Island pluton, granite

5 Harzburgite, serpentinized

2

3

6

7

8

Lithologic contact; obs

Fault; observed, projec

Pr

1 of

ffs

intermediate rocks;

breccias, and minor flows;
es

olcanic stratigraphy;

uffs and flows

2	Dominanty fine tuffs of variable composition, with minor interbedded sedimentary rocks
3	Dominantly volcaniclastic and sedimentary rocks, with minor interbedded tuff, and basaltic to dacitic flows; includes phyllite and hornfelsed equivalent formerly mapped as Ellsworth Formation, and black graphitic shale formerly mapped as Penobscot Formation
6	Mixed rocks occurring between Sedgwick and South Penobscot plutons; includes dioritic border phase of South Penobscot pluton, granofels, hornfels, and injection gneiss
7	Quaternary and Recent deposits, undifferentiated
8	Not mapped or not compiled for this study

Lithologic contact; observed, projected, inferred.

Fault; observed, projected, inferred

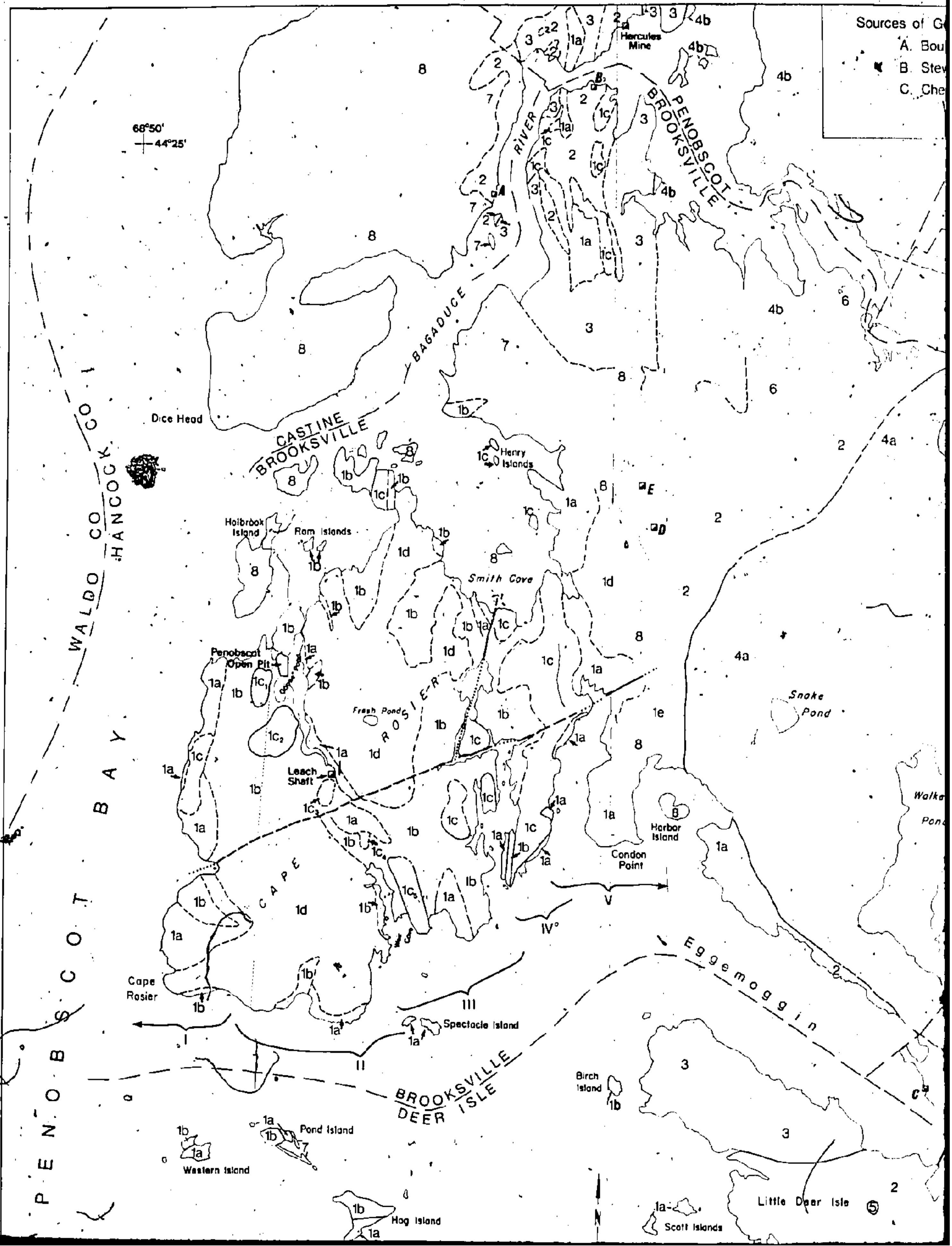
Prospects described in text

A	North Castine-Emerson
B	Jones, Jones-Dodge
C	Eggemoggin
D	Tapley
E	Shepardson
F	Deer Isle

2/2

1 of

Figure



Sources of G
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B. Stev
C. Che
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44°25'
Hercules Mine
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CASTINE
BROOKSVILLE
WALDO CO
HANCOCK CO
PENOBSCOT BAY
Dice Head
Henry Islands
Holbrook Island
Ram Islands
Smith Cove
Penobscot Open Pit
Fresh Pond
ROSIER
Leach Shaft
CAPE
Cape Rosier
Snake Pond
Walke Pon
Harbor Island
Condon Point
Eggemoggin
Spectacle Island
BROOKSVILLE
DEER ISLE
Birch Island
Pond Island
Western Island
Hog Island
Scott Islands
Little Deer Isle
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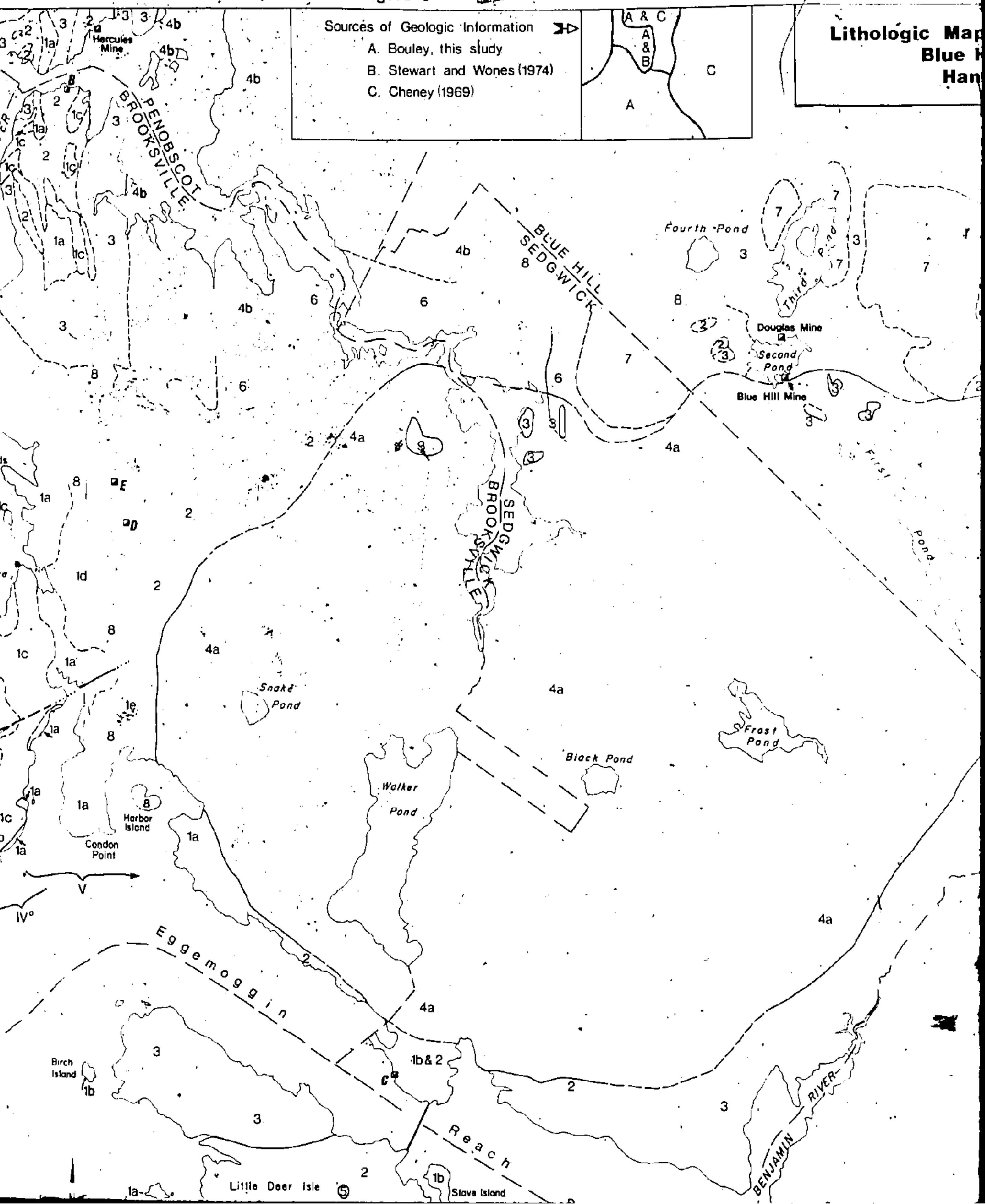
Figure 3



Sources of Geologic Information
A. Bouley, this study
B. Stewart and Wones (1974)
C. Cheney (1969)
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Lithologic Map
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Blue Hill Mine
First Pond
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BROOKSVILLE
Snake Pond
Walker Pond
Black Pond
Frost Pond
Harbor Island
Condon Point
Eggemoggin Reach
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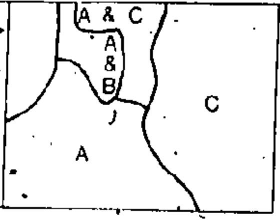
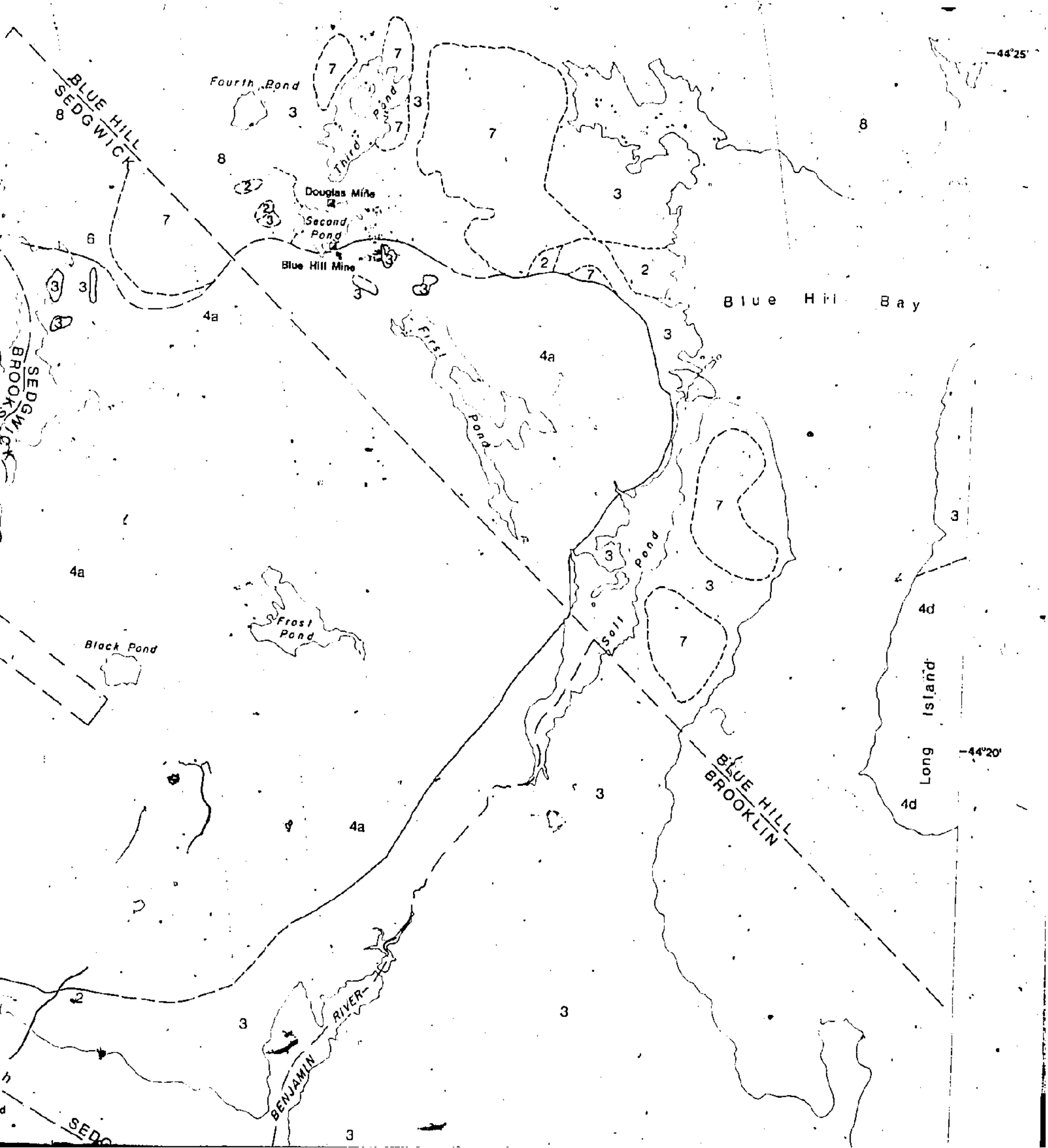
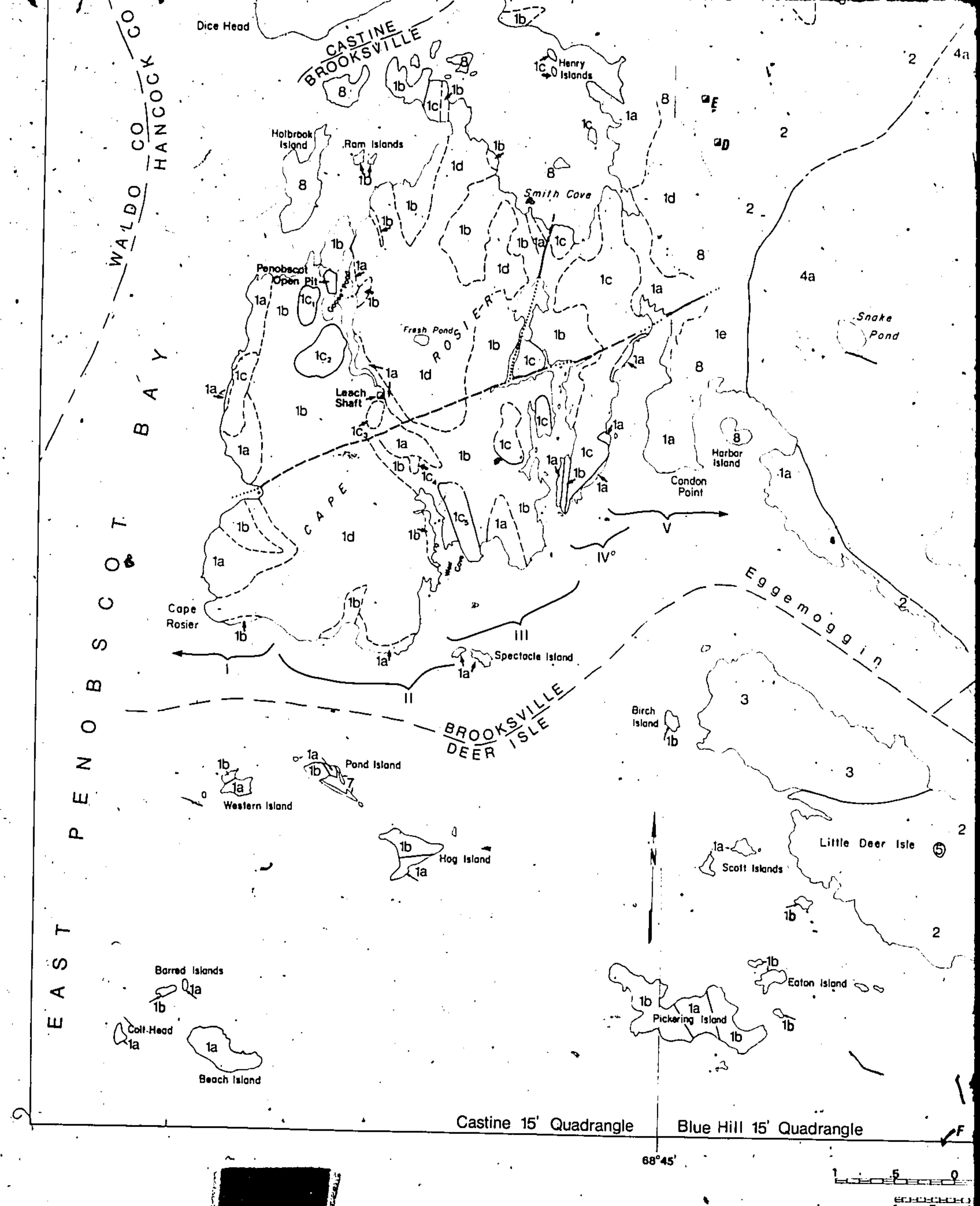


Lithologic Map of Parts of the Castine and Blue Hill 15' Quadrangles, Hancock County, Maine

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Castine 15' Quadrangle
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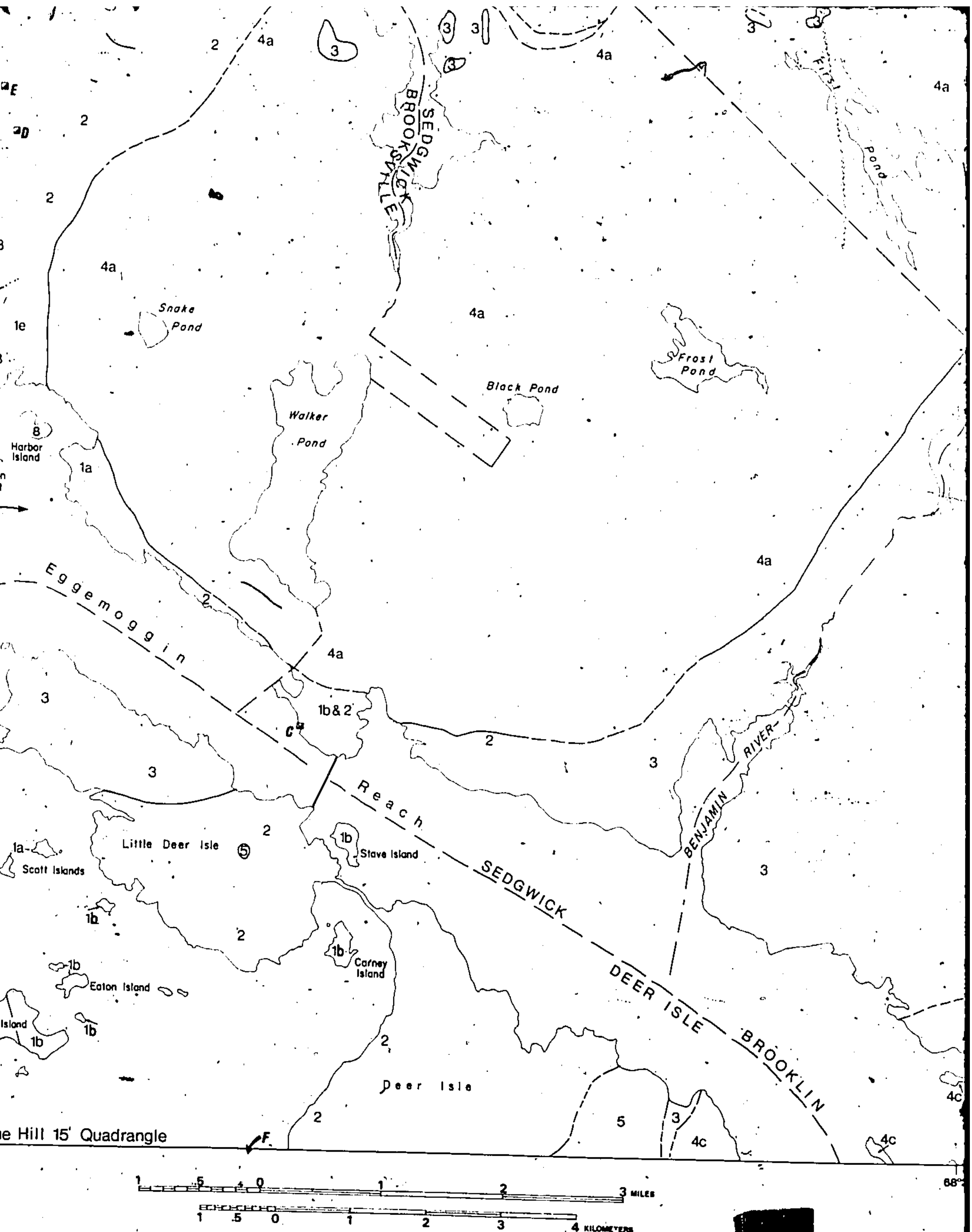
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Stave Island
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DEER ISLE
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Carney Island
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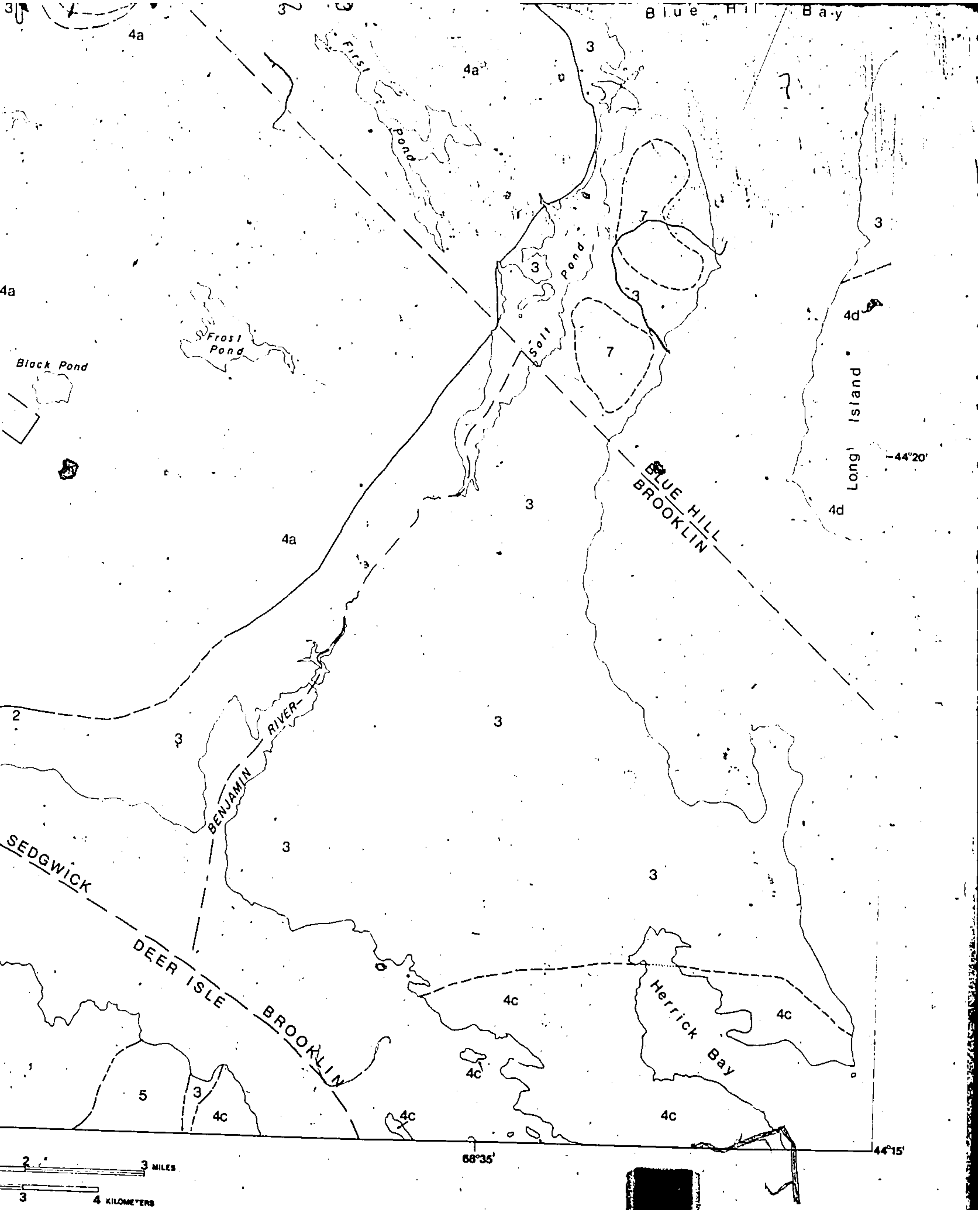
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Salt Pond
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Long Island
44°20'
BLUE HILL
BROOKLIN
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SEDGWICK
DEER ISLE
BROOKLIN
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Herrick Bay
4c
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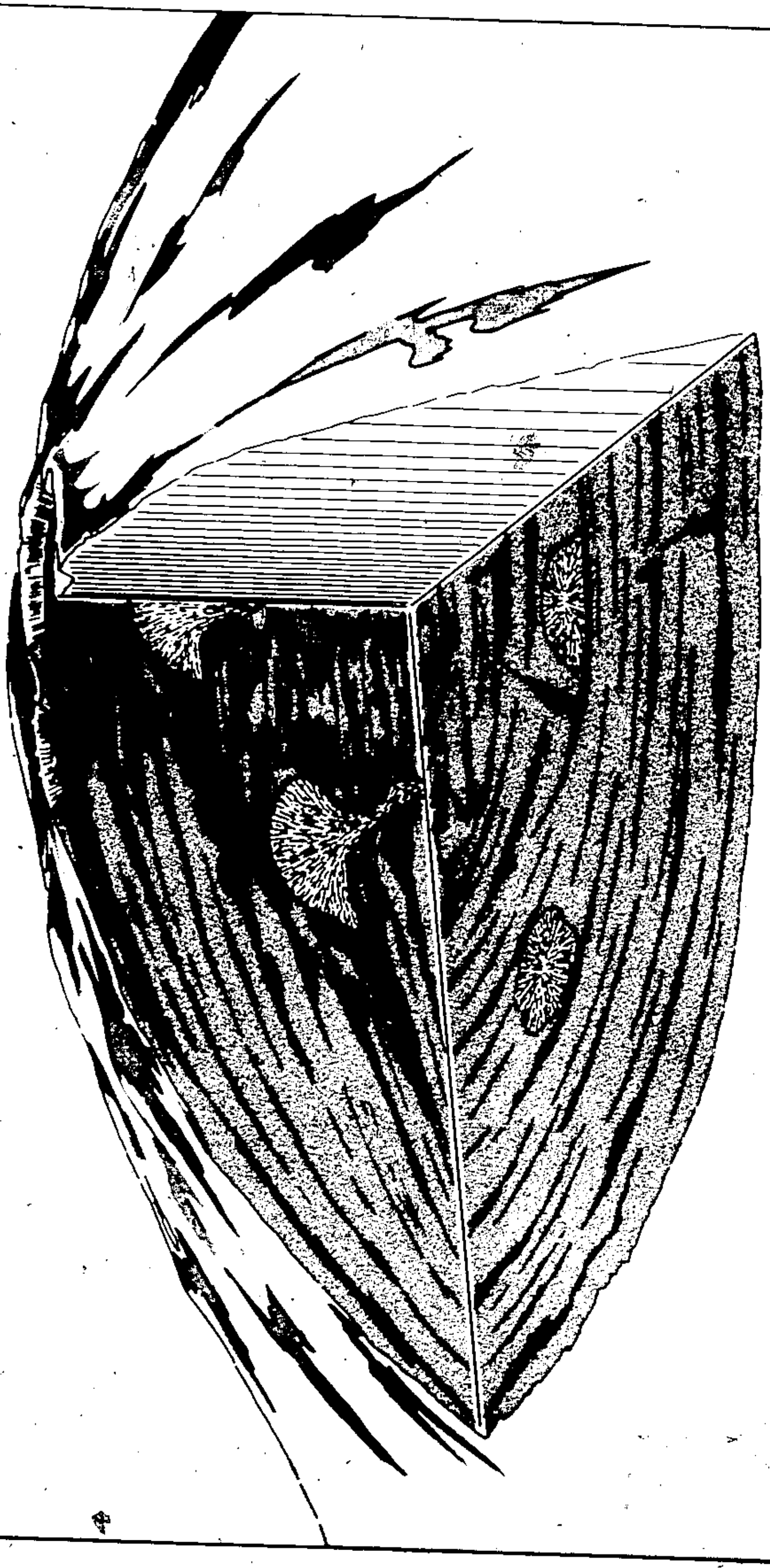
3
4c
4c
4c
68°35'
44°15'
2
3 MILES
3
4 KILOMETERS

stratigraphic columns, as is common for layered sedimentary rocks. However, recognition of a broad succession based on cyclicity or repetition of basaltic through rhyolitic volcanic products can be deduced from nearly continous shoreline outcrop. In the Castine and Blue Hill areas the volcanic succession is homoclinal, with flows, coarse tuffs and breccias, conglomerates, and lava domes near local eruptive centers, and finer tuffs and reworked volcaniclastic sedimentary rocks farther from eruptive centers. The transition between the two environments of accumulation is gradational, and is mappable as the transition from Castine to Ellsworth Formations proceeding east from Cape Rosier to Blue Hill. Broad curvature within this volcanic and volcanic-sedimentary succession is interpreted as relict, representing erosional intersection with the layered and concentric structure of a composite stratovolcanic edifice several to tens of kilometers in diameter (Fig. 4).

Basalt and Andesite

Rocks of basaltic and andesitic composition (Table 2) are black, grey, or green on weathered surfaces. They are pillowed (Plate 1A), massive, have columnar joints (Plate 1D), and in some places are fragmental with coarse to fine pyroclastic (Plates 1E, 1F), autoclastic, or epiclastic textures. Devitrified hyaloclastic breccia is well-exposed at several localities (Plates 1B, 1C). Rubbly, autobrecciated flow tops and amygdaloidal zones are numerous, and, together with pillowed units, provide reliable geopetal indicators. Basalt



no scale intended

Figure 4. Interpreted Reconstruction of Castine Stratovolcanic Edifice

Table 2: Whole Rock Analyses, Castine Formation Basalts and Andesites

	A	B	C	D	E	F	G	H	I	J	K	L
SiO_2	48.01	47.45	46.23	53.35	54.18	51.19	51.04	48.69	57.29	50.00	49.31	48.27
TiO_2	1.28	1.79	2.27	1.69	2.20	1.79	1.62	1.24	2.76	1.54	1.15	0.89
Al_2O_3	17.56	22.55	18.54	14.79	17.59	17.40	17.02	12.58	14.14	16.57	17.88	18.28
Fe_2O_3	2.80	3.31	3.79	3.22	3.72	3.31	3.13	2.76	4.28	2.44	2.66	1.04
FeO	7.16	6.71	4.34	5.41	6.66	6.06	2.86	7.09	6.53	6.62	3.37	8.31
MnO	0.18	0.14	0.28	0.17	0.25	0.20	0.12	0.23	0.92	0.16	0.12	0.17
MgO	10.24	4.34	4.61	7.65	3.60	4.61	4.05	18.39	7.89	8.36	8.97	8.96
CaO	4.85	3.04	10.05	7.02	3.88	7.26	11.63	6.23	1.12	11.69	10.30	11.32
Na_2O	5.48	3.10	6.69	4.18	5.32	3.59	5.67	0.70	2.77	2.58	3.34	2.80
K_2O	2.13	7.27	2.78	2.24	2.20	4.19	2.56	1.90	1.57	0.04	2.63	0.14
P_2O_5	0.29	0.32	0.41	0.27	0.42	0.40	0.28	0.20	0.83	0.00	0.27	0.07
Pb	10	5	5	5	5	5	5	5	5		10	
Ni	56	52	59	79.9	42	74	161	819	27		187	
Cu	41.4	84.8	35.6	115	28.3	35.6	155	35.6	504		78.8	
Zn	132	143	148	239	128	133	89.5	129	342		89.5	
Cr	192	251	270	58	198	200	276	912	143		195	
Co	58	53	58	ND	49	51	65	112	44		52	
Sr	85.3	93.9	158	199	71.9	71.4	436	56.0	49.7		588	
V	182	199	306	310	307	14	259	210	257		198	
Be	3.0	4.2	4.2	3.6	3.3	4.4	3.9	2.8	2.0		3.5	
Ba	930	1490	740	470	590	1140	1340	620	590		1180	

Totals recalculated to 100%; locations given in Appendix 1.

Oxides given in weight percent; elements in parts per million.

Analyses by radio frequency induction coupled plasma emission spectroscopy, at Barringer Research, Limited, Toronto, Ontario.

Analysis J by J. Descarreaux for Kerramerican, Inc.

Analysis L typical high alumina basalt (Carmichael, Turner, and Verhoogen, 1974, p. 33).

Note: Iron determined as Fe_2O_3; FeO by calculation.

PLATE 1

Macroscopic Features of Basalt and Andesite

A. Spherical cross-section of undeformed pillow in basalt, Bald Island, South Penobscot Bay (not shown on map).

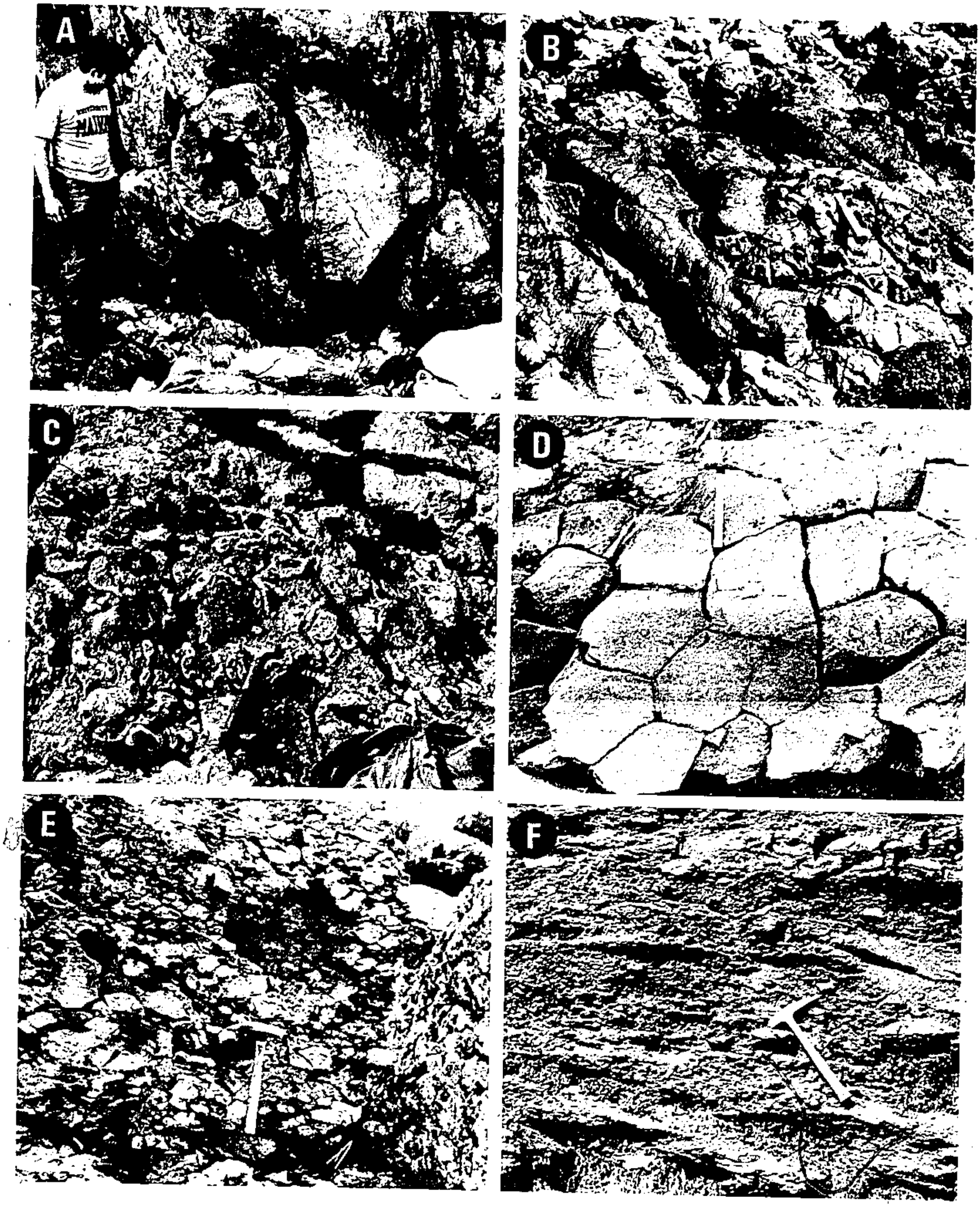
B. Toes of pillowed lava flows and interpillow hyaloclastite debris, Condon Point, South Brooksville. Hammer length is 34 cm.

C. Small tubular pillows in pumpellyite-bearing, devitrified, hyaloclastite breccia, Bald Island. Hammer length is 40 cm.

D. Columnar joints in basalt, west side of Smith Cove in Brooksville. Horizontal striae are glacial grooves; hammer length is 34 cm.

E. Basaltic agglomerate, west side of Bucks Harbor, South Brooksville. Hammer length is 34 cm.

F. Bedded lapilli tuff and basaltic agglomerate, east of Weir Cove in cycle 3 basalt, Cape Rosier. Hammer length is 34 cm.


A
B
C
D
E
F

flows tend to have greater areal extent than neighboring less mafic rocks. Amygdales usually are filled with chlorite, quartz, epidote, or calcite. Except for minor tensional cracks and fractures with little or no apparent offset, the rocks lack tectonic or metamorphic fabric.

Although their sites are occupied by calcite, epidote, albite, chlorite, and other minerals, outlines and textures typical of original minerals indicate that the pre-metamorphic mineralogy consisted of 40-60% calcic plagioclase, 30-50% clinopyroxene, 10-60% glass, 0-10% hornblende, with accessory apatite, pyrite, magnetite, and ilmenite. Albite and sodic oligoclase are commonly as water clear crystals in the groundmass, or as jackets around more calcic cores, derived by greenschist alteration of original andesine or labradorite. Whole rock chemical analyses indicate that normative feldspar compositions for these rocks are in the range of An_{26} to An_{80}, with a mean of An_{51}, normal values for basalt. Pseudomorphs of original calcic plagioclase by sodic plagioclase, clay minerals, sericite, chlorite, and epidote (Plate 2B) preserve crystal outlines and remnants of crystals. Diabasic texture is a common feature, especially in thicker, holocrystalline flows (Plate 2C).

The pyroxenes are titanaugite, augite, and pigeonite, with the former two most abundant on Cape Rosier, although Dow (1965) reports augite predominant for Thorofare Andesite on North Haven Island. Ophitic texture is common, as is poikilitic enclosure of small plagioclase crystals in clinopyrox-

PLATE 2

Microscopic Features of Basalt and Andesite

A. Water-clear albite crystals in pilotaxitic alignment, with small, quartz-filled amygdales. Sample Ca-145, crossed nicols.

B. Large plagioclase crystals (PL), replaced by clay minerals and epidote. Groundmass is mostly chlorite and actinolite. Sample Ca-149, plane light.

C. Ophitic texture; much water-clear felted albite intergrown with actinolite and chlorite, intersertal magnetite and minor pyrite. Sample Ca-200, plane light.

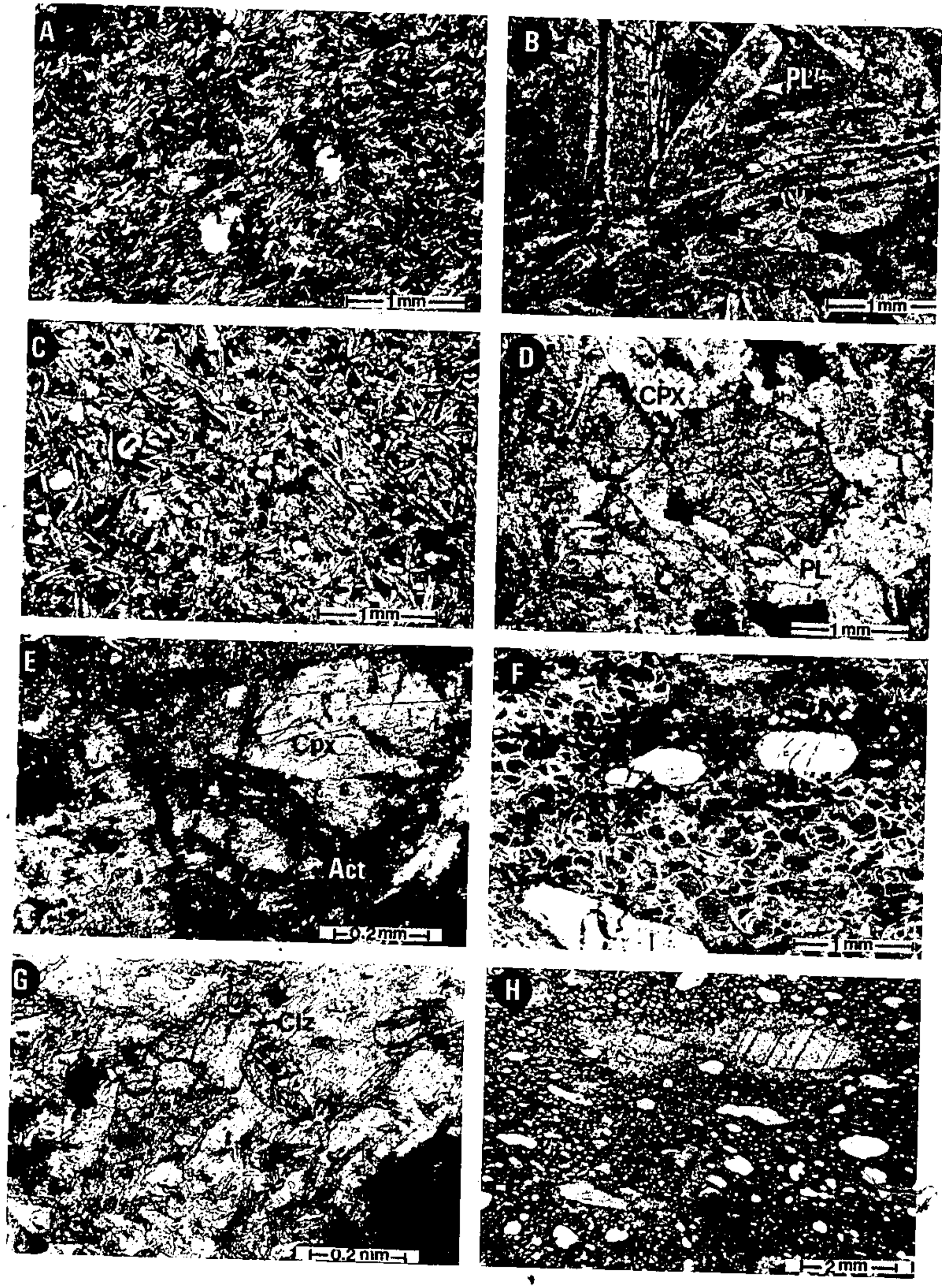
D. Large, euhedral titanaugite crystal (CPX) poikilitically enclosing small plagioclase lath (PL). Sample Ca-158, plane light.

E. Clinopyroxene grain (CPX) with rim and veins of uralite (Act). Sample Ca-182, crossed nicols.

F. Perlitic cracks in basaltic glass with included aligned and broken feldspar crystals. Sample Ca-93, plane light.

G. Prisms of clinozoisite (Clz), with adjacent actinolite and biotite, and a large magnetite crystal (black area) in corner. Sample Ca-149, plane light.

H. Fine-grained basalt, with quartz and chlorite-calcite amygdales. Sample Ca-94, plane light.


A
1mm
B
PL
1mm
C
Q
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D
CPX
PL
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E
Cpx
Act
0.2mm
F
1mm
G
Clz
0.2 mm
H
2mm

-ene euhedra (Plate 2D). Pseudomorphous replacement of pyroxene by talc, chlorite, and uralite is variable in intensity, and in most instances original crystals are recognizable only by crystal outline. Most grains are 40 to 60% relict pyroxene, and exhibit cores rimmed by uralite, or have incipient uralite along cleavage planes (Plate 2E). Minute grains of magnetite or ilmenite are scattered throughout uralitic amphibole.

Primary hornblende occurs sparingly, and is restricted to volumetrically minor hornblende andesite flows. It is pale brown, and in some instances (Wingard, 1961) blue absorption parallel to the gamma vibration direction indicates a sodic composition (Deer and others, 1966). Fibrous amphibole is prevalent, especially in the eastern parts of Cape Rosier. It occurs as felted aggregates within otherwise turbid groundmass, presumably after original glass or ferromagnesian minerals, and also as uralite veins and rims in pyroxene (Plate 2E), consisting of larger and more optically continuous patches of uralite than that of the groundmass. Most amphibole of rocks of the Castine Formation adjacent to granitic plutons are granoblastic sprigs and sheaves which cut discordantly across primary fabric and mineralogy, and therefore are attributed to thermal contact metamorphism.

Chlorite occurs on several minerals, and in various habits, although two predominate: 1). Microlites of chlorite are along cleavage planes and as aggregates in pyroxene. In this habit fibrous chlorite and amphibole are intimately in-

-tergrown and the two become indistinguishable as grain size approaches limits of resolution. 2). Fine-grained to submicroscopic aggregates of chlorite, with or without amphibole, form complete pseudomorphs of pyroxene grains interstitial to plagioclase. In some instances the exceedingly fine grain size and random alignment are suggestive of devitrification textures. Most of the mafic rocks contain some areas with such textures, which, by virtue of grain size, are optically isotropic. Perlitic cracks attest to the unquestionable glassy origin of some of these isotropic regions (Plate 2F), and interpillow debris, hyaloclastic breccia, and tephra beds were no doubt deposited in glassy state. Mafic tuffs interbedded with basalt flows may consist totally of chlorite, and because of their finely laminated and fissile aspect have been called chlorite schist (Wingard, 1961; Cheney, 1969). In almost all instances chlorite is clear to pale green, feebly to moderately pleochroic, and sometimes exhibits anomalous interference colors.

Clear clinozoisite with anomalous interference colors occurs within albite as minute kernels, and also as euhedral prisms dispersed in chloritic groundmass (Plate 2G). It rarely comprises more than 5% of the rock, and, like chlorite, in some instances appears to be a product of devitrification. Calcite occurs as disseminated and irregular patches, as veins, and as amygdale fillings. Quartz is invariably intergrown with chlorite, epidote, and calcite in amygdales and patches in the groundmass, or as cross-cutting and presumably later veinlets

(Plate 2H). Nowhere has quartz of unequivocal primary origin been observed.

Magnetite and rare pyrite are accessory minerals, and the latter is more abundant in mafic tuffs. Magnetite is present in virtually all the mafic rocks, usually intersertal to plagioclase with diabasic texture (Plate 2C), or as minute octahedra within chlorite and amphibole of the groundmass. Sphene, zircon, apatite, chalcopyrite, sphalerite, and hematite are accessory to trace minerals.

Analyses (Table 2) and normative mineralogy both indicate that the mafic rocks are basalts (Figs. 5A, 5B). Attempts to identify magmatic lineage by use of standard petrologic diagrams have not been definitive, and indeed alkaline affinities on one plot (Fig. 6A) contradict the calc-alkaline affinity on another (Fig. 6B). Pervasive greenschist facies regional metamorphism, with attendant modification of original mineralogy, is presumably responsible for the high soda content of these rocks.

Quartz Andesite, Dacite, Trachyte, and Latite: The Rocks of Intermediate Composition

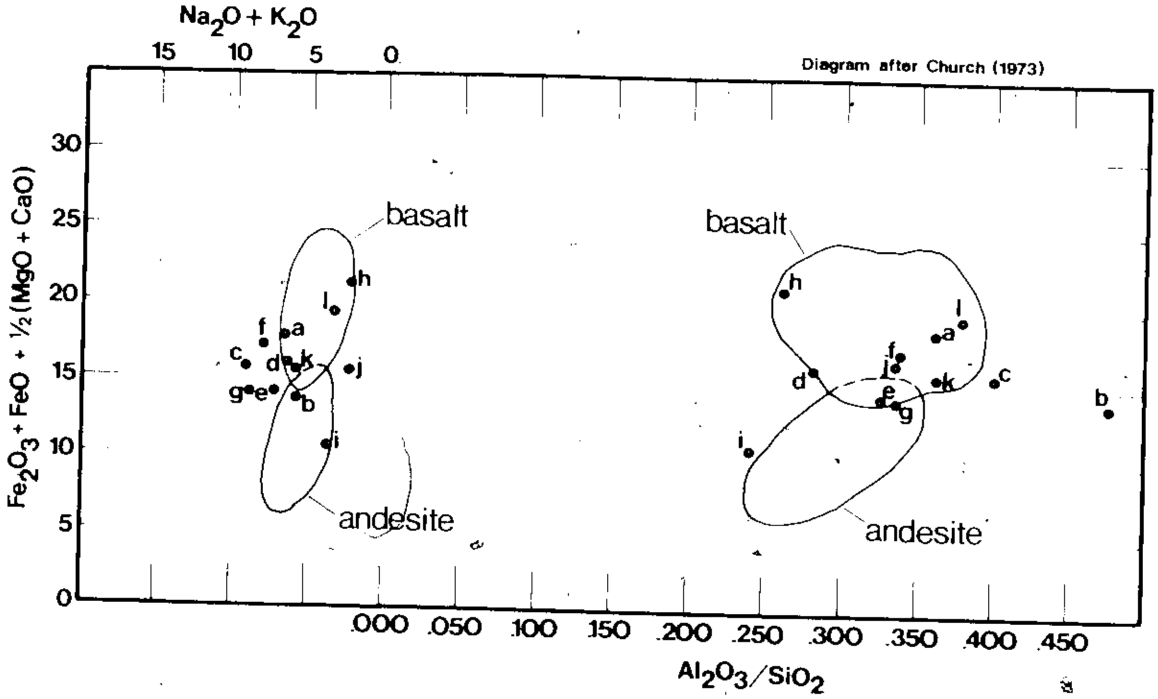
Rocks of intermediate composition (Table 3) in the Castine Formation are divisible into two groups based upon texture: 1). Vitric, crystal, and lithic tuffs.

2). Thin but massive flows of limited areal extent.

The most obvious feature of the tuffs is their heterogeneity (Plates 3, 4, 5). In general, these rocks have a wide range in fragment and matrix composition, grain size,

Figure 5A

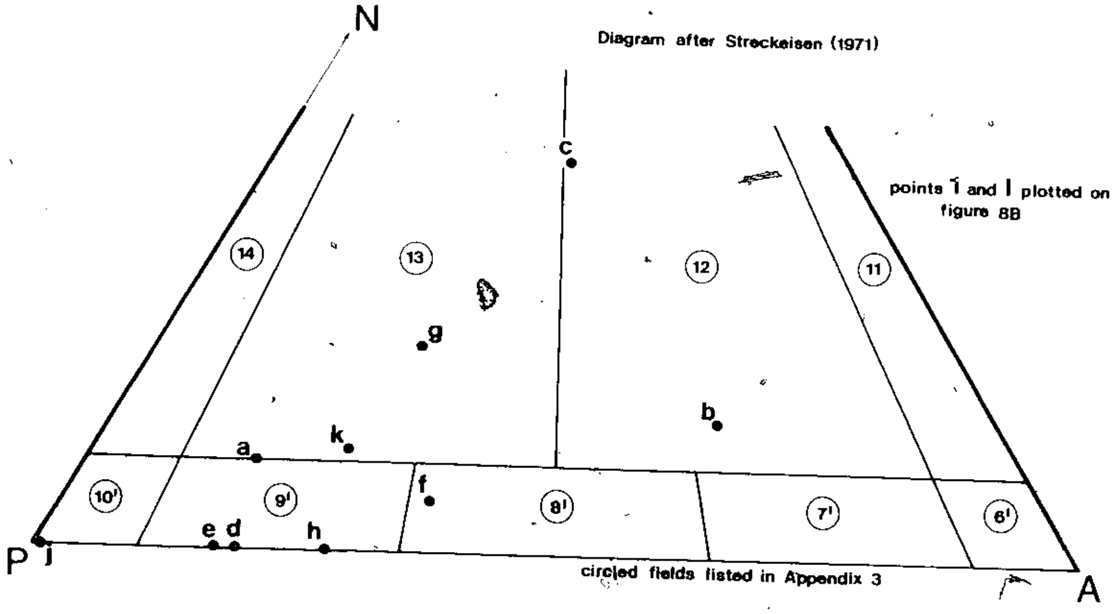
Classification by chemical analyses



Letters refer to Table 2

Figure 5B

Classification by normative mineralogy



A = alkali feldspar   P = plagioclase   N = nepheline

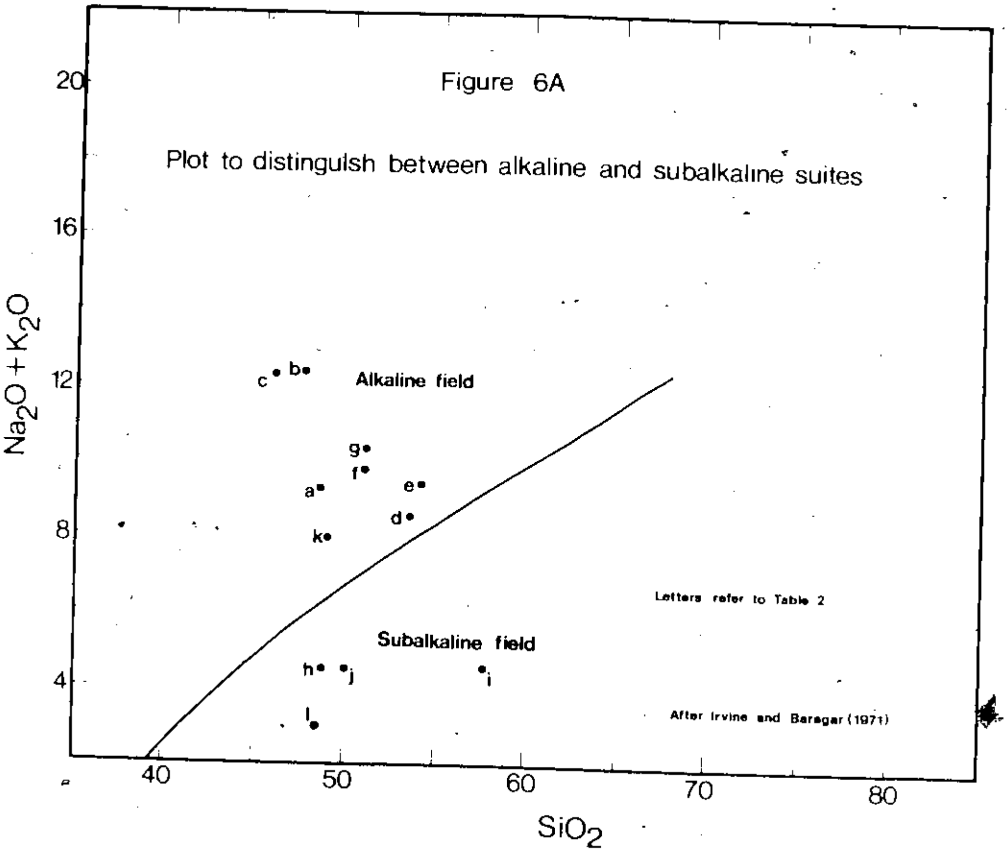


Figure 6A

Plot to distinguish between alkaline and subalkaline suites

Figure 6B

Plot to distinguish between calc-alkaline and tholeiitic suites

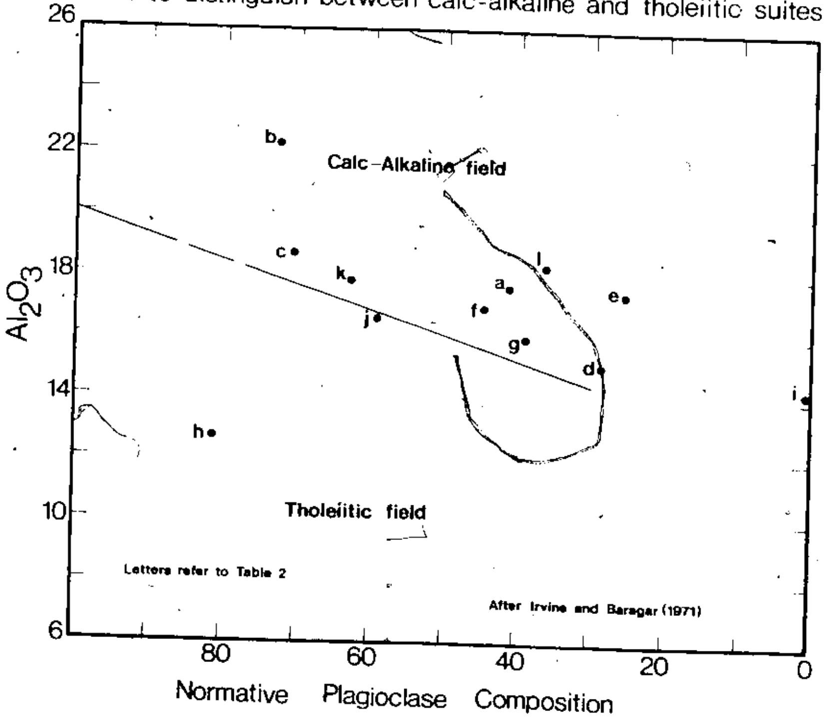


Table 3: Whole Rock Analyses, Castine Formation Quartz andesites, Dacites, Trachytes, and Latites; The Rocks of Intermediate Composition

	A	B	C	D	E	F	G	H	I
SiO_2	72.14	65.00	74.23	57.64	67.77	68.12	72.10	65.62	64.43
TiO_2	0.44	0.56	0.17	0.27	0.38	0.19	0.21	0.40	0.44
Al_2O_3	15.37	18.72	12.02	21.36	15.85	15.55	14.38	17.71	17.76
Fe_2O_3	1.95	2.07	1.68	1.78	1.89	1.69	1.72	1.91	1.95
FeO	0.11	1.27	2.20	4.87	1.58	1.68	1.21	1.78	1.58
MnO	0.01	0.01	0.46	0.04	0.04	0.04	0.03	0.13	0.11
MgO	3.19	2.71	3.72	3.91	2.11	1.54	3.22	1.68	2.03
CaO	0.45	1.11	0.37	0.29	0.36	0.46	0.09	0.55	0.65
Na_2O	3.42	3.68	2.78	1.77	4.80	8.63	4.63	9.06	7.23
K_2O	2.91	4.68	2.37	8.08	5.21	2.11	2.41	1.16	3.61
P_2O_5	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.20
Pb	10	10	5	10	5	5	5	5	5
Ni	8	12	7	11	8	8	7	7	14
Cu	16	5.8	6.2	131	5.8	6.2	5.9	8.1	20.4
Zn	89.5	129	171	157	67.5	163	64.9	80.6	111
Cr	43.0	64.7	52.5	65.3	55.1	58.9	49.0	52.5	69.7
Co	8	8	6	21	3	8	3	13	9
Sr	157	279	99.1	25.5	26.7	176	33.9	51.2	54.5
V	16	27	12	24	14	15	12	16	56
Be	2.7	3.7	2.6	4.1	2.3	1.3	1.8	2.3	1.0
Ba	1990	1460	590	1440	530	930	330	250	840

Totals recalculated to 100%; locations given in Appendix 1.

Oxides given in weight percent; elements in parts per million.

Analyses by radio frequency induction coupled plasma emission spectroscopy, at Barringer Research, Limited, Toronto, Ontario.

color index, proportion of matrix to clast, dominant clast type, and fragment shape. They are generally polymictic (Plates 3B, 3C, 3E, 3G), with accidental clasts of volcanic rocks, volcanic-derived sedimentary rocks, and occasional plutonic clasts. Finer-grained types frequently contain small lithic fragments (Plate 3B) and feldspar crystals in a chlorite or chlorite-sericite groundmass. Within some fragmental beds, cross-bedding, scour marks, graded bedding, and other sedimentary textures indicate a transported origin (Plate 3H). However, the more prevalent immature and unsorted nature of fragments and matrix, the proximity of coarse breccias to unequivocal flow rocks and autobreccias, and the rarity of fluviatile features, point to a dominantly subaqueous pyroclastic origin. Coarse, fragmental-textured rocks (Plate 3A) are evident in many localities, and include agglomerates composed largely of bombs (Plate 3F). Medium-grained fragmental rocks contain both non-foliated and foliated clasts, randomly oriented in foliated chloritic or sericitic groundmass (Plate 3B), whereas fine-grained tuffs usually have foliation in the groundmass and an alignment of phenocrysts or lithic clasts (Plate 4G). In all instances, any observable foliation within the groundmass is parallel to, or at very small angles with bedding or inferred bedding. Crystals and lithic fragments are oriented randomly with respect to one another (Plate 4A), although poorly-defined trachytoidal alignments of plagioclase laths are present (Plate 4B). Groundmass mineralogy ranges from fine-grained, through barely resolvable at 630x magnifi-

PLATE 3

Macroscopic Features of Intermediate Rock Types

A. Polymictic breccia with large volcanic clasts, west side Goose Pond. Hammer length is 34 cm.

B. Medium-grained lithic-crystal tuff. Polymictic clasts, some rounded, in random orientation within foliated chlorite and sericite matrix. Sample Ca-87; notebook is 15 cm long.

C. Coarse-grained polymictic volcanic breccia, with preferred orientation of tabular clasts. Sample site of Ca-134, hammer length is 34 cm.

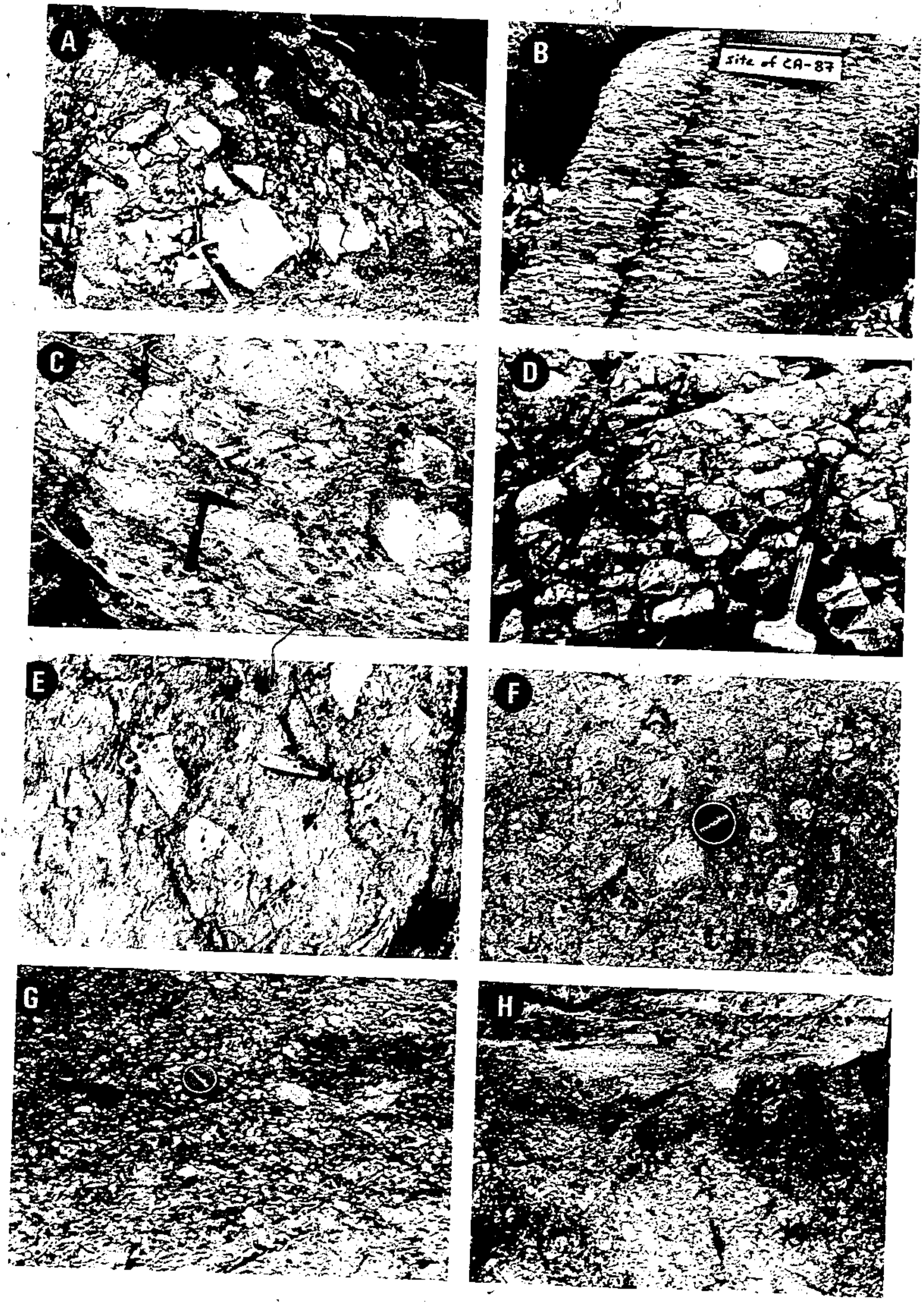
D. Rounded clasts of vesicular andesite in fine-grained matrix of small, rounded volcanic clasts, chlorite, and feldspar phenocrysts, many of which are rounded or broken. Ames Knob, North Haven Island (not shown on maps), hammer length is 40 cm.

E. Polymictic volcanic breccia of rounded, subrounded, and angular fragments in fine-grained matrix, North Porcupine Island. Knife length is 8 cm.

F. Fragments of basalt, rounded and vesicular, some with aerodynamic shapes and breadcrust texture, suggesting airfall origin. West side of Cape Rosier, north of Orr Cove. Lens cap diameter is 5.3 cm.

G. Moderately well-sorted bed of rounded and subrounded clasts with variable compositions; Cape Rosier. Lens cap is 5.3 cm in diameter.

H. Graded bed; polymictic breccia at base, fine chloritic crystal-laden, well-foliated tuff at top. Lens cap diameter is 5.3 cm.


A
B
site of CA-87
C
D
E
F
G
H

-cation, to submicroscopic. Where either clasts or matrix are mafic, the greenschist assemblage of albite, epidote, calcite is present (Plates 4D, 4F). More felsic varieties usually contain quartz, sericite, and chlorite. Basaltic and rhyolitic fragments are not common, and are subordinate to clasts of intermediate compositon, all suspended in a matrix of fine-grained chlorite, chlorite-sericite, comminuted feldspar and quartz phenocrysts, glass shards, and fine lithic debris. Both feldspar and quartz phenocrysts occur in a groundmass whose mineralogy is obscured by fine grain size. Feldspar phenocrysts constitute from 50% to 5% of these rocks, and range in length from a few tenths of a millimeter to more than a centimeter. Plagioclase exceeds potassium feldspar by about 2:1, but original plagioclase compositons are mostly indeterminate because of alteration to albite, chlorite, epidote, sericite, and clay minerals.

Plagioclase phenocrysts usually are bent, broken, corroded, rounded, or exhibit undulose extinction (Plate 4C). Commonly, adjacent crystals are misoriented with respect to one another (Plate 4D). In places crude alignment of clasts or phenocrysts defines a foliation which is further accentuated by parallel streaks of micaceous groundmass interstitial to fragments and crystals (Plate 4E). In most instances this foliation wraps around phenocrysts and lithic clasts (Plate 4F), and invariably groundmass material separates broken or cracked phenocrysts (Plates 4B, 4C, 4D, 4G). In one instance, perlitic glass, only partly devitrified, veins and corrodes a

PLATE 4

Microscopic Features of Crystal and Lithic-Crystal Tuffs

A. Mixed lithic clasts and comminuted phenocrysts. One large clast (outlined) consists of may smaller clasts and comminuted crystals, and a large clast of contorted quartz-biotite laminae. Sample Ca-236, plane light.

B. Broken and corroded albitic plagioclase crystals; cracks and embayments are infilled by groundmass, which is mostly sericite and chlorite, with minor quartz. Sample Ca-184, crossed nicols.

C. Large plagioclase lath with undulose extinction and rounded edges. Cracks are filled with groundmass, mostly chlorite-sericite. Adjacent crystals misoriented, but also broken and corroded. Sample Ca-190, crossed nicols.

D. Many broken crystals in random orientation, all infilled by sericite-chlorite groundmass. Sample Ca-184, crossed nicols.

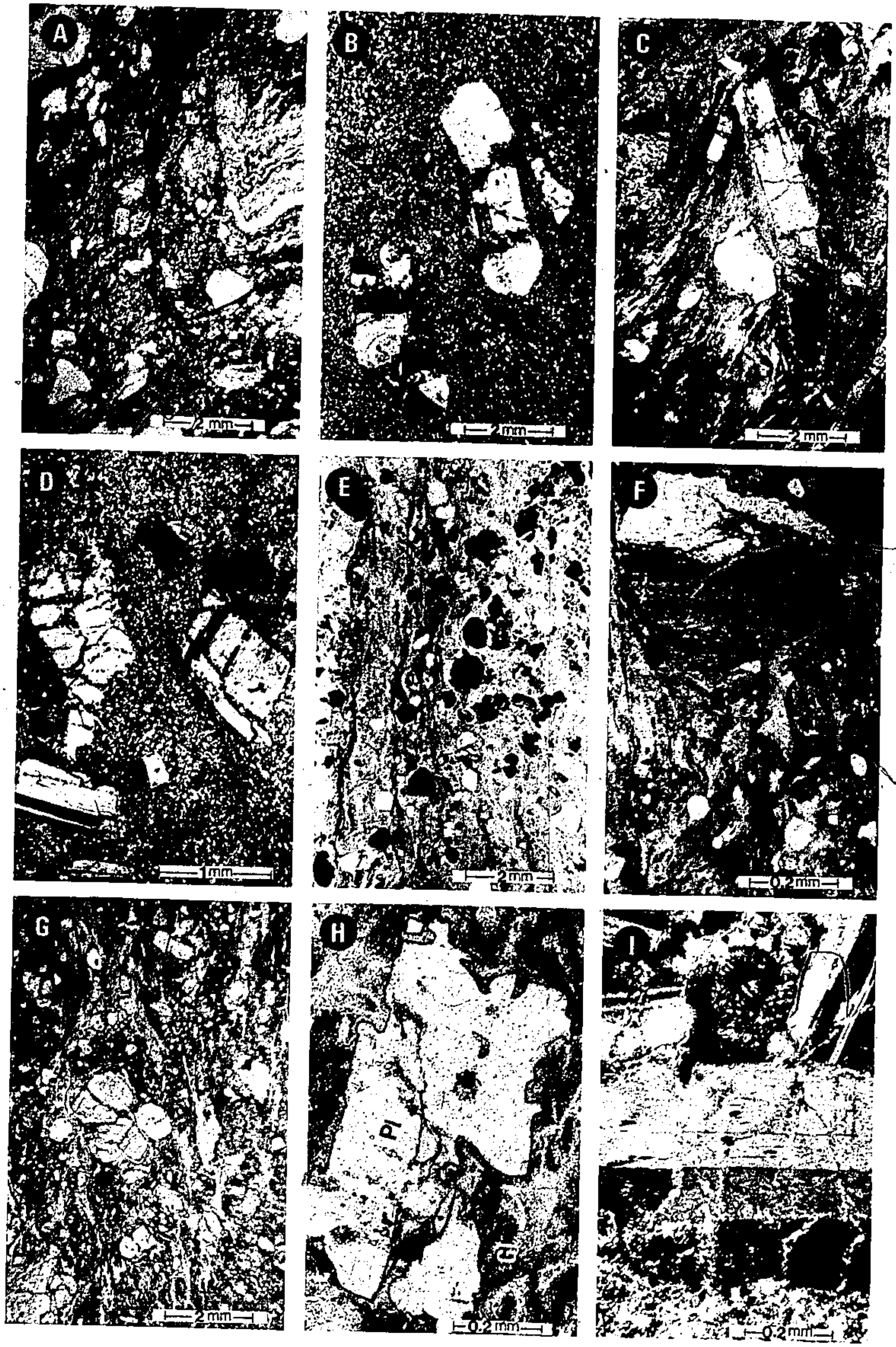
E. Many rounded quartz and feldspar (orthoclase) phenocrysts in well-foliated tuff. Note wrap-around of phenocrysts by foliation defined by chlorite and sericite. Sample Ca-208, crossed nicols.

F. Large lithic clast within crystal tuff. Foliation in clast nearly 90° to foliation in tuff, which wraps around the clast and around phenocrysts. Sample Ca-100, plane light.

G. Randomly-oriented, rounded, strained, and broken potassium feldspar and albite phenocrysts in a well-foliated tuff. Foliation defined by chlorite and sericite exhibits wrap-around of phenocrysts. Sample Ca-83, plane light.

H. Plagioclase crystal embayed and corroded by devitrified perlitic glass containing microlites of chlorite. Sample Ca-93, plane light.

I. Albitic plagioclase crystal; rims and veins of sericite and quartz with minor chlorite alter the crystal. Sample Ca-41, crossed nicols.


A
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I
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rounded and strained plagioclase phenocryst (Plate 4H).

Quartz phenocrysts are not as abundant as alkali feldspar phenocrysts. They commonly are rounded, and have the same range in size and degree of deformation and interaction with groundmass minerals as does alkali feldspar. However, instead of separated crystal trains and deformed laths, as is characteristic of feldspar, subgrain growth is the dominant method of deformation in quartz. Wisps or bands of fine-grained quartz are present in siliceous tuffaceous rocks, generally parallel to the dominant foliation. Throughgoing quartz veins commonly transect all primary structures and contain hematite, chlorite, muscovite, or sulfide minerals.

Most chlorite is extremely fine-grained to submicroscopic, and constitutes up to 70% of some tuffs; the remainder consists of plagioclase, potassium feldspar, and sometimes quartz. In such rocks there may be a distinctive greenish hue, and anomalous interference colors in chlorite suggest penninite composition. Microlites of groundmass chlorite occur along faces of alkali feldspar crystals, or in hairline veinlets throughout a single feldspar crystal (Plate 4I). Corrosion, infilling, or embayment of crystals is commonly by chlorite, or to a lesser extent by sericite. Chlorite mostly appears to be a product of devitrification.

Lithic fragments have a wide range in size and composition (Plates 5A, 5B, 5D, 5E), but in general are subrounded to rounded accidental volcanic clasts, presumably derived from nearby rocks of the volcanic succession. Less abundant

PLATE 5

Microscopic Features of Lithic Tuffs

A. Lithic clast consisting of potassium feldspar and albitic plagioclase in quartz-sericite-chlorite matrix, surrounded and partly embayed by crystal tuff of similar composition. Sample Ca-50, plane light.

B. Polymictic assemblage of many fine-grained and rounded lithic clasts, with some bent and corroded feldspar phenocrysts. Sample Ca-153, crossed nicols.

C. Single large clast (left) consisting of alternating quartzose and micaceous bands, within a polymictic assemblage of rounded clasts and minor phenocrysts. Sample Ca-97, plane light.

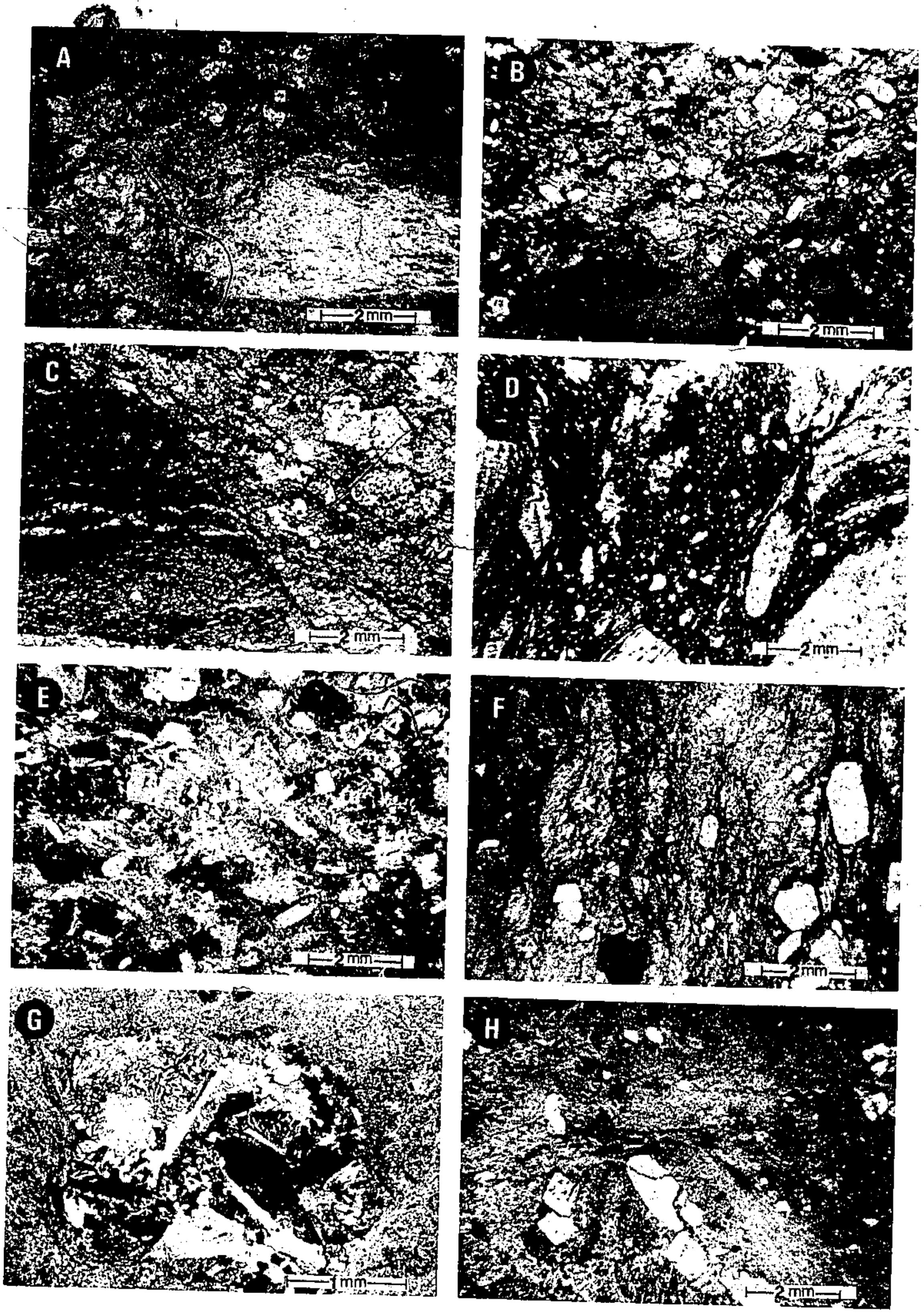
D. Quartzofeldspathic clasts and minor phenocrysts within biotitic matrix. Sample is from within biotite isograd of Sedgwick Granite or South Penobscot Pluton. Sample Ca-252, crossed nicols.

E. Heterogeneous accumulation of fine fragments and phenocrysts, all rounded and corroded, within chlorite-sericite matrix. Crude foliation defined by alignment of micaceous minerals in bands. Sample Ca-139, crossed nicols.

F. Cognate xenolith (x) identifiable by misorientation of foliation within it with respect to matrix. Foliation attributable to alignment of micaceous minerals and minor trachytic alignment of plagioclase crystals. Sample Ca-168, plane light.

G. Myrmekitic quartzofeldspathic intergrowth within single clast which is enveloped by foliation of groundmass. Sample Ca-231, crossed nicols.

H. Volcanic clast consisting of broken and rounded phenocrysts in a foliated micaceous matrix, contained within a lithic and crystal tuff of comminuted crystals and clasts. Sample Ca-180, crossed nicols.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are cognate xenoliths, recognizable where chlorite or sericite within them defines a foliation which is misoriented with respect to that of the matrix (Plate 5F). Of minor importance and occurring only in intermediate rocks, are rounded clasts with myrmekitic and granophyric quartz-feldspar intergrowths, and clasts of lithic tuff within which are clasts of another lithic or crystal tuff (Plate 5H).

Either chlorite or sericite may be more abundant in the matrix of tuffaceous rocks, and a complete gradation exists between dominantly sericitic and dominantly chloritic end members. The habit and mode of occurrence of the two are identical. Epidote-group minerals are far less abundant than in basalts, occurring in mafic clasts, as minute crystals dispersed in matrix, or rarely developed at the expense of calcic plagioclase through greenschist facies metamorphism. The paucity of epidote minerals suggests a highly sodic initial plagioclase composition, with insufficient calcium for formation of epidote. Magnetite and pyrite are common accessory minerals, and chalcopyrite, arsenopyrite, graphite, hematite, and apatite have been observed.

Much less abundant than fragmental rocks are flows of quartz andesite, latite, and trachyte, which are usually interbedded with coarse pyroclastic units. In some instances flows are traceable into coarse autobreccias, and ultimately into separated or entrained pyroclastic material with fine-grained matrix. These flow rocks are black, grey, to dark green, and commonly weather to a blocky or rubbly surface.

Accessory pyrite is common, and rusty weathered surfaces are prevalent.

Minute plagioclase phenocrysts can be randomly oriented or in trachytic alignment, within extremely fine-grained quartzofeldspathic or chloritic to sericitic groundmass (Plate 6A). Anhedral, ragged quartz and intergrown albite, with microlites of chlorite, in an interlocking random mosaic (Plate 6B), suggest that upon extrusion these flows were glassy, with minor feldspar phenocrysts, and subsequently have been devitrified.

Despite wide textural variability, whole rock compositions of 9 representative specimens (Table 3) all are within trachyte and dacite fields (Fig. 7A). Plots of normative mineralogy (Fig. 7B) suggest much the same classification, with representatives in andesite, quartz andesite, quartz-latite-andesite, rhyodacite quartz-trachyte, and quartz-latite fields.

Dacite, Rhyodacite, and Rhyolite

Rhyolitic pyroclastic rocks constitute an end member in the spectrum of fragmental rocks, which extends from basaltic tephra through all the heterogeneous intermediate fragmentals. Thus, pyroclastic rocks with rhyolite or rhyodacite clasts contained in siliceous matrix are gradational with texturally similar intermediate dacites and quartz andesites, and manifest the same textural heterogeneity. However, unlike intermediate fragmentals, rhyolitic breccias occur only within upper parts of basalt through rhyolite successions; whereas

Figure 7A

Classification by chemical analyses

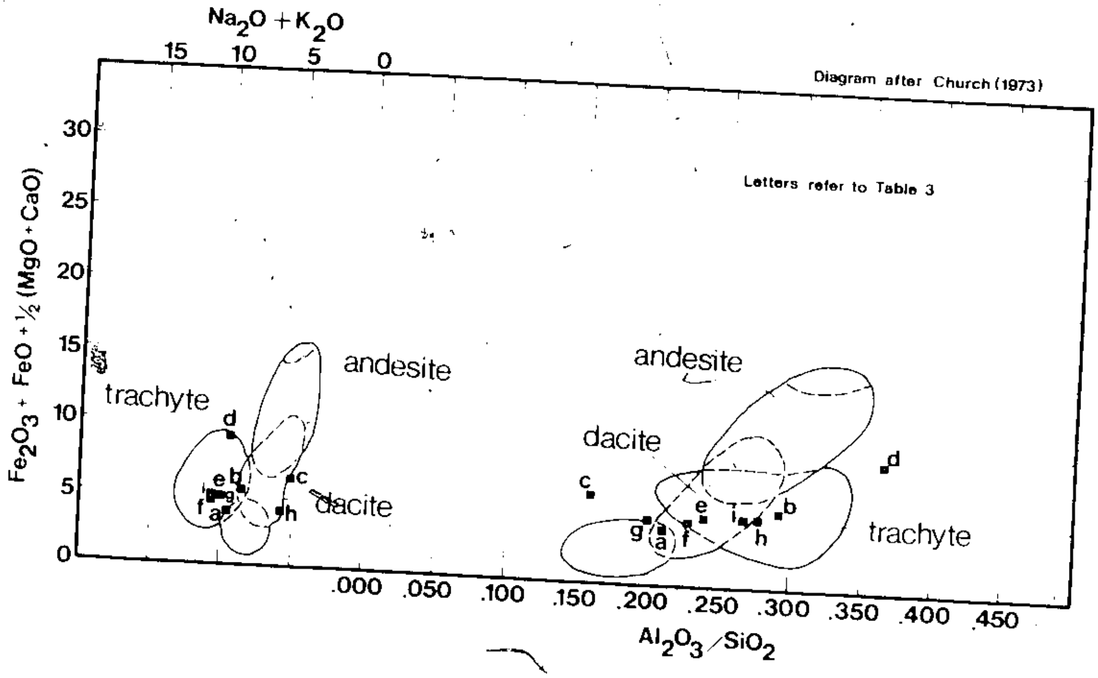
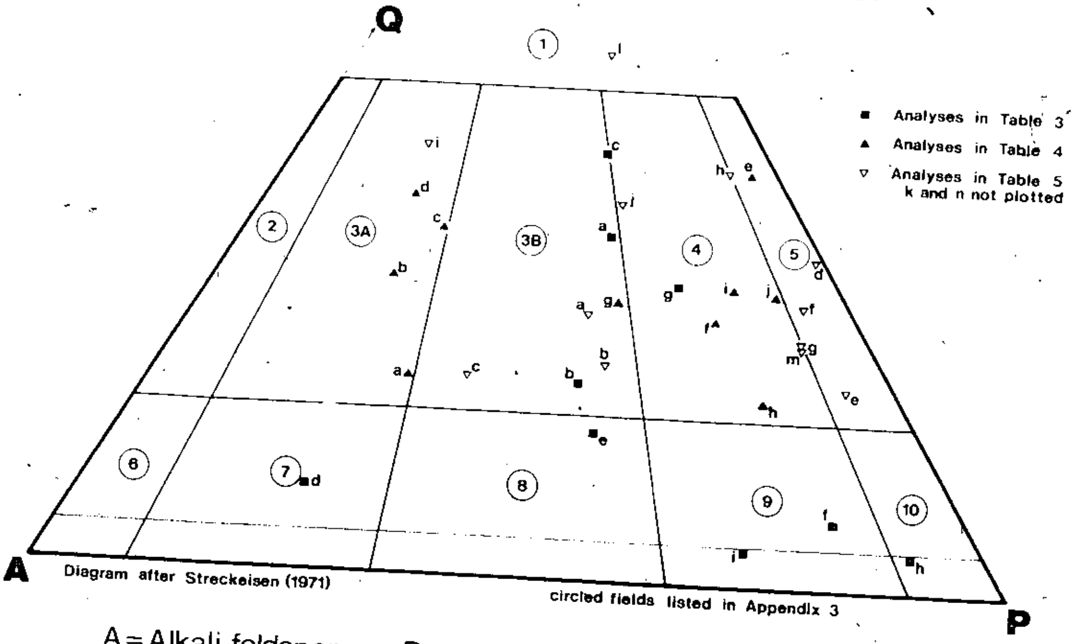


Figure 7B

Classification by normative mineralogy



A = Alkali feldspar P = plagioclase Q = quartz

PLATE 6

Intermediate Flows and Rhyolitic Lava Domes

A. Water-clear albitic feldspar microlites in trachytic alignment. Sample Ca-209, crossed nicols.

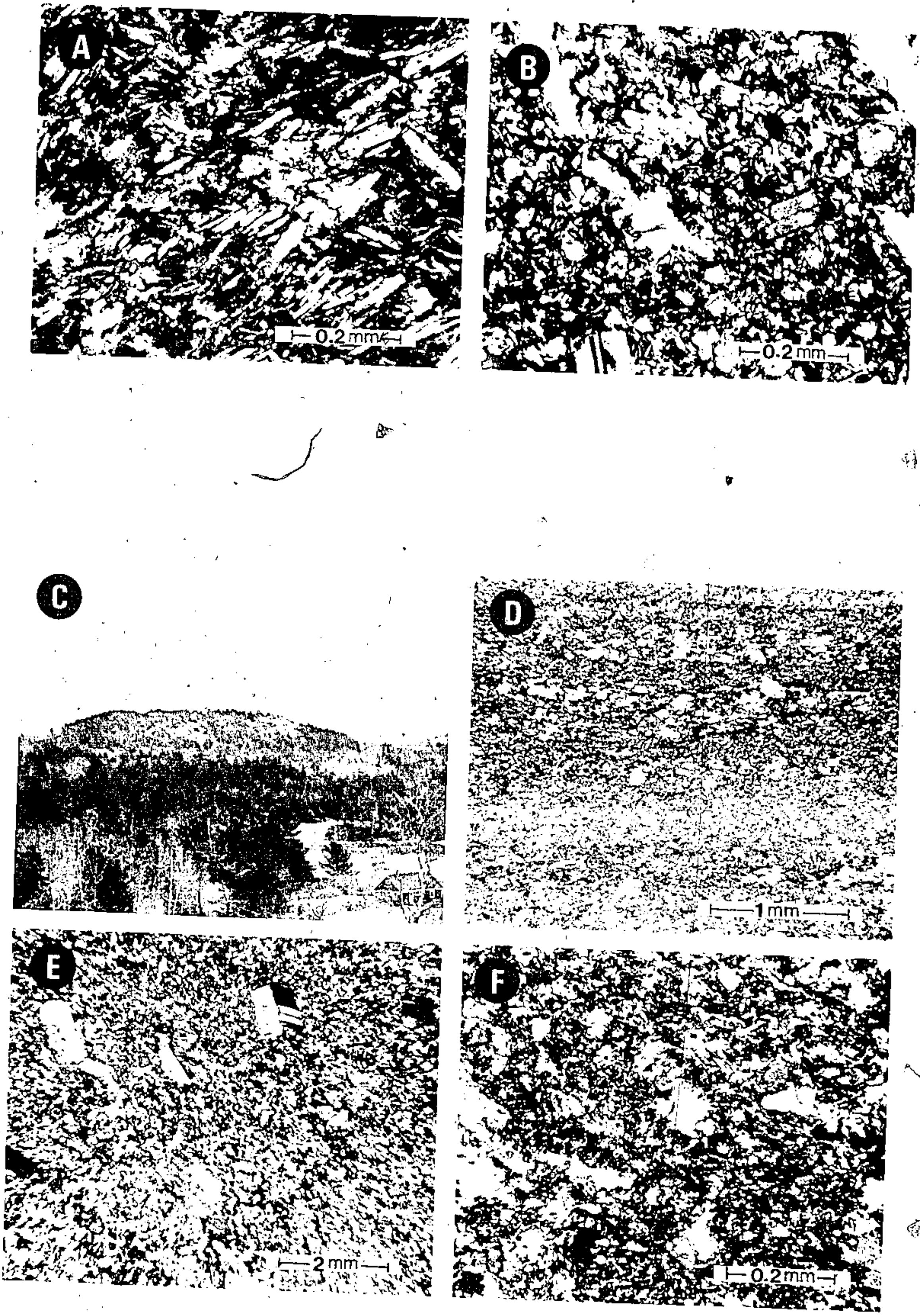
B. Mosaic texture; anhedral ragged quartz with albitic plagioclase and minor chlorite microlites. Sample Ca-210, crossed nicols.

C. Symmetrical and steep sides of John B Mountain, a typical lava dome on Cape Rosier, viewed from Backwoods Mountain across Horseshoe Cove.

D. Flow-banded rhyolite; banding defined by grain size, and by varying proportions of quartz and feldspar. Sample Ca-244, crossed nicols.

E. Microphenocrysts of albitic plagioclase in fine-grained siliceous groundmass. Sample Ca-42, crossed nicols.

F. Fine-grained to submicroscopic aggregates of ragged interlocking anhedral quartz grains. Much of the section is isotropic. Sample Ca-43, crossed nicols.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the former are ubiquitous throughout the succession. Although silicic clasts occur in polymictic breccias, the converse situation of basaltic clasts in rhyolitic breccias is virtually unknown. Sericite, rather than chlorite, and abundant quartz and albite, are the predominant matrix minerals. These rocks grade rapidly into intermediate fragmental types with increasing numbers of less felsic exotic clasts and concomitant increase in mafic content. Rapid vertical and lateral lithofacies changes are typical.

Silicic lava domes are spherical to oblate in plan, and appear to be nearly as thick as they are wide (Plate 6C). The interiors of domes are massive, and may have delicate flow banding on weathered surfaces and in thin section (Plate 6D). These rhyolites are black to near white, with shades of light grey predominant where fresh, and chalky to buff-colored on weathered surfaces, although many weather brown due to their appreciable content of disseminated pyrite. Stockwork vein systems rich in silica, with sulfide or hematite, probably represent former fumaroles. Rhyolite domes lack prominent plagioclase phenocrysts, the absence of which is a major field distinction between these and otherwise texturally similar flows of intermediate composition.

Rhyolite consists of microporphyritic albitic plagioclase crystals (Plate 6E), usually in pronounced trachytoidal alignment in a groundmass of fine-grained to submicroscopic aggregates of ragged, interlocking, anhedral quartz and albitic plagioclase. Chlorite is minor or absent. The ex-

Table 4: Whole Rock Analyses, Castine Formation Rhyolites and Rhyodacites

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
SiO_2	63.83	74.74	78.14	76.05	81.61	74.88	77.13	71.92	77.02	76.53	81.53	66.40	71.70	74.65
TiO_2	0.51	0.25	0.24	0.22	0.14	0.36	0.24	0.19	0.16	0.17	0.21	0.21	0.24	0.15
Al_2O_3	19.18	12.97	10.85	11.57	10.13	13.67	12.15	13.75	11.88	10.89	10.07	12.52	14.89	12.88
Fe_2O_3	2.02	1.74	1.75	1.72	0.0	0.0	0.0	1.68	1.67	1.68	0.0	0.0	1.95	1.97
FeO	1.95	0.06	0.03	1.22	1.07	1.20	1.19	1.79	0.87	0.94	1.10	1.07	0.13	0.14
Mno	0.0	0.02	0.02	0.24	0.02	0.03	0.01	0.05	0.01	0.03	0.01	0.00	0.00	0.00
Mgo	2.81	0.65	0.41	1.13	1.11	0.43	0.33	1.27	0.67	1.09	0.15	0.95	1.12	0.00
Cao	0.20	0.09	0.08	0.36	0.18	0.42	0.10	0.05	0.07	0.09	0.16	1.30	0.30	0.16
Na_2O	2.54	2.00	2.31	1.46	5.13	5.83	4.86	7.02	5.84	7.66	4.62	4.78	4.23	6.00
K_2O	6.77	7.48	6.18	6.04	0.41	2.51	3.97	2.28	1.81	0.91	1.82	2.40	4.54	3.00
P_2O_5	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.09	0.10	0.10
Pb	5	5	10	65	5	5	5	5	5	5	40	135	35	55
Ni	7	4	6	5	7	7	5	4	7	5	ND	ND	ND	ND
Cu	16.0	5.8	9.6	16.0	7.5	18.2	12.1	5.6	5.9	26.2	10.0	19.1	4.0	12.0
Zn	89.5	48.5	44.1	872	62.2	73.8	168	157	54.0	27.4	408	[illegible]36	360	650
Cr	56.8	58.6	65.8	64.1	37.5	50.6	56.2	48.2	54.3	48.7	68	47	47	73
Co	6	ND	6	13	ND	8	9	8	6	4	2	ND	ND	3
Sr	114	21.9	41.3	32.9	80.9	48.4	66.4	26.6	36.2	26.1	51.4	54.1	31.8	32.5
V	27	10	12	10	6	13	8	10	7	10	4.1	7.5	6.4	5.6
Ba	1830	740	1490	580	280	990	860	900	250	610	922	1550	1180	809
Be	5.1	1.2	1.3	3.2	1.3	2.7	1.7	1.7	2.6	3.3	1.13	1.31	1.13	2.29

Totals recalculated to 100%; locations given in Appendix 1.

Oxides given in weight percent; elements in parts per million.

Analyses by radio frequency induction coupled plasma emission spectroscopy, at Barringer Research, Limited, Toronto, Ontario.

-ceptionally fine grain size, presence of optically isotropic areas, mosaic and felted textures, all suggest devitrification. The assemblage quartz-sericite-albite is interpreted as characteristic of greenschist facies metamorphism, although identical mineralogy could represent original igneous composition.

Coarse rhyolitic breccias flank rhyolite or rhyodacite lava domes, and breccia fragments are often of the same composition as the adjacent dome, suggesting derivation from it. In some places dome-flanking breccias merge gradationally with massive dome rhyolite, and in the fourth volcanic cycle on Cape Rosier (Fig. 3), five or more domes occur so close to one another that the adjacent rhyolite breccias have coalesced and precluded field recognition of individual units.

Chemical analyses of 14 representative samples (Table 4) which were regarded in the field as rhyolites, plot as rhyolites (Fig. 8A). However, normative mineralogy suggests a compositional range from rhyolite to quartz-andesite if plotted on the Streckeisen (1967) double triangle of classification (Fig. 7B). Therefore, the best correspondence of field and petrographic observations with petrochemical data is obtained by plotting chemical analyses (Fig. 8A).

Summary and Discussion of Petrochemical Data

Forty-one samples were analyzed for major elements, and 31 of these for minor elements. The three-fold aim in performing the analyses has been to determine typical element abundances for volcanic rocks of the Castine Formation (Tables

Figure 8A

Classification by Chemical Analyses

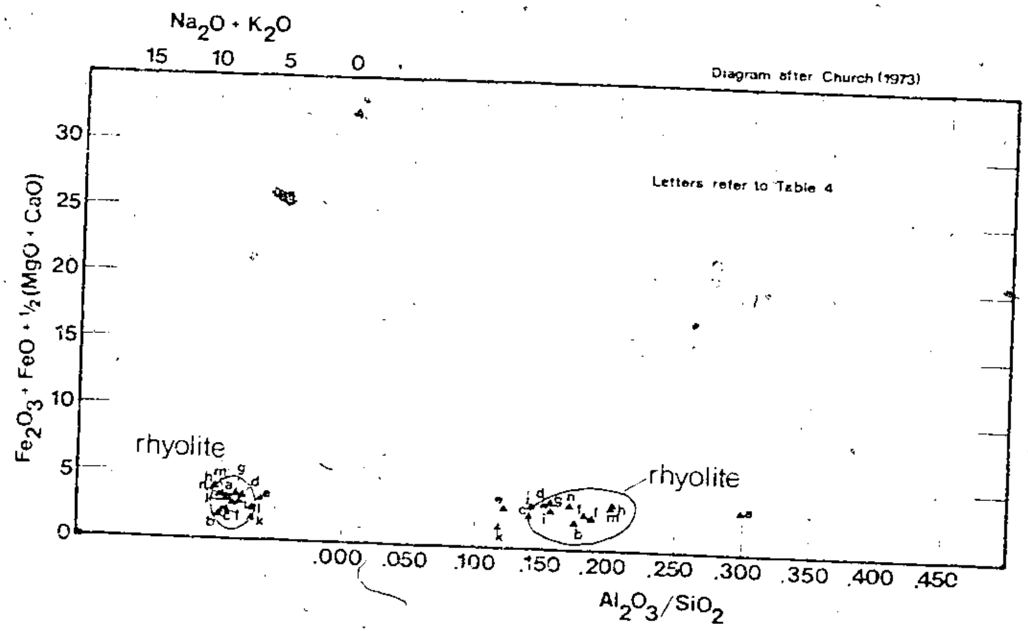


Figure 8B

Classification of Rocks of the Castine Formation by Chemical Analyses

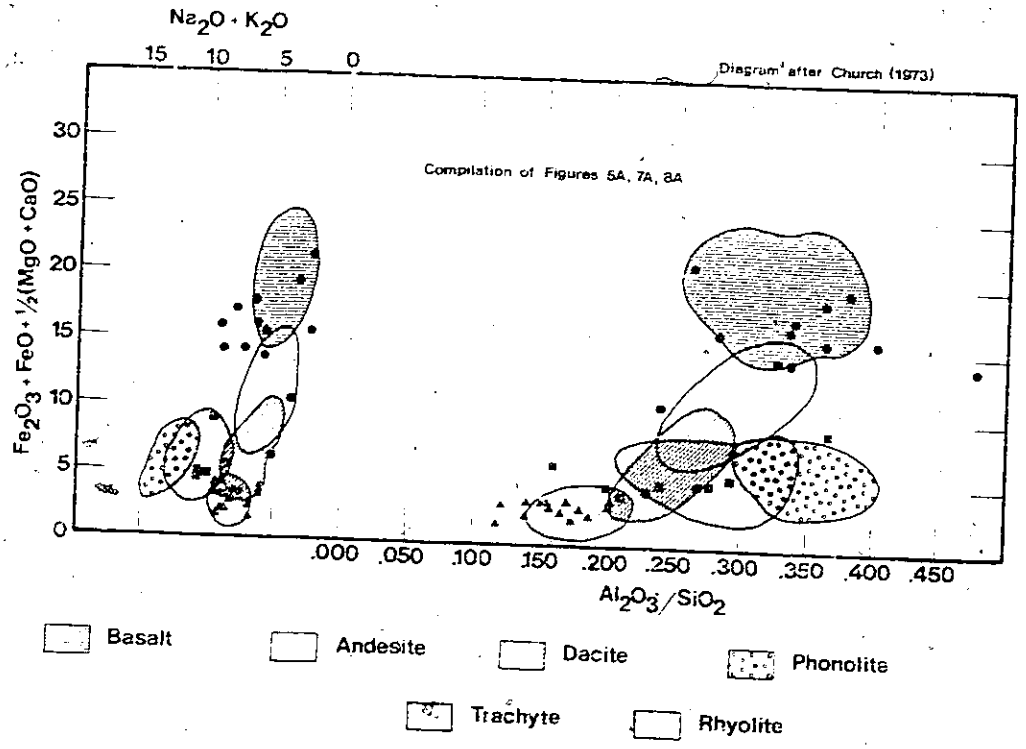


Figure 9A

Classification of Rocks of the Castine Formation by Normative Mineralogy

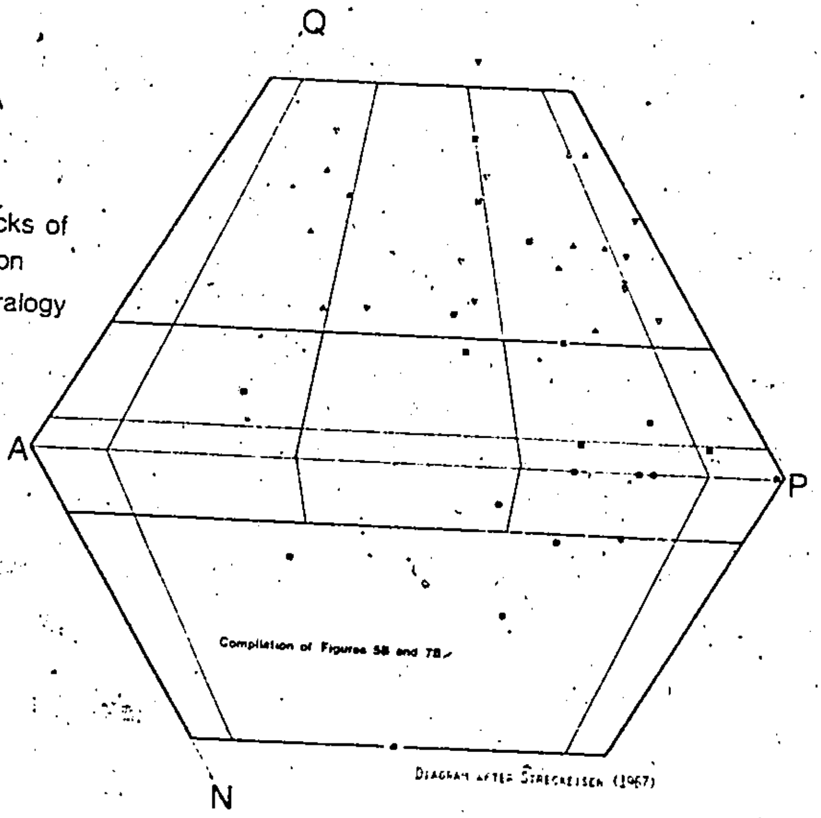


Diagram after Streckeisen (1967)

In Figures 9A and 9B.

● = Data in Table 2

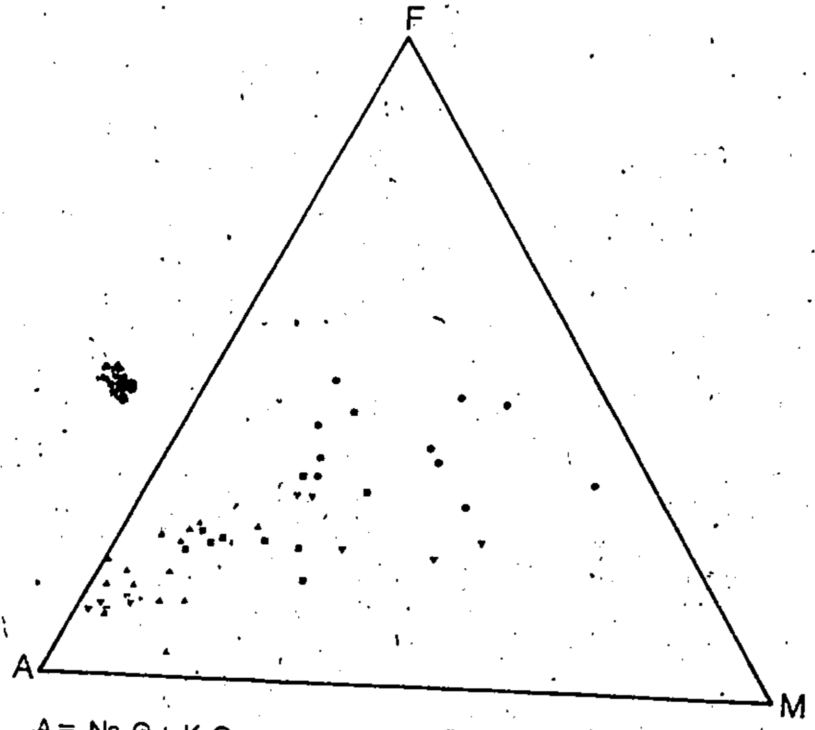
■ = Data in Table 3

▲ = Data in Table 4

▼ = Data in Table 5

Figure 9B

AFM Diagram



A = $Na_2O + K_2O$ F = FeO^* M = MgO

2, 3, 4), to provide a basis for comparison of field and thin section petrography, and to investigate the magmatic affiliations of the volcanic rocks. Combination of Figures 5A, 7A, and 8A suggests a well-differentiated sequence, with representatives within all fields (Fig. 8B). Similarly, compilation of normative plots (Figs. 5B and 7B) onto the double triangle of classification (Fig. 9A) also indicates a well-differentiated sequence, ranging from nepheline normative basalts, through andesites, quartz andesites, latites, and dacites, to rhyodacites and rhyolites. The majority of analyzed samples have anomalously high soda content (Carmichael and others, 1974, p. 33, 35). Plots involving elements or normative minerals little affected by migration of mobile elements (e.g., Fig. 6B) show a strong calc-alkaline trend. Moreover, high alumina values for basalts and the postulated island arc origins make the calc-alkaline trend more plausible than the alkaline affinity. Construction of the standard AFM diagram (Fig. 9B) is not definitive, probably because of alkali introduction with resultant shifting of data towards the alkali apex. The conclusion is that the entire volcanic sequence should be regarded as a spilite-keratophyre assemblage, with alkalies contributed through initial interaction between lavas and seawater, and possible subsequent modification during greenschist facies metamorphism.

Discussion of Structure of the Castine Formation

The attitudes of flow units and primary compositional layers, and geopetal indicators, all indicate that the se-

-quence is east-facing and moderately dipping. Bedding attitudes within cycles 1 and 2 tend to be steep but consistently face east. There is no evidence of folding within the sequence, except for minor slump structures within intervolcanic sedimentary horizons, interpreted as soft sediment deformation of preconsolidational origin. Numerous faults, most with small displacement, appear to be late, perhaps isostatic adjustments. Truncation of one of the more continuous faults by the Sedgwick Granite (Stewart and Wones, 1974) indicates that faulting either preceeded emplacement of the pluton, or was related to emplacement. Either way, the faulting must have been nearly contemporaneous with the deposition of the Castine Formation, because the pluton is considered comagmatic with the volcanic rocks (Brookins and others, 1973).

Strain indicators within rock units, such as spherical and cylindrical pillows and lava tubes, columnar joints, spherical to ameboid-shaped vesicles and amygdales, and pyroclasts, all retain their original shapes, indicating minor to insignificant directed stress during regional metamorphism. Random orientation of crystals and lithic clasts, compactional envelopment of clasts by matrix, parallelism between compositional banding and foliation, local perturbations in foliation attitude, and unequivocal interaction between phenocrysts and original glassy groundmass (Plate 4H), all indicate that the dominant rock fabric is premetamorphic, and was probably produced through a combination of volcanic, compactional, and diagenetic processes. Compactional foliation analogous to that of eutaxitic texture in subaerial ash flows is suggested by aligned collapsed clasts, and by platy minerals aligned parallel with primary layering. Local relief variation of underlying units resulted in differential compaction, accounting for observed local irregularities in foliation, and occasional non-coincidence of foliation with compositional layering. Much well-defined foliation is original flow-banding and relict vitrophyric texture, accounting for wrap-around textures between groundmass and phenocrysts. Submarine flowage of pyroclastic debris down paleoslope from topographically higher volcanic source areas is the envisaged mode of accumulation for many of the well-foliated lithic and crystal tuffs.

Chapter Four

Base Metal Sulfide Deposits in the Castine Formation

The Penobscot Mine

History and Production

The Penobscot mine of Callahan Mining Corporation, also known as the Harborside, Cape Rosier (or Cape Rozier), or Callahan mine, is on Cape Rosier, in Brooksville Township, Hancock County, Maine (Fig. 3). It is 25 kilometers west-southwest of Kerramerican mining operations at Blue Hill, Maine. Gossanous, copper-stained exposures at the Penobscot mine site were known to early European settlers in the seventeenth century, and were worked on a small scale. High metal prices supported production of approximately 10,000 tons of ore averaging 20% zinc and 2.8% copper, from 1881 to 1883 (Rand, 1957). In 1940-41 St. Joseph Lead Co. did 5500 feet of diamond drilling, followed by almost 3000 feet drilled by the United States Bureau of Mines (Levin and Sanford, 1948). The Penobscot Mining Corporation acquired the property in the mid-1950's, and initiated further exploratory work.

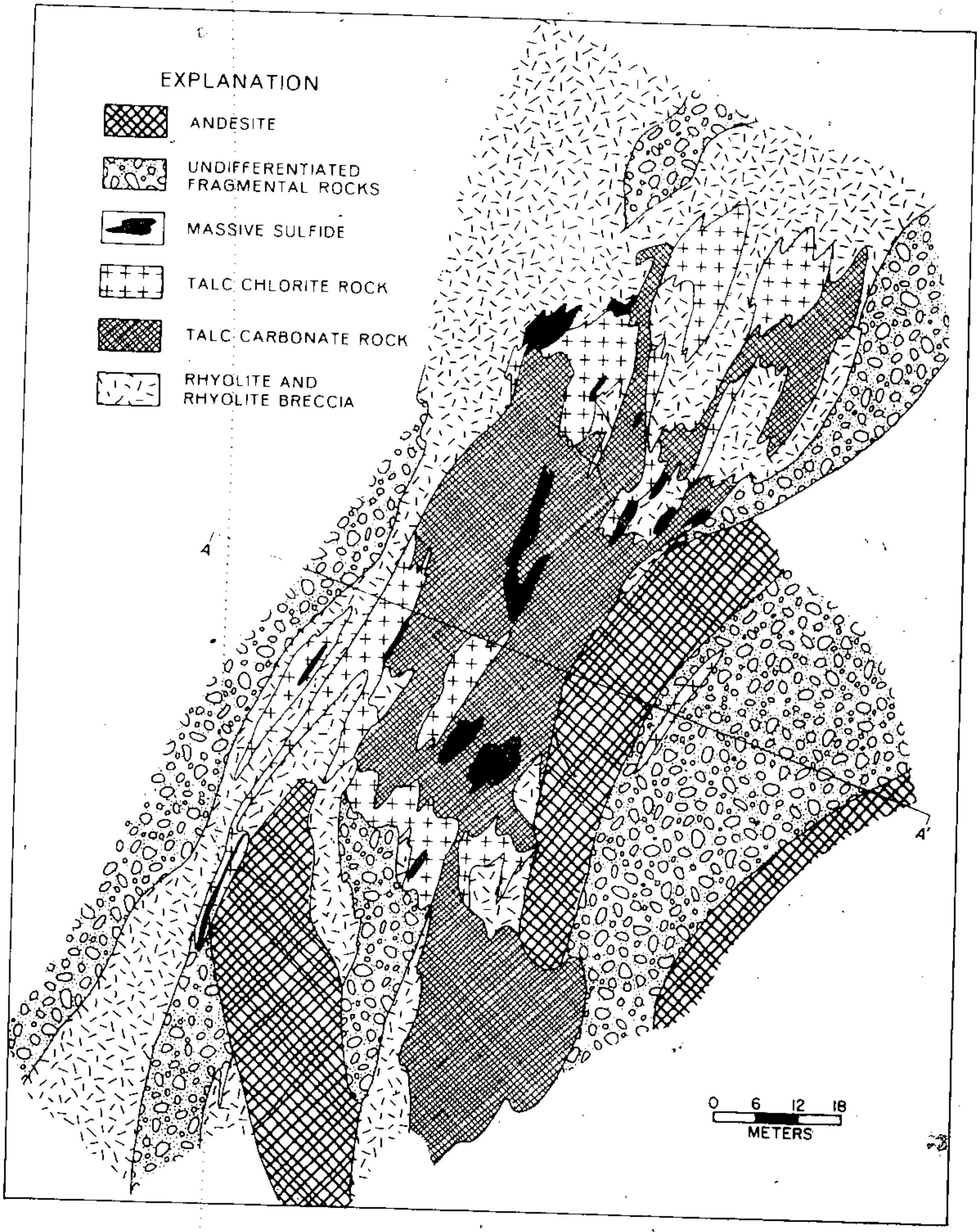
Exploration work by Callahan Mining Corporation in the mid-1960's delineated a small orebody, and production followed from combined open pit and underground operations. From 1968 until exhaustion of ore reserves in 1972, Callahan mined 800,000 tons of ore averaging 5.5% zinc, 1.25% copper, 0.5% lead, and 17.1 g/ton silver. The pit and underground operations exploited the down-dip extensions of the surface showings and old workings, as well as additional massive base metal sulfide bodies previously unknown. Although individual sulfide lenses were rich, their irregular distribution and small dimensions made grade control difficult, and much massive ore remains at the site on large waste dumps. Some ore occurred beneath and within shattered domal rhyolite, and was extracted by underground mining methods from two adits collared in the pit wall.

Site restoration involved flooding the entire area, contouring and seeding waste piles, and dismantling and removal of the mill and most buildings. Experimentation continues to produce a self-sustaining flora on the mill tailings. The flooding has rendered the mine inaccessible for study, except around the pit edges and on the waste dumps. Therefore, rock samples for this study were from dumps, exposures near the mine and along the coastline, and diamond drill core.

Mine Geology

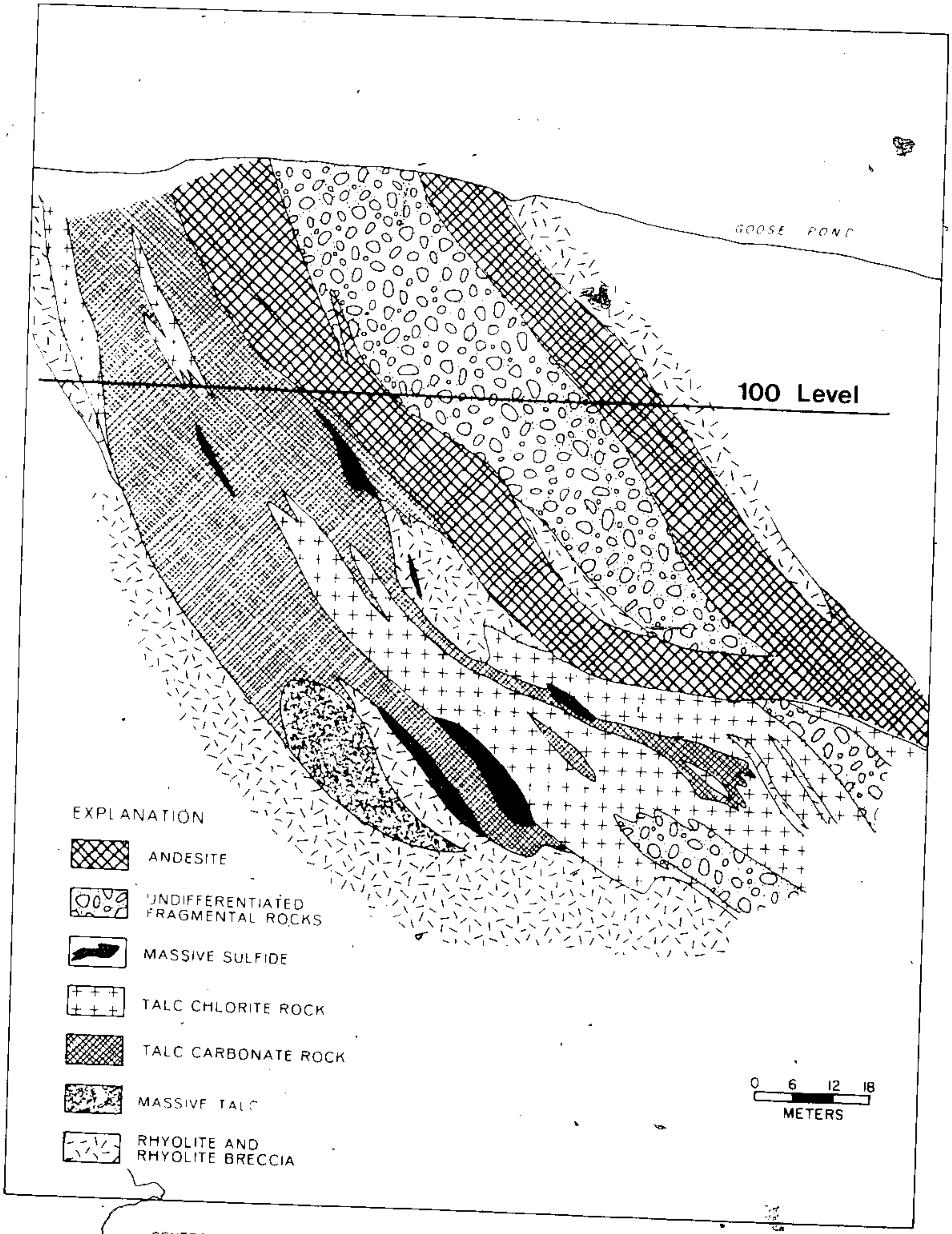
The principal base metal sulfide concentrations at the Penobscot mine are within 100 to 200 meters of a polymictic fragmental rock of intermediate composition, which dips steeply away from the east side of a rhyolite dome, and which is overlain by rhyolite breccia contiguous with the dome. The sequence of fragmental rocks is the culmination of the third volcanic cycle on Cape Rosier, and the ore horizons within it are intercalated with dominantly magnesian rocks which include talc, talc-carbonate, and talc-chlorite assemblages. The distribution of these rocks in plan and section (Figs. 10, 11) illustrate their complex intercalated relationships and their

Figure 10



GENERALIZED PLAN OF GEOLOGY, 100 LEVEL, HARBORSIDE MINE, MODIFIED AFTER CALLAHAN MINING CORPORATION MAP (1966).

Figure 11

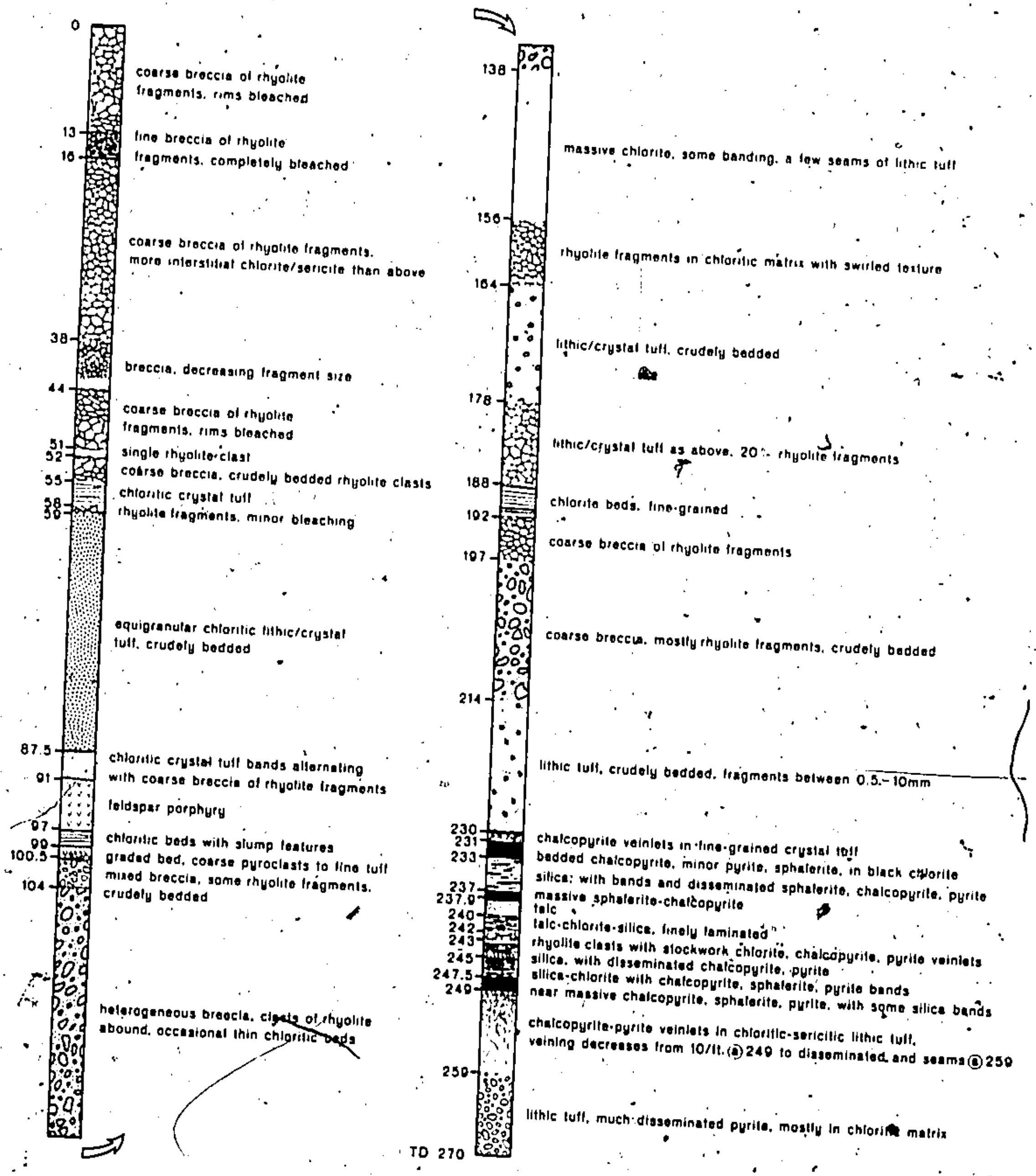


GENERALIZED GEOLOGIC CROSS SECTION A–A′, LOOKING NORTHEAST, HARBORSIDE MINE MODIFIED AFTER CALLAHAN MINING CORPORATION MAP (1966)

Figure 12

Graphic log, Diamond Drill Hole 72-83 Penobscot Unit, Callahan Mining Corporation, Harborside, Maine

inclination, -90°, total depth 270', Bx wireline



rapid lateral and vertical lithofacies changes. Diamond drill hole 72-83 intersected the complete stratigraphic succession near the orebody (Fig. 12; Plate 7), and core was saved for possible future study. It represents the only available uninterrupted representative section across rocks of the hanging wall, ore zone, and foot wall, and therefore was studied in detail. The hole was logged, and 83 samples representing all compositional and textural variations in rock types were selected for thin sectioning. Sixteen polished surfaces were prepared from 2 meters of sulfide-bearing intersection.

The footwall breccia at Penobscot (Plate 9F) is texturally variable, structureless, very coarse-grained, polymictic with fragments to 0.5 m, and interbedded with fine-grained crystal tuff, lithic tuff, and stratified transported sediment. Intrusive into this assemblage is a rhyolite dome (dome $1C_1$ of Fig. 3), shown by Callahan drilling and underground mining to be rootless. Coarse oligomictic breccias of rhyolite fragments (Plate 8E) flank this dome. Fragment size decreases away from the dome, and rounded and comminuted rhyolite clasts are noticeably lighter in color than large black clasts close to the dome. Fragments of rhyolite from the dome in these breccias suggest that dome emplacement was at least partly extrusive, and their repetition in the sequence records episodic breccia development. The interior of the dome and its margins, except where adjacent to the sulfide bodies, are devoid of rhyolite breccias.

Rock types restricted to the mineralized interval and

PLATE 7

Pictorial Log, Diamond Drill Hole 72-83, Penobscot Mine

A. Rhyolite clast cut by siliceous vein with angular clasts of perlitic glass. Sample collected at 4 feet, crossed nicols.

B. Flow-banded clast (right) within breccia of angular, fine-grained and partly isotropic siliceous fragments. Minor chlorite and sericite in matrix. Sample collected at 36 feet, plane light.

C. Angular to rounded, mostly isotropic, rhyolitic clasts in siliceous matrix. Sample collected at 42 feet, crossed nicols.

D. Rhyolite clasts separated by wispy, isotropic bands. Patches of quartz and minor quartz veins cut both clasts and matrix. Sample collected at 52 feet, crossed nicols.

E. Diabasic texture in basaltic flow. Sample collected at 63 feet, crossed nicols.

F. Crystal tuff, feldspar phenocrysts rounded and corroded. Groundmass foliation defined by chlorite and sericite wraps around phenocrysts. Sample collected at 80 feet, crossed nicols.

G. Flowage textures in matrix of crystal tuff. Sample collected at 93.5 feet, plane light.

H. Rhyolite clasts laced with quartz veins; sample collected at 94 feet, plane light.

I. Flowage textures in crystal tuff; sample collected at 101 feet, plane light.

J. Feldspar porphyry; albitic plagioclase phenocrysts in quartz-sericite matrix. Sample collected at 116 feet, crossed nicols.

K. Lithic tuff; cognate fragments in crystal-rich tuffaceous matrix, within which are smaller although similar clasts. Sample collected at 162 feet, plane light.

PLATE 7 - continued

L. Lithic-crystal tuff; heterogeneous assemblage of rounded phenocrysts and lithic clasts. Talc with Leisegang structure (lower left) overgrows primary fabric. Sample collected at 190 feet, crossed nicols.

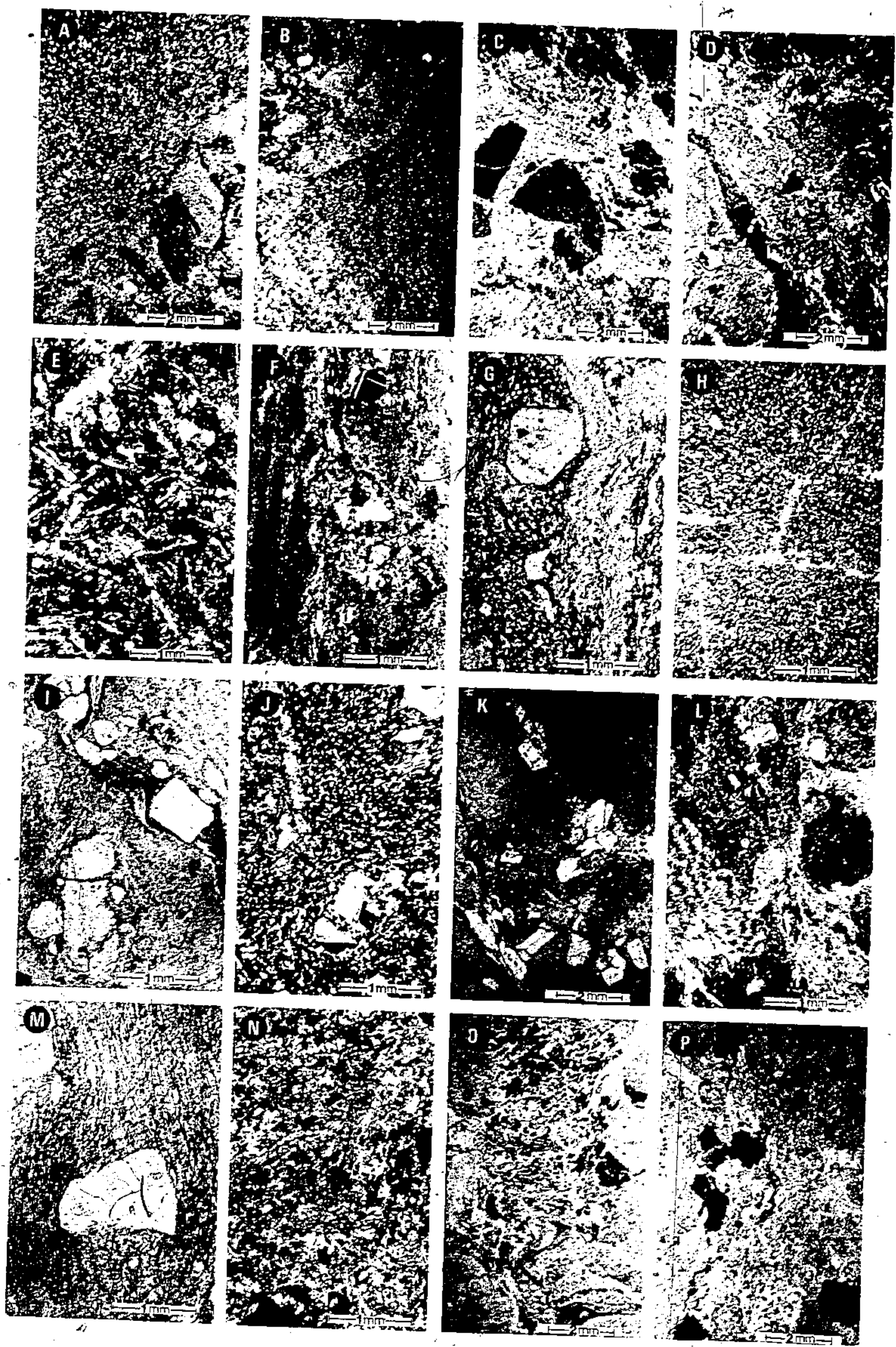
M. Crystal tuff; well-developed foliation, defined by micaceous minerals, surrounds corroded and cracked feldspar crystals. Sample collected at 213 feet, plane light.

N. Coarse, relict, diabasic texture in basaltic flow rock. Sample collected at 229 feet, crossed nicols.

O. Sphalerite (opaque) within poorly defined veinlet consisting of black chlorite (in hand specimen). Sample collected at 230.1 feet, plane light.

P. Large blebs of sphalerite (opaque) within talc-carbonate rock; sample collected at 234 feet, plane light.

Modal mineralogy given in Appendix 4.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intimately associated with ore are talc, talc-carbonate (Plate 8C), talc-chlorite, hematitic chert, minor dolostone, and tuffaceous to jasperoidal mudstone (Plate 8G, 8H). This sequence is overlain by basalt and coarse polymictic volcanic breccia (Fig. 11), nearly identical with underlying footwall breccia, but distinguishable from the latter by the absence of 2-5 cm clasts of granophyric rhyolite present in the footwall variety. However, this distinction, and these rock types as mappable units, fade with distance from the ore zones.

Diamond drill hole 72-83 penetrates at least six coarse rhyolitic pyroclastic units apparently derived from the nearby dome, and at least two other horizons of coarse debris that apparently were contributed from more than two sources as evidenced by their variable fragment compositions. Most contacts in this sequence are gradational, and rock types are distinguished by progressive increase or decrease in an essential clast component, or change in matrix characteristics. For example, a single 0.3 m thick rhyolite clast at 52 feet (Fig. 12) is overlain by coarser breccia. This gradually becomes finer upward until it becomes a crudely bedded lithic tuff, with rhyolite fragments and alkali feldspar phenocrysts in a chloritic matrix. Foliation is present only in fine-grained, fissile, well-laminated beds or massive chloritic horizons, and is parallel to subparallel to bedding, suggesting a depositional or compactional origin for the foliation. Crenulation cleavage and kink bands are well-developed in

PLATE 8

Major Rock types at the Penobscot Mine and Vicinity

A. Bedded sphalerite (sph) and chalcopyrite (cpy) ore, collected on Penobscot waste dumps.

B. Bedded sphalerite (sph) and chalcopyrite (cpy) ore, collected from Leach occurrence by Callahan personnel.

C. Talc-carbonate rock; patches of talc surrounded by rusty-weathering carbonate. Collected on Penobscot waste dump.

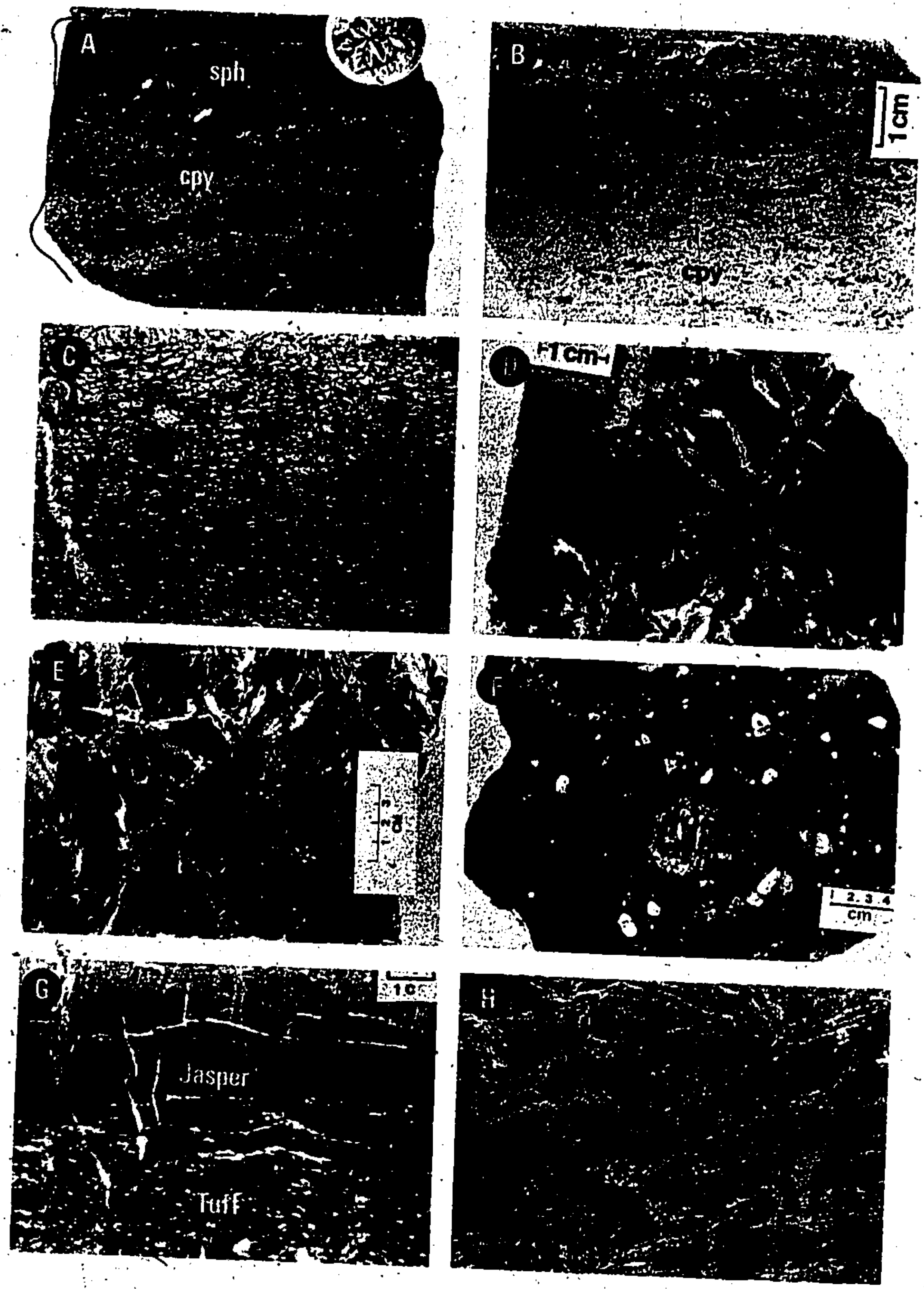
D. Rhyolite breccia, cut by quartz veins with galena and sphalerite, minor chalcopyrite and pyrite. Collected from underground workings by R. W. Hutchinson, 1970.

E. Coarse breccia of rhyolite clasts with bleached rims, contained in sericite-chlorite matrix. Collected on Penobscot waste dumps.

F. Coarse polymictic conglomerate; note bleaching of clasts, and clast of sulfidic rock (near center of picture). Typical footwall breccia, collected from waste dump at Penobscot mine.

G. Ferruginous chert (jasper) and chloritic crystal tuff (tuff), collected near Weir Cove along drainage ditch.

H. Alternating bands of crystal tuff and ferruginous argillite, collected near the Leach occurrence along the drainage ditch. Pen length is 13.5 cm.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Tuff
H

these finer tuffs. An abrupt change in the section occurs at 230 feet. Stockwork chalcopyrite veinlets below are terminated at this contact, and overlain by crudely bedded lithic tuff. The underlying 29 feet of core is characterized by fine-grained rocks which include massive sulfide horizons, cryptocrystalline silica, talc, and one thin band of rhyolite breccia. These horizons are finely laminated, and display relict sedimentary textures including slump features, load casts, and cross-bedding. Beneath the lowest massive sulfide horizon is a dense stockwork of ramifying chalcopyrite-pyrite veinlets. This stockwork gradually decreases downward in intensity from greater than ten veinlets per foot to mere dispersed grains and seams of pyrite in the lowermost sericite-chlorite tuff and underlying coarse lithic breccia.

Petrologic and Mineralogic Studies, Penobscot Mine

The rhyolite dome which forms such a conspicuous topographic feature at the Penobscot mine is dense, black, columnar-jointed, and usually contains minute (<5mm) alkali feldspar phenocrysts in an aphanitic groundmass (Plates 9A, 9B). At its margins it is nearly lacking phenocrysts, which gradually increase inward in size and abundance. In plan the rhyolite dome is roughly egg-shaped (Fig. 3, dome $1C_1$) and is 250 x 500 meters, about average dimensions for these domes on Cape Rosier. Flow banding is evident on weathered surfaces. Near the southeast corner of the body, nearly vertical laumontite-lined open veins transect the dome in random orientation.

The rock has a groundmass of albite, quartz, and minor sericite as a random, anhedral, ragged, interlocking mosaic. Albitic feldspar phenocrysts have a weakly developed trachytoidal alignment. X-ray powder diffraction studies on pulverized whole rocks indicate abundant quartz, plagioclase, probable sanidine, and possible muscovite (sericite). The fine-grained nature, ragged mosaic texture, combined with perlitic cracks in breccia fragments derived from the dome, all indicate that it was emplaced as a glass. The rock is silica-rich rhyolite (Table 5), and has an appreciable alkali content.

Breccia clasts derived from the dome are mineralogically identical to the parent dome, and are coarse near their source, but decrease in size away and become increasingly comminuted with marked light-colored rims. All gradations exist between completely white fragments and pristine black parental rhyolite. Large blocks of waste rock, diamond drill hole data, and exposures in the pit wall, all record the stages accompanying fragmentation of dome rhyolite and the subsequent deposition of the derived pyroclastic breccias.

Rhyolite unaffected by these processes beyond the limits of brecciation (Plates 9A, 10A) was glassy, with microphenocrysts of albitic plagioclase. Nearly identical is black rhyolite cut by veins of barren quartz (Plate 9B). Fragmentation and incipient bleaching of rhyolite are unequivocally indicated where comminuted fragments of rhyolite separate unbleached but clearly rotated and disrupted rhyolite clasts

PLATE 9

Macroscopic Changes Involved in Transition from Black Rhyolite to White Rhyolite Breccia

A. Massive, dense, black rhyolite from columnar-jointed southeast margin of lava dome (Dome $1C_1$, Figure 3).

B. Slightly porphyritic rhyolite, 10 meters from contact with intruded tuffs. Note quartz vein (right) and microphenocrysts of albite.

C. Oriented and random stockwork quartz veins cutting black rhyolite. Minor chlorite developed in some veins. Very minor disruption of fragments.

D. Similar to C, but veining and disruption slightly more intense.

E. Noticeable disruption with several stages of quartz veining. Breccia fragments are clearly rotated, with minor amounts of comminution around edges.

F. Separated and bleached rhyolite fragments, contained in a sericite-chlorite matrix. Smaller fragments totally bleached; larger ones bleached only along selvages.

G. Totally bleached, translucent rhyolite clasts, contained in chlorite-sericite matrix. Fragments are rounded and comminuted.

H. Small, rounded, translucent fragments of originally black rhyolite, contained in chlorite matrix, with minor sericite.

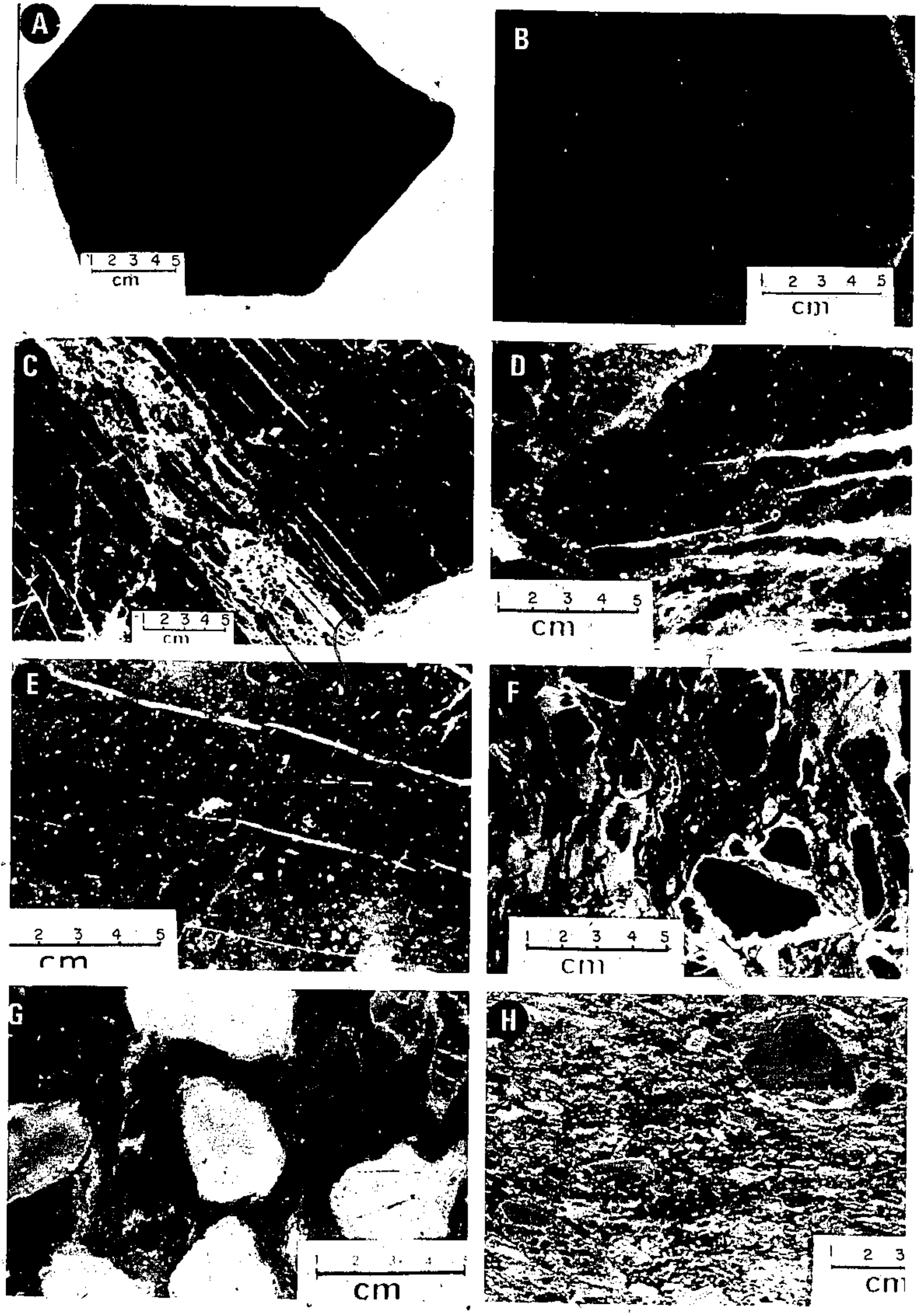
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PLATE 10

Microscopic Features of Transition from Black Rhyolite Lava Dome to White Rhyolite Breccia

A. Black rhyolite, section cut from rock in Plate 9A, crossed nicols. Mode:

61%	albite
25%	quartz
11%	chlorite
2%	magnetite
1%	K-feldspar
trace	leucoxene

B. Black rhyolite clasts (ry), rims unbleached, but disrupted and within coarser matrix of quartz and sericite, with minor chlorite. Section cut from rock in Plate 9E, crossed nicols.

C. Rhyolite clast (ry) with bleached selvage (sel) and nearby siliceous matrix (M). Section cut from rock in Plate 9F, crossed nicols.

D. White rhyolite clasts, well-rounded, contained in quartz-feldspar matrix. Section cut from rock in Plate 9G, crossed nicols.


A
0.2mm
B
ry
ry
1mm
C
sel
M
ry
1mm
D
1mm

(Plates 9C, 9E, 10B). The matrix is recognizable as comminuted, very angular rhyolite, with minor sericite and less chlorite. Intensity of quartz veining increases to intense silicification of the rock itself (Plate 9D), and rhyolite fragments are separated by chloritic and sericitic matrix without obvious clasts. Smaller, rounded rhyolite clasts have bleached selvages (Plates 9F, 10C). No major mineralogical changes are discernible in thin section in these bleached selvages. However, minute grains of magnetite, usually less than 100 μm in diameter, which are ubiquitously distributed as a minor mineral within black rhyolite, are absent in the white rims. More intensely bleached fragments are separated completely, and contained in a chlorite-sericite-quartz-albite matrix (Plates 9G, 10D). The former dense, black, rhyolite has been fragmented, comminuted, and bleached, to form rounded, white, translucent clasts (Plate 9H).

Major changes in K_2O and Na_2O contents take place during rhyolite fragmentation and bleaching (Table 5, analyses A through I; Plate 9). With initial brecciation and concomitant increase in matrix volume (Plate 9C) the rock is enriched in Na_2O and K_2O (Table 5D). This trend continues with increasing brecciation, separation, comminution, and transport (Table 5E, 5H; Plates 9D, 9E, 9F). Analysis of the chlorite-sericite matrix enclosing bleached fragments (Table 5I) and comparison with analyses for black rhyolite (Table 5A, 5B) show that K_2O and to a lesser extent FeO* are selectively

Table 5: Whole Rock Analyses, Common Rock Types at the Penobscot Mine

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
SiO_2	75.92	74.46	73.02	78.45	74.65	77.85	75.97	77.58	75.47	75.24	49.31	71.07	71.28	20.3
TiO_2	0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.15	0.49	0.28	0.01
Al_2O_3	12.78	13.55	13.97	10.56	13.99	12.06	12.27	11.15	11.23	12.09	17.88	12.85	13.53	0.35
Fe_2O_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.66	2.05	1.76	0.0
FeO	1.53	1.46	1.40	1.39	0.80	1.39	1.98	2.57	3.98	3.02	3.37	1.18	2.59	0.34
MnO	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.12	0.15	0.06	0.99
MgO	0.28	0.26	0.41	0.57	0.48	0.66	1.13	3.24	2.94	5.83	8.97	6.41	3.05	12.4
CaO	0.16	0.07	0.08	1.93	0.55	0.32	0.30	0.24	0.27	0.41	10.30	0.58	0.25	40.4
Na_2O	4.47	5.46	3.87	6.95	8.66	6.95	7.40	4.49	1.14	1.97	3.34	2.85	6.22	0.0
K_2O	4.62	4.75	7.25	0.15	0.87	0.76	0.94	0.73	4.97	1.44	2.63	2.38	0.99	4.90
P_2O_5	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00
Pb											5	5	5	500
Ni											187	30	20	20
Cu											78.8	39.8	7.1	496
Zn											89.5	156	103	1190
Cr											195	122	86.5	40.5
Co											52	19	13	16
Sr											588	47.1	118	211
V											198	70	30	15
Be											3.5	2.3	1.4	6.6
Ba											1180	1030	80	ND

Totals recalculated to 100%; Locations given in Appendix 1. Analysis N not recalculated; total as presented is 80.2%; remainder is CO_2.

Oxides given in weight percent, elements in parts per million.

Analyses A through J at Univ. Western Ontario by X-Ray Fluorescence; K through N by radio frequency induction coupled emission spectroscopy, at Barringer Research, Limited, Toronto.

Analysis A: Rhyolite of Plate 9A; B: similar massive Rhyolite; C: Rhyolite of Plate 9B; D: Rhyolite of Plate 9C; E: Rhyolite of Plate 9D; F: Rhyolite breccia like that of Plate 9D; G: Breccia of Plate 9E; H: Rhyolite breccia of Plate 9F; I: Matrix to rhyolite breccia of Plate 9F; J: Conglomerate of Plate 8F; K: Basalt near south margin of open pit; L: Conglomerate similar to that of Plate 8F; M: Ferruginous argillite of Plate 8G; N: Talc-carbonate rock of Plate 8C.

leached from the clasts and concentrated in the matrix. MgO increases also, but apparently was introduced from external sources with a resulting increase in chlorite content of the matrix relative to albite, quartz, and sericite. The ultimate depository for many fragments are the polymictic fragmental rocks which received combined debris from several source areas, including rhyolite domes. At the Penobscot mine such breccias have Na_2O and K_2O abundances near the median for the analyzed suite of rhyolite and rhyolite breccia, although they are enriched in MgO (Table 5J, 5L).

Talc-carbonate rock is the only rock type within the mine sequence that has a constant relationship to ore horizons, and is always in contact with, and usually beneath, massive layered sulfide. It consists of varying proportions of talc and rusty-weathering carbonate which appears to vein and enclose irregular patches of talc (Plates 8C, 11A, 11B). Massive talc forms lenses up to 5 m by 3 m within talc-carbonate horizons, but massive carbonate without talc is unknown. Colloform spheroids of intergrown talc-carbonate enveloped by cryptocrystalline silica range in size from less than 1mm to balls as large as 5cm in diameter. This textural variety is not as common as structureless talc-carbonate rock. X-ray diffraction studies indicate common talc $(Mg_6Si_8O_{20})(OH)_4$ and normal calcite. Deer and others (1966) report that as much as 5 to 10 mol percent $FeCO_3$ is possible in solid solution within calcite, and one sample of rusty-weathering talc-carbonate contains almost 0.5% (Table 5N). Abnormal concen-

-trations of copper, lead, and zinc for rocks without sulfide minerals indicate that not all metallic cations are fixed as sulfide phases.

Foliated talc-chlorite rock (Figs. 10, 11) occurs throughout the mine sequence, and contains up to 20% pyrite as disseminated euhedral crystals or as massive seams. Finely laminated pyrite-chlorite compositional layers define bedding. Upon weathering the rock slakes into fine, chloritic scales and granules of pyrite, readily visible on the waste dumps. Optical determination of chlorite composition shows it is not as ~~magnesian~~ as that commonly associated with stratabound sulfide deposits (Sangster, 1972), and is probably near penninite or clinochlore.

Finely laminated dolostone was noted occasionally on mine dumps, and differs from carbonate of talc-carbonate rock in its grey rather than brown weathering, and failure to effervesce in cold, dilute hydrochloric acid. It is not recorded in diamond drill hole logs nor mine plans, and considering its scarcity on dumps, was probably a rare and minor rock type.

An ironstone consisting of hematite bands finely interlaminated with white chert is found sparingly on the dumps, and in one instance magnetite-chert iron formation was noted. Like dolostone, these rocks are uncommon, and not recorded in mine plans nor drill hole logs.

Tuffaceous mudstone with jasper bands is the most widespread rock which appears related to the ore horizons. It

PLATE 11

Photomicrographs of Ore and Gangue Assemblages
Penobscot Mine

A. Large anhedra of carbonate with minor interstitial talc. Sample collected from a block of talc-carbonate rock on the waste dump.

B. Fine-grained talc-carbonate rock with much dissemated (opaque) sphalerite. Sample collected from block on waste dump.

C. Euhedral to subhedral pyrite as laminae within mass of anhedral sphalerite grains, minor chalcopyrite. Sample collected on waste dump.

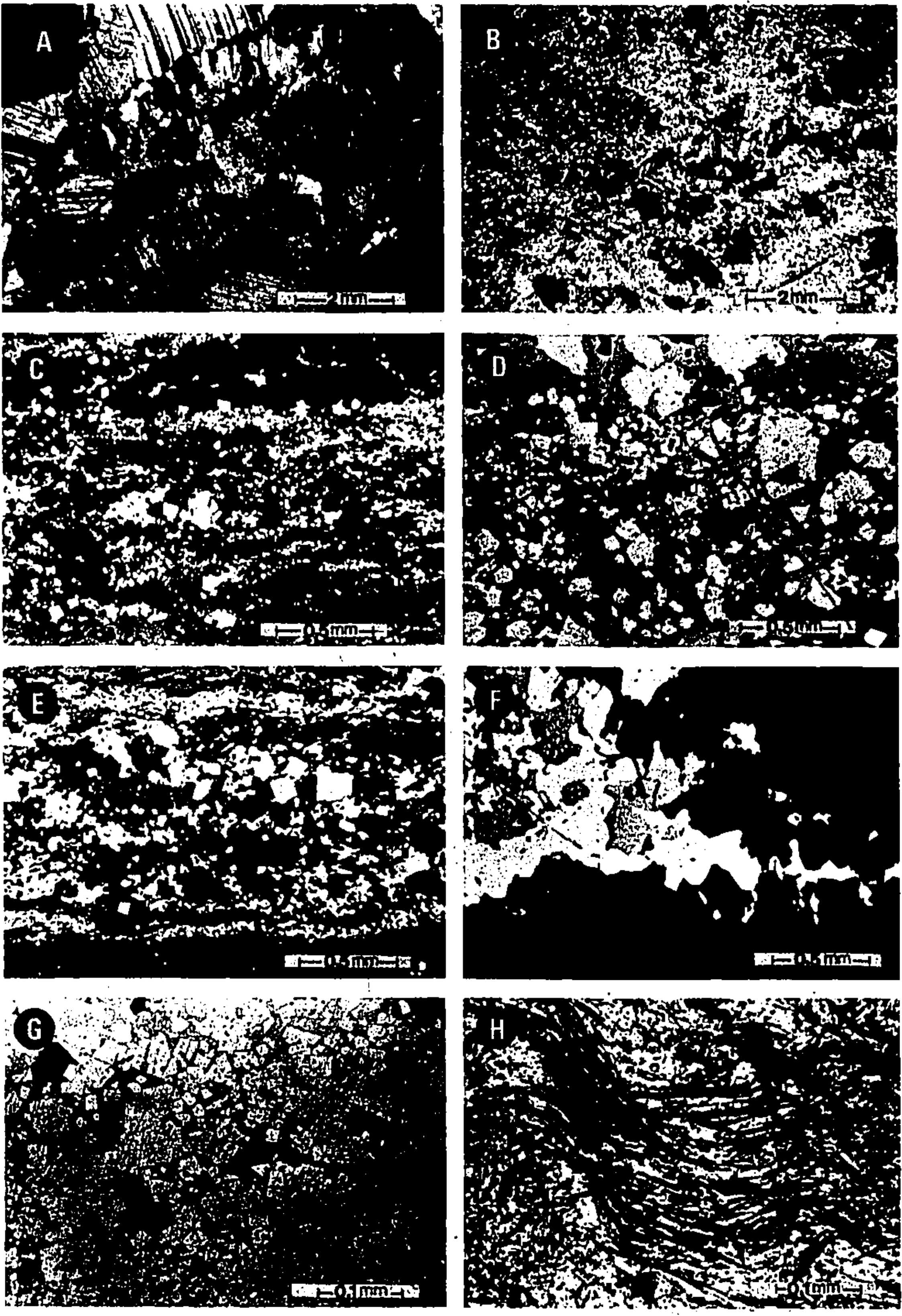
D. Subhedral to anhedral pyrite surrounded by massive chalcopyrite. Foliation defined by crude compositional banding in sulfides, and by alignment of micaceous minerals. Sample collected on waste dump.

E. Combination of delicate and crude banding within pyrite-sphalerite ore and silicate gangue. Sample collected on waste dump.

F. Pyrite-sphalerite veinlet cutting dome rhyolite, with minute unmixed blebs of chalcopyrite in the sphalerite. Sample collected from diamond drill hole 72-83 at 230'.

G. Mosaic of euhedral to subhedral pyrite crystals surrounded by structureless chalcopyrite. Silicate inclusions in pyrite give poikilitic appearance. Sample collected on waste dump.

H. Minor crenulation fold developed in finely laminated talc-sphalerite bands. Sample collected from diamond drill hole 72-83 at 232 feet.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0.5mm

consists of alternating microbands of silica, jasper, and chlorite, with frequent beds less than 1 cm thick, or crystal tuff in chlorite matrix (Plates 8G, 8H), and granule-sized lithic clasts. As in all finely laminated rocks on Cape Rosier and within the mine sequence, foliation is parallel to compositional banding. Crenulation folds and cleavage, box folds, and kink bands are numerous and well-developed. Whole rock analyses of this rock (Table 5N) coincide with analyses for bleached and altered rhyolite clasts.

Sulfide Mineralogy, Penobscot Mine

The sulfide assemblage at Penobscot is mineralogically simple, consisting of predominant pyrite, with lesser sphalerite, chalcopyrite, and minor galena. Study of 22 polished sections failed to disclose any other sulfide minerals as major constituents, although Park and Bastille (1973) described safflorite, marcasite, arsenopyrite, and mackinawite as 1-100 μm blebs in pyrite. Callahan production figures indicate that Zn:Cu was 4.4:1, and visual estimation of pyrite:sphalerite is about the same. The ores are thinly bedded (Plates 11C, 11E, 11H), with monomineralic layers as thin as 0.01 mm, although thicker layers, usually sphalerite-rich, are as much as 10 cm thick. Near-massive (90%+) sulfide bands occur, but are subordinate to sulfide interbedded with chlorite or talc, and a gradation extends from nearly pure sulfide, to chloritic rocks with trace sulfide, usually pyrite (Plate 11H). Descriptions of sulfide mineralogy and textures (Plates 8 and 11) are for specimens selected to represent most of the observed variations in sulfide ores of the Penobscot mine.

Sphalerite is dark brown to black, and even within sphalerite-rich layers it forms anhedral blebs and streaks, often intimately intergrown with chalcopyrite or surrounding euhedral pyrite crystals. Exsolution of chalcopyrite along cleavage traces in sphalerite is rare and poorly developed. Pyrite also occurs as distinct monomineralic bands, and disseminated among other sulfide minerals. It is generally very fine-grained, although grain size varies considerably. It always occurs as euhedral to subhedral cubes. Clusters of cubes arranged in concentric shells define colloform textures (Plates 12B, 12C), and these grade downward in grain size to framboids of minute cubes clustered about nuclei of clay minerals, sphalerite, and rarely chalcopyrite, galena, or unidentified opaque phases (Plates 12D, 12E). Many colloform clusters are aggregates of pyrite with intergrown sphalerite and chalcopyrite (Plates 12F, 12G). Poikilitic and inclusion-riddled pyrite has a mottled appearance (Plate 11G).

Anhedral streaks and irregular patches of chalcopyrite have much the same habit as sphalerite, and both frequently surround euhedral pyrite grains (Plates 11A, 11H). Galena is rare, occurring as an accessory mineral within bedded and near-massive chalcopyrite and sphalerite. It is rarely associated only with pyrite. It occurs sparingly on grain boundaries between pyrite and chalcopyrite as minute, anhedral patches with straight cleavage traces. The average mine

PLATE 12

Photomicrographs of Ore Assemblages, Penobscot Mine

A. Fine pyrite dust consisting of minute pyrite euhedra and a band of coarser sphalerite-pyrite. Sample collected on waste dump.

B. Framboidal aggregates of pyrite euhedra. Individual clusters average about 0.5 mm, and together define a larger colloform aggregate greater than the field of view. Sample collected from diamond drill hole 72-83 at 232 feet.

C. Large colloform ball of sphalerite and pyrite, composed of smaller clusters of framboidal sulfide. Sample collected from diamond drill hole 72-83 at 232 feet.

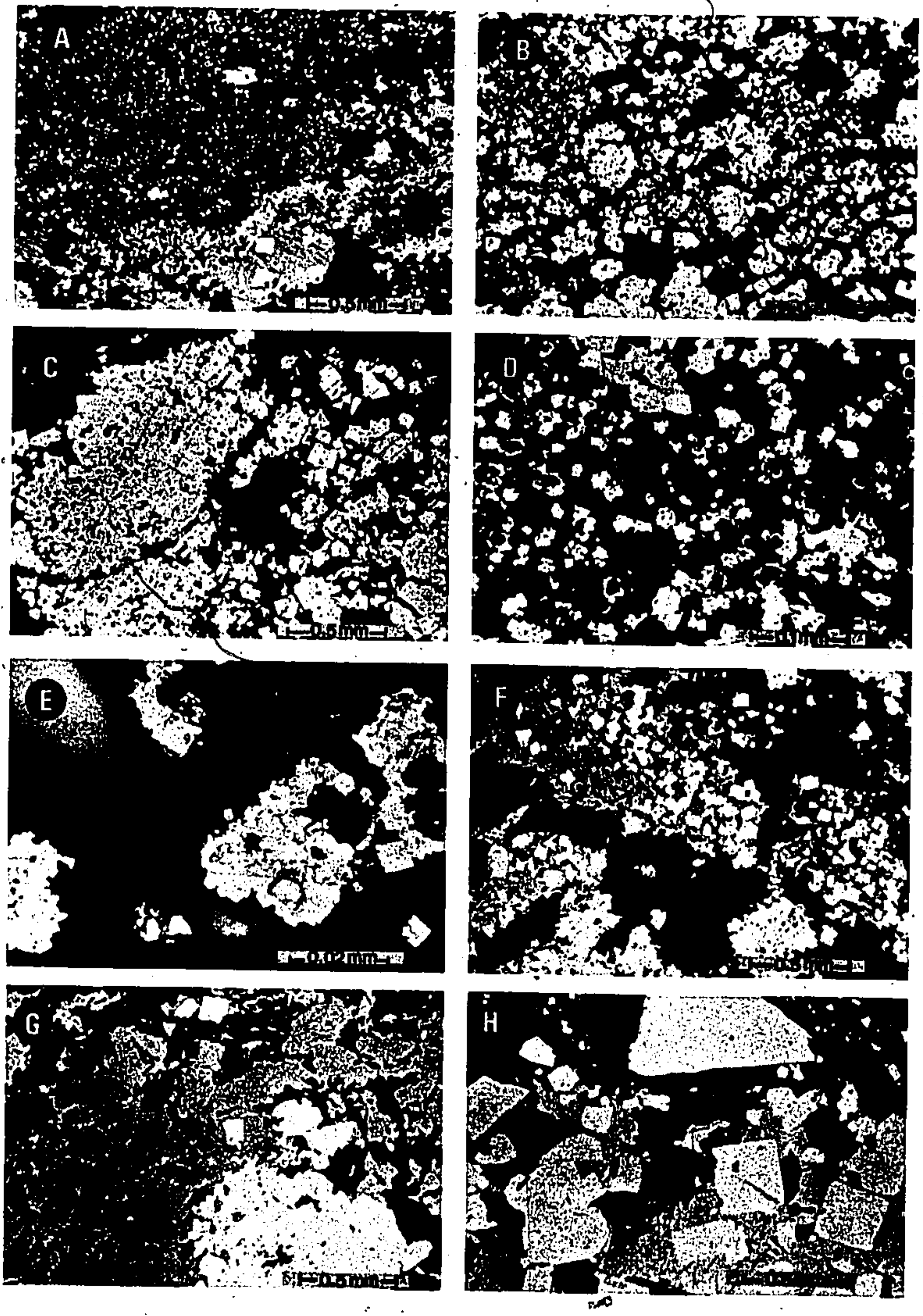
D. Spherical framboids consisting of euhedral pyrite grains around silicate nuclei. Sample collected from diamond drill hole 72-83 at 232 feet.

E. Detail of framboid structure. In this instance, minute pyrite euhedra surround a core of unidentified sulfide. Sample collected from diamond drill hole 72-83 at 237 feet.

F. Clots of pyrite and sphalerite, the latter consisting of framboidal aggregates. Sample collected from diamond drill hole 72-83 at 238 feet.

G. Colloform texture defined by concentric shells of structureless sphalerite and silicate gangue around a core of framboidal pyrite. Sample collected from diamond drill hole 72-83 at 238 feet.

H. Anhedral structureless chalcopyrite around large, euhedral to subhedral pyrite crystals. Sample collected on waste dump.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D
E
0.02 mm
F
G
0.5 mm
H

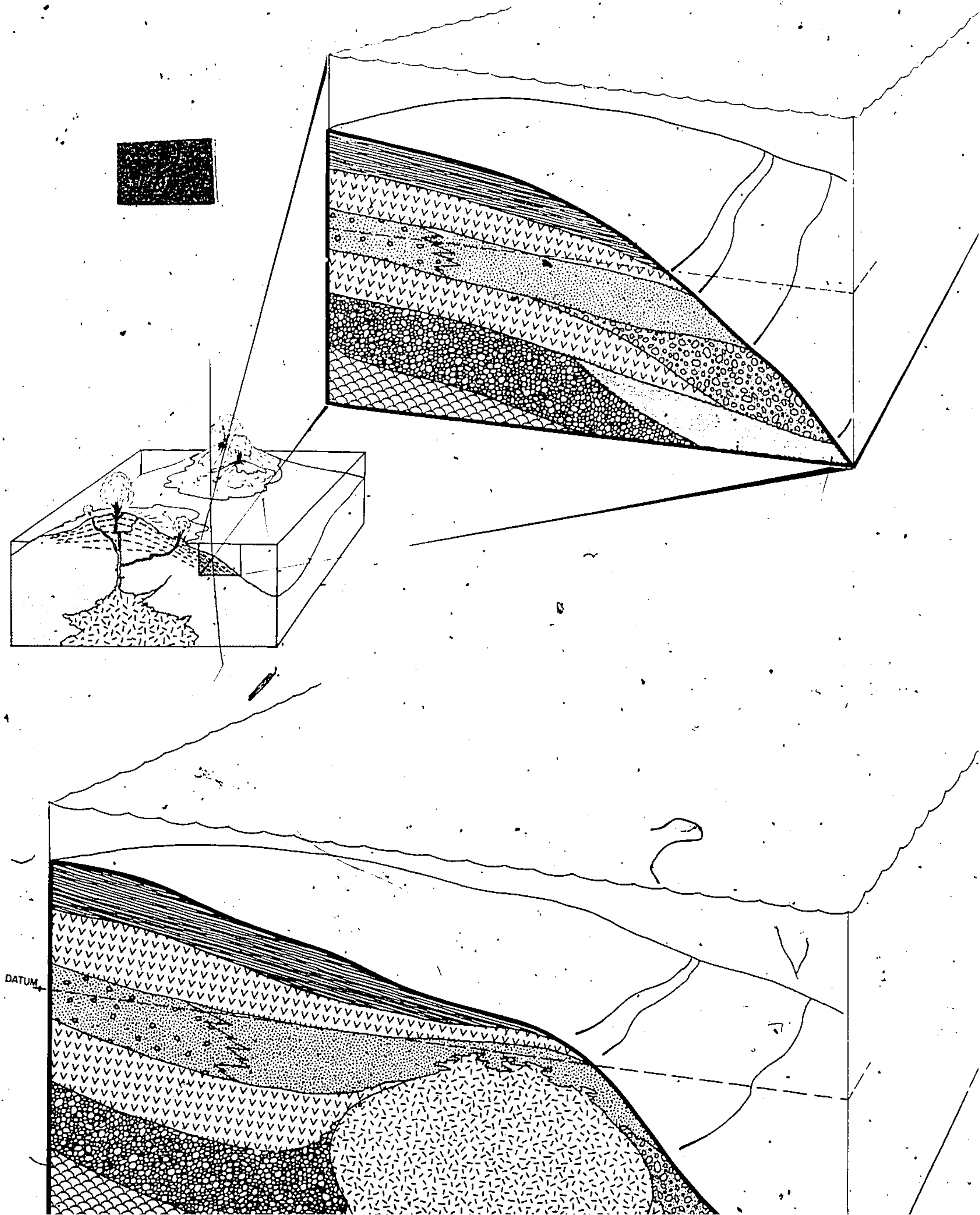
grades of 0.5% lead and 17.1 g/ton silver were contributed largely from an anomalously rich pod of galena with sphalerite, which occurred near the south end of the rhyolite dome and was mined underground (R. W. Hodder, personal communication, 1977).

Colloform to framboidal textures, fine-scale compositional layering, minute grain size, absence of pyrrhotite, and the absence of metamorphic textures are all consistent with an interpreted origin wherein coprecipitation of sulfide phases occurred from a submarine fumarole during a period of relative quiescence. The degree of metamorphic recrystallization has not been sufficient to destroy framboidal pyrite grains, generate pyrrhotite, or effectively separate mineral phases.

Interpreted History of Sequential Development of Massive Sulfide Bodies

Considering all these data, the following sequence of events is suggested for the geologic evolution of the Penobscot sulfide bodies and enveloping rocks (Figs. 13-15). Prior to emplacement of dome rhyolite, the footwall breccia at Goose Pond had accumulated to considerable thickness, probably as a local volcanic conglomerate on the flanks of a stratovolcanic edifice (Figure 13A). Diapiric emplacement of domal rhyolite ensued, resulting in local warping (Figure 13B). Further domal growth promoted cooling shrinkage and cracking of the carapace, permitting access of seawater into the interior. As seawater was heated, steam was produced, and

Figure 13A



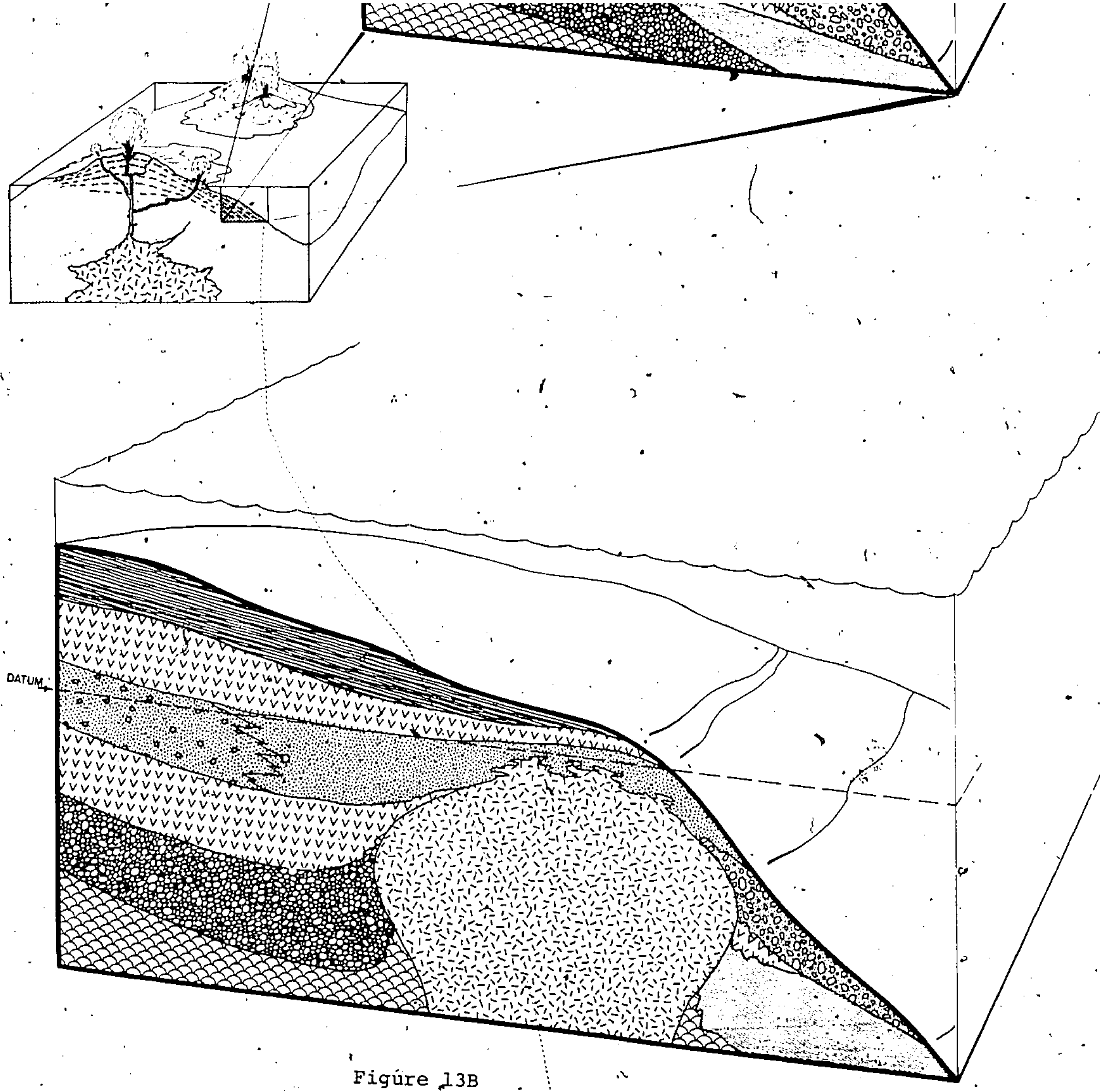


Figure 13B

Figure 13

vapor pressure exceeded confining pressure to break up part of the dome, contributing fragments to existing fragmental rocks (Figure 14A). The coarsest clasts were deposited closest to the shattered dome, but finer debris and ash were carried farthest away. Continued domal growth resulted in additional local deformation and renewed explosive activity (Figure 14B), and ultimately the shattered dome and related highly permeable fragmental rocks became the loci for submarine fumarolic discharge (Figure 14B). Chemical sedimentary rocks formed near the flanks of the dome and on the apron of coarse explosion breccia as a result of this brine emission. Another pulse of domal growth produced repeated shattering and additional pyroclastic horizons above the chemical sedimentary rocks (Figure 15A). Finally, domal growth and magmatism ceased, and portions of the dome and related rocks were overlain by basalt and conglomerate of the next volcanic cycle (Figure 15B).

In this context, downslope movement of the explosion-generated, dense, debris-laden slurry off the dome left behind denser and larger clasts, but smaller and lighter clasts were carried farther. The interaction between clasts and seawater is recorded as the fragmentation, comminution, and bleaching of the fragments. Those which have travelled farthest are smallest and most bleached. The spatial proximity and inferred temporal equivalence of jasperoidal tuff with explosion breccias, and the similarity of composition, suggest that the tuffs represent the slurrying and transporting

Figure 14A

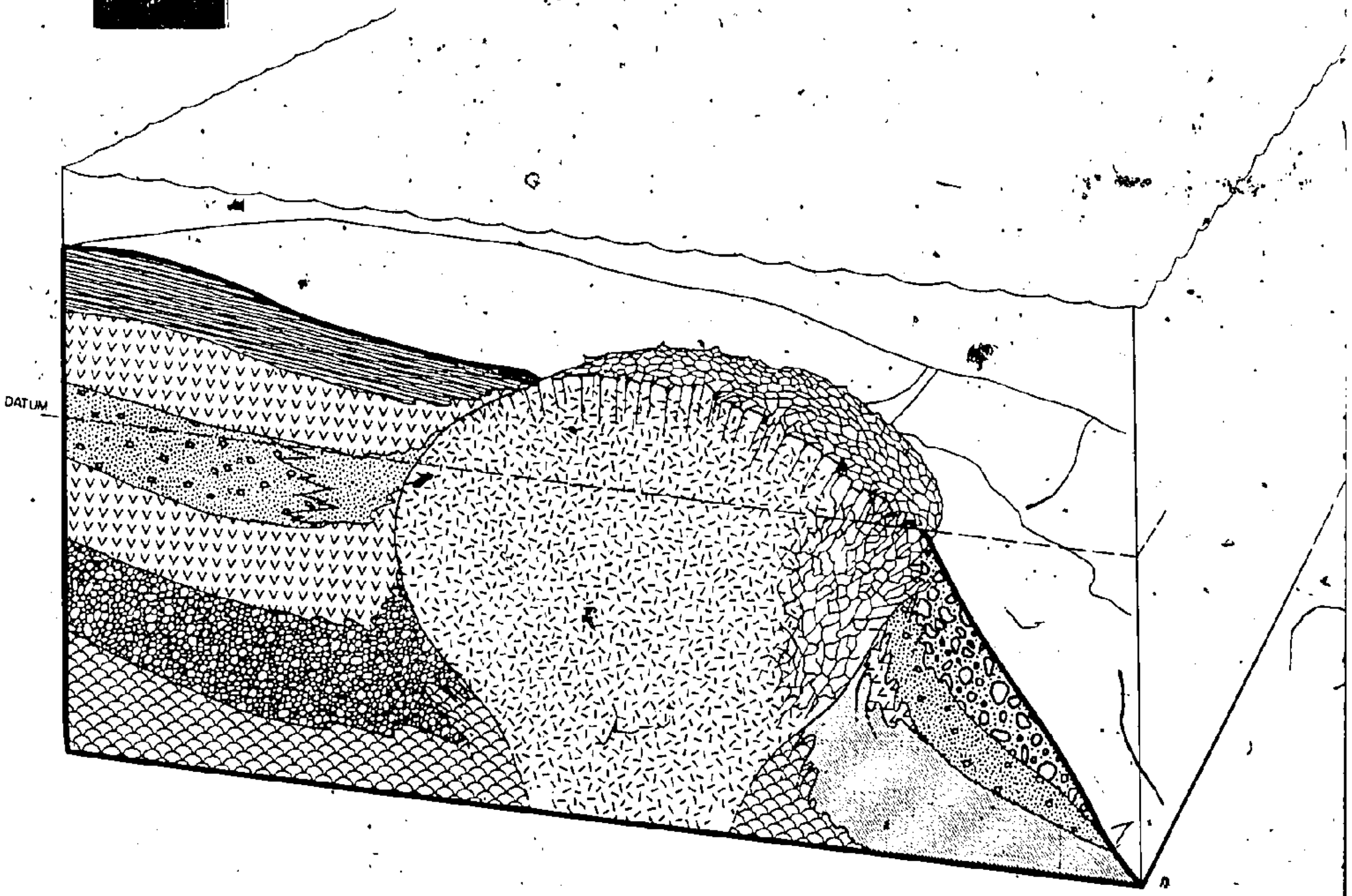
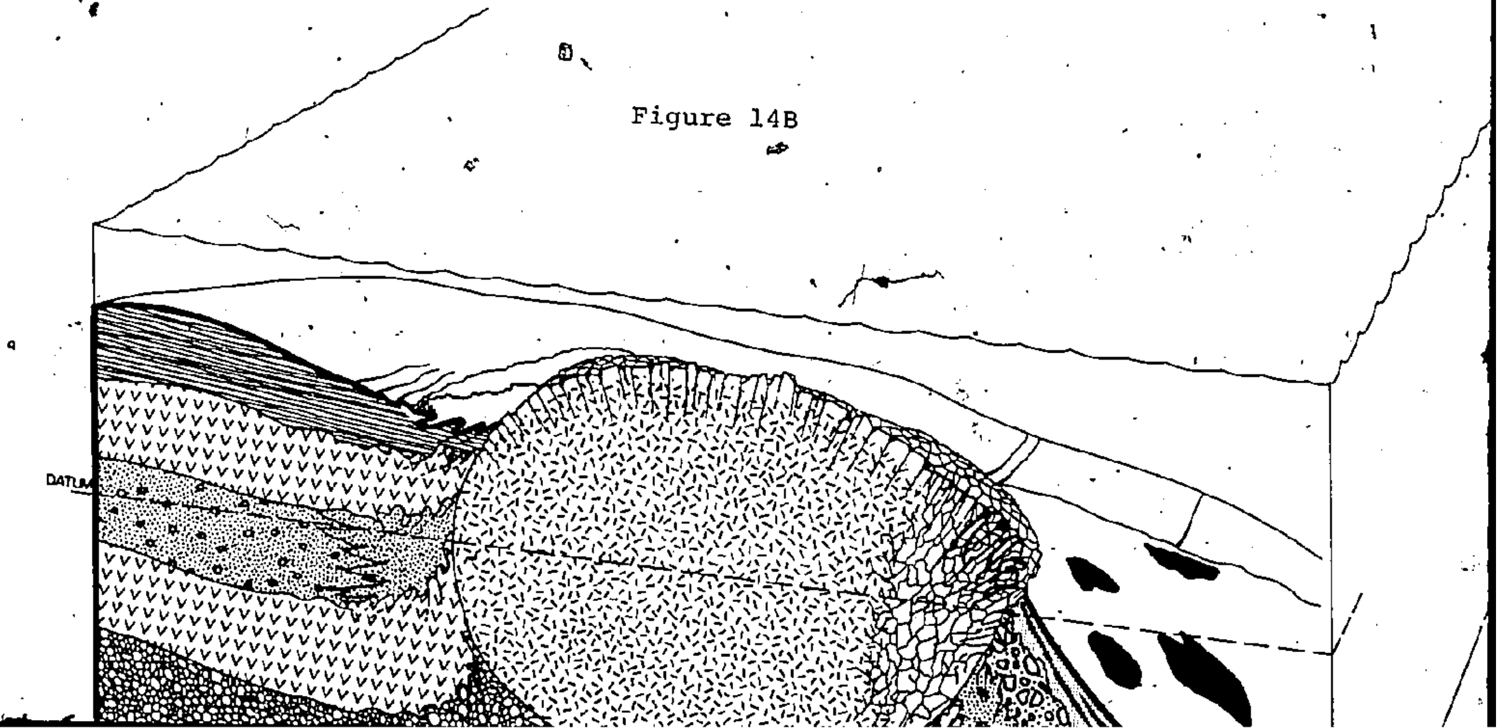


Figure 14B



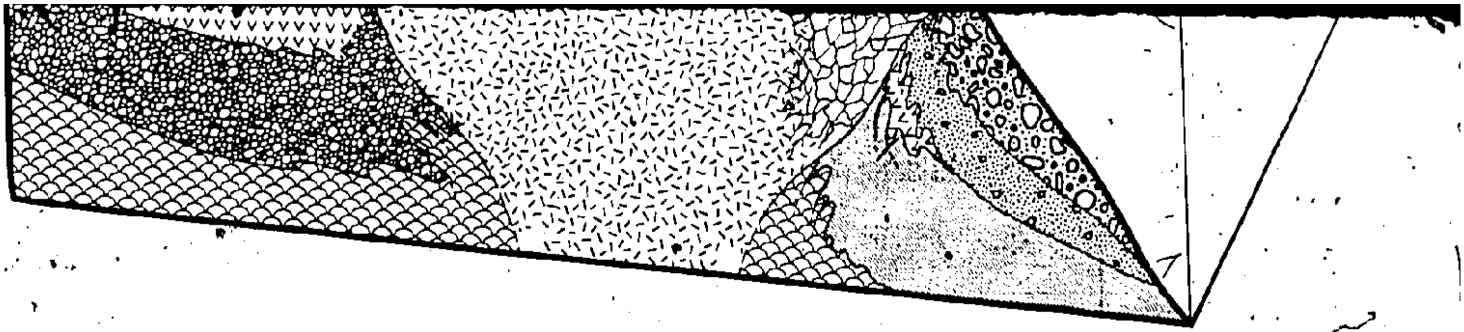


Figure 14B

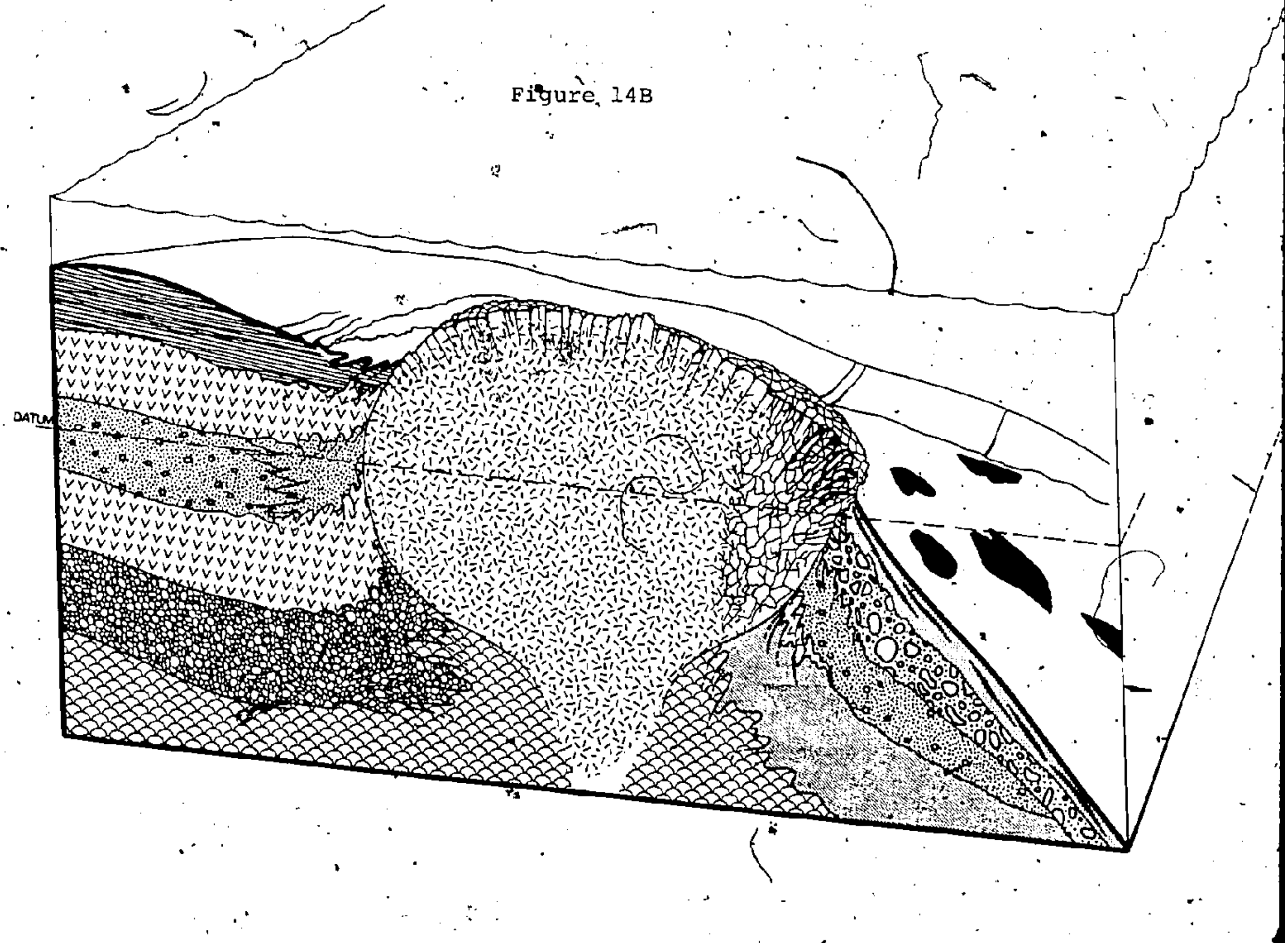


Figure 14

Figure 15A

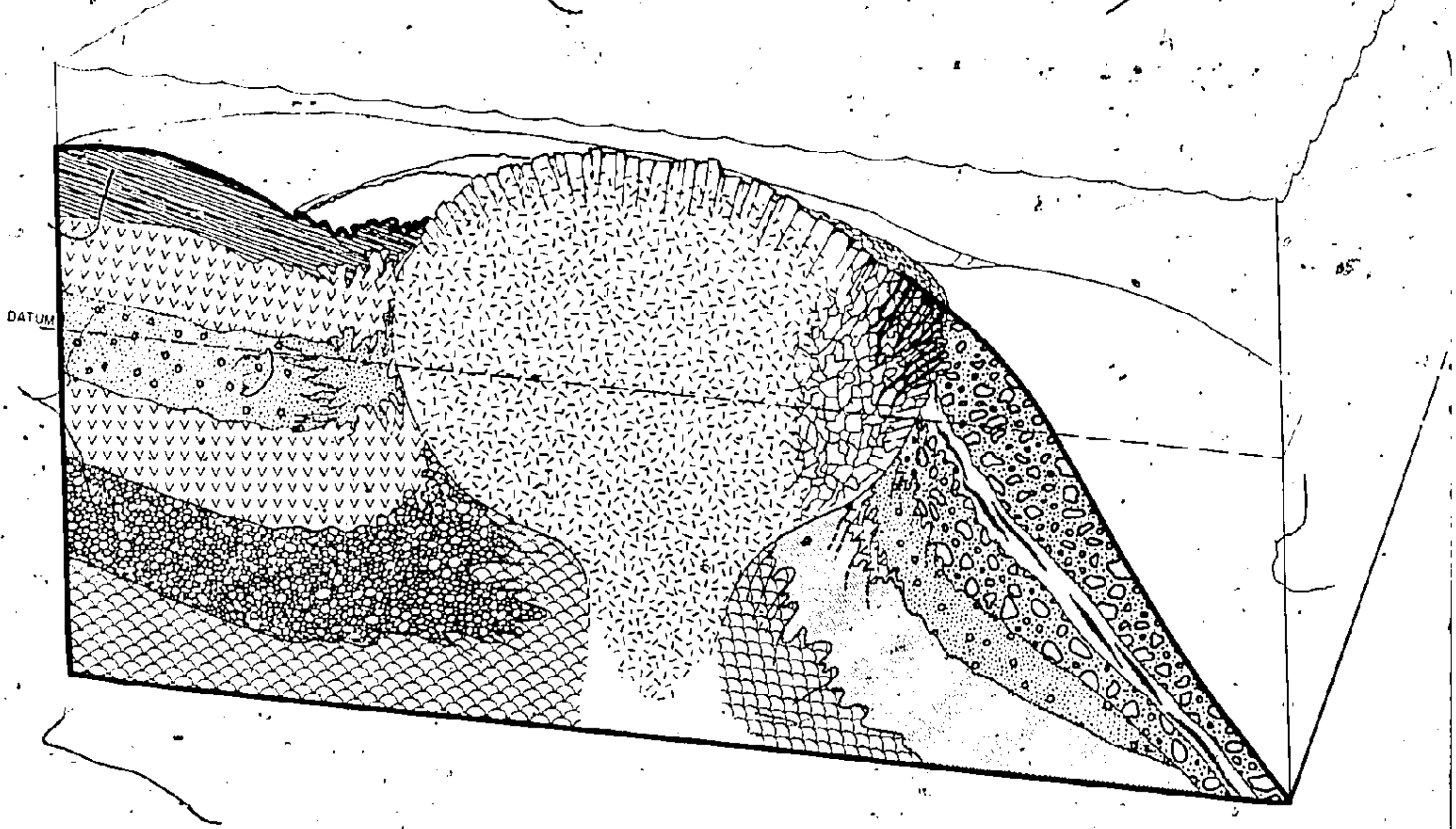
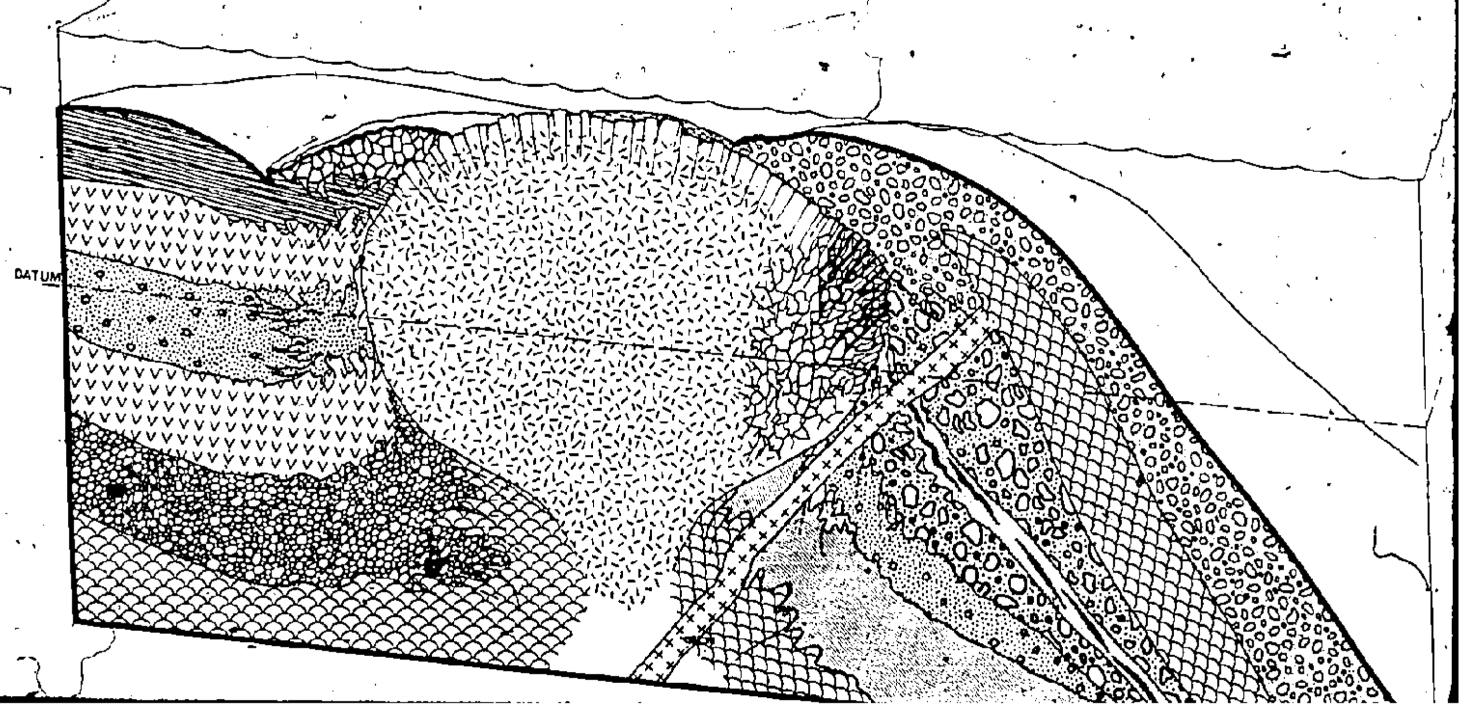


Figure 15B



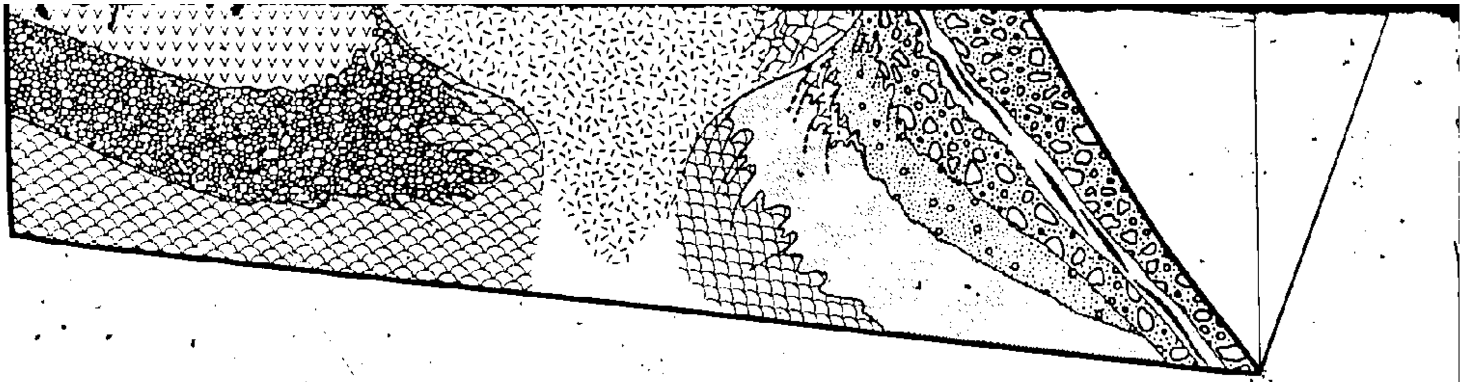


Figure 15B

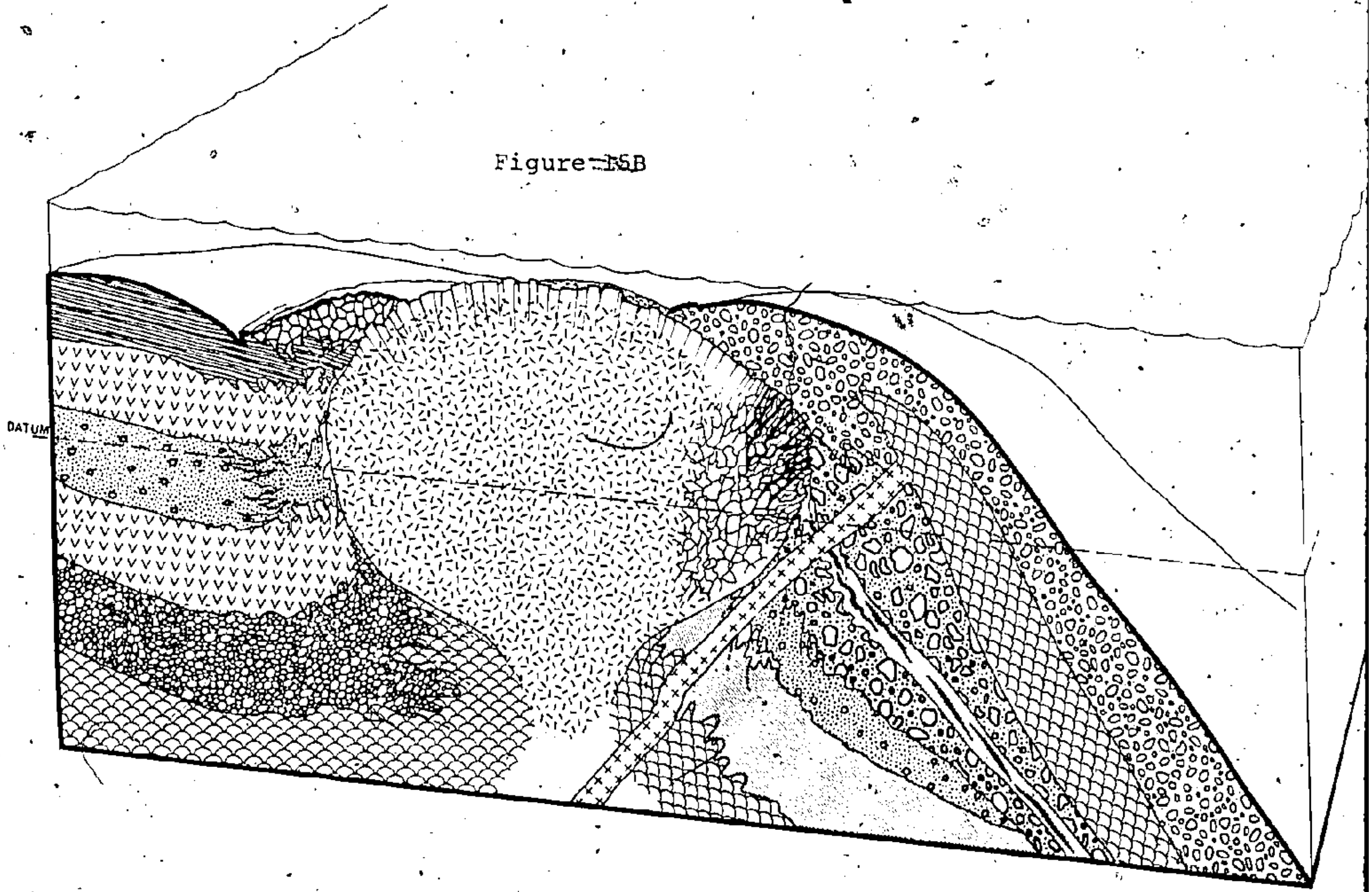


Figure 15

medium for the breccias. These slurries spread out and away from the site of fragmentation, leaving all but the smallest clasts and entrained crystals behind. Alternating jasper and chlorite bands indicate conditions fluctuating across the ferrous-ferric redox boundary in a seafloor brine pool saturated with silica and iron, and receiving periodic influx of ash fall and ash flow components. The resulting jasper-chlorite rocks are analogous to ferruginous and siliceous chemical sedimentary rocks laterally equivalent to massive sulfide bodies within Archean sequences in Canada and elsewhere (Sangster, 1972; Sangster and Scott, 1976). They are most similar to tuffaceous mudstones described in the Kuroko fields of the Green Tuff region of Japan (Sato, 1974).

The fine-grained, well-laminated horizons interbedded with, and unique to the mineralized sequence, record a period of relative quiescence in an otherwise turbulent environment. The underlying stockwork of pyrite-chalcopyrite veinlets represents part of a submarine discharge system through which metal-laden brines emanated onto the seafloor. Many of the economic sulfide lenses overlay such vein networks, but in many instances vein networks were not accompanied by overlying layered sulfide minerals. Where vein density and metal values were sufficient, these were mined. Many of the larger sulfide lenses were irregularly shaped, discoid, or with keels. Some had a convex downward geometry with nearly planar upper surfaces, suggested in Figure 11. It is suggested that such forms represent small basins of accumulation within a larger field of brine emission. The stagnant and quiescent conditions necessary for accumulation of mineral-rich chemical sedimentary beds were terminated by renewed nearby volcanism.

Comparison with Japanese Deposits

The nature of volcanic products on Cape Rosier, the spatial association of rhyolite domes with base metal sulfides, and the inferred island arc origins, are strikingly similar to the well-described Kuroko deposits of the Green Tuff region of Japan. Although there are minor mineralogical differences, the overall similarities (Table 6) are numerous and close enough to consider Penobscot as a North American analogue of the Kuroko deposits (Figure 16).

The Leach Occurrence

The Leach orebody was discovered by Callahan Mining Corporation during exploration in 1969. A small rhyolite dome 1500 meters south of the Penobscot open pit, and within the same volcanic cycle (Figure 3, dome $1C_3$), is flanked to ~~the~~ northeast by a horizon of massive chalcopyrite and sphalerite, estimated from diamond drilling to contain over 100,000 tons of more than 8% combined copper and zinc. The sulfide body is within a complex sequence of talc, talc-carbonate, and talc-chlorite strata, as at Penobscot. The sulfide-bearing horizon is 75 meters below the surface, and dips shallowly to the northeast. A development shaft was drilled to provide access to the ore zone, and some under-

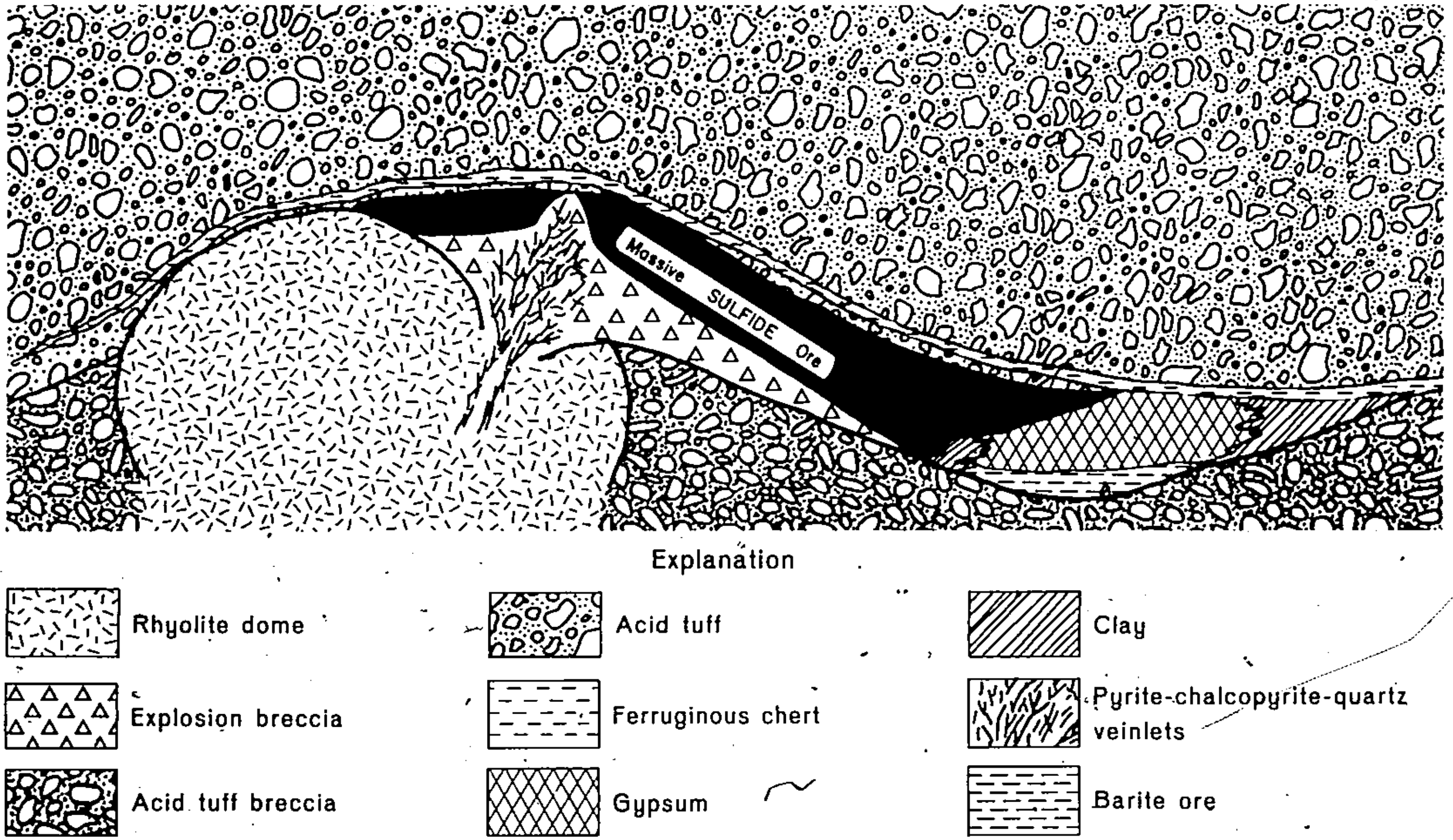
TABLE 6

Comparison of Mineralogical, Petrological, and Structural Features of the Penobscot Mine and a Typical Kuroko Deposit

	Typical Kuroko (Sato, 1974; Lambert and Sato, 1974)	Penobscot Mine
1.	Miocene subaqueous felsic volcanism	Siluro-Devonian subaqueous felsic volcanism
2.	Bedded, stratabound, massive sulfide minerals	Bedded, stratabound, massive sulfide minerals
3.	Economic Cu, Pb, Zn, Ag and Au	Recoverable Cu, Zn, Ag
4.	Abundant Ba and Ca sulfate minerals	Sulfates absent, but carbonates present
5.	Stockwork vein system beneath massive ore	Stockwork vein system beneath massive ore
6.	White rhyolite dome	Black rhyolite dome
7.	Coarse explosion breccia in footwall	Coarse explosion breccias in footwall and hanging wall
8.	Clusters of individual massive sulfide bodies	Clusters of individual massive sulfide bodies
9.	Ore bodies zoned	Ore bodies poorly zoned
10.	Sulfosalts important	Sulfosalts absent
11.	Ferruginous chert horizons well-developed	Ferruginous chert horizons poorly developed
12.	Subjacent mudstone	Subjacent mudstone
13.	Felsic tuff breccias in hanging wall	Felsic tuff breccias in hanging wall
14.	Structurally undeformed	Structurally undeformed
15.	Low greenschist metamorphism	Low greenschist metamorphism
16.	Calc-alkaline differentiated sequence	Calc-alkaline differentiated sequence

Figure 16

Cross-section of a typical Kuroko deposit, modified after Sato (1974)



-ground work was done, but engineering and economic difficulties forced termination of proposed work in 1971, and the deposit remains unmined. Sulfide ores removed during development work are comparable to those at the Penobscot mine (Plate 8B), consisting of fine-grained, well-laminated, sphalerite and chalcopyrite-rich bands.

The Hercules Mine

The abandoned Hercules mine consists of a two-compartment shaft on an island accessible at low tide, on the north side of Bagaduce Narrows, in Penobscot Township, Maine (Figure 3). The shaft is in steep-dipping devitrified rhyolite tuff mapped as Castine Formation (Smith and others, 1907; Cheney, 1969), and explores a concordant body of layered sulfide minerals which overlies poorly developed stockworks of quartz-sulfide veinlets in the footwall (Emmons, 1910). The tuffs are buff-colored on weathered surfaces, but locally are brown because of weathering of abundant disseminated pyrite. Extremely coarse cordierite and andalusite porphyroblasts (Plate 13A) in nearby dacitic tuffs, flame and mosaic textures and triple point junctions in pyrrhotite, poikiloblastic growth of amphiboles and cordierite, and retgrograde exsolution textures in sulfide minerals (Plates 13B, 13C, 13D, 13E), are evidence of thermal metamorphism attributable to the South Penobscot pluton, 1½ km to the east. Abundant pyrrhotite, unknown in the region except for sulfide bodies within contact metamorphic aureoles, probably reflects thermal desulfurization of original pyrite. The ores are primari-

PLATE 13

Ore and Gangue Assemblages
Hercules Mine

A. Coarse cordierite porphyroblasts in dacitic tuff, 200 meters west of Hercules shaft. Knife is 3.5 cm long.

B. Blebs of tetrahedrite (tt) with intergrown pyrrhotite (po) and galena (gn), with nearby sheaf of amphibole (g). Sample collected at Hercules dump.

C. Ragged intergrowth between gangue silicates (g) and pyrrhotite (po), sphalerite (s), and galena (gn). Sample collected at Hercules dump.

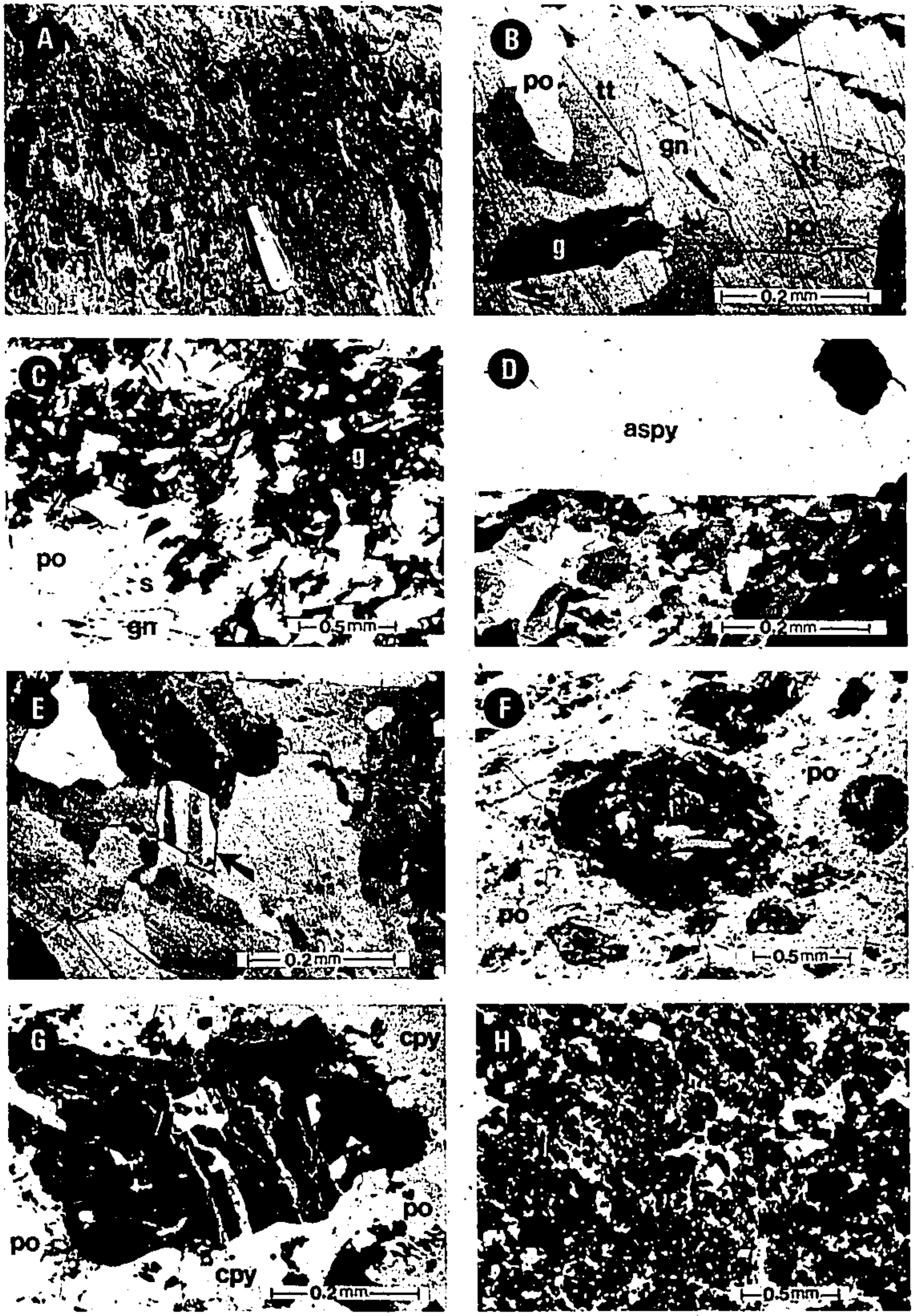
D. Large euhedral arsenopyrite crystal (aspy) poikiloblastically enclosing unidentified gangue (upper right). Arsenopyrite surrounded by strongly anisotropic pyrrhotite exhibiting triple point boundaries and flame textures. Sample collected at Hercules dump, crossed nicols.

E. Single pyrrhotite grain (outlined and arrowed) with flame texture, and triple point boundaries against adjacent pyrrhotite grains. Sample collected at Hercules dump.

F. Cordierite, poikiloblastically enclosing scattered grains of sphalerite, with neighboring smaller cordierite clots. Abundant pyrrhotite contains much fine disseminated sphalerite (darker grey). Sample collected at Hercules dump.

G. Unidentified gangue silicate mineral, veined by chalcopyrite, pyrrhotite, and sphalerite. Sample collected at Hercules dump.

H. Pyrrhotite and chalcopyrite outlining grain boundaries of unidentified silicate minerals. Sample collected at Hercules dump.


A
B
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tt
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-ly sphalerite and galena, with minor chalcopyrite.

Diamond drilling by Denison Mines, Ltd. in 1964 cut 0.7 meters of massive sulfide within fine tuffs, thin flows, and reworked volcanic-sedimentary debris (Fig. 17). This section lacks the coarse breccias, massive domes, and thicker flows at the focus of volcanism on Cape Rosier, and apparently represents a depositonal environment characterized by thinner, more areally extensive rock units, accumulated under less turbulent conditions than on Cape Rosier. The sulfide assemblage is enriched in lead and zinc relative to copper as compared to the Penobscot mine and the Leach occurrence.

TABLE 7

Metal Content of Selected Samples from Hercules Mine

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
* 0.113	3.8	4.9	0.6	0.01	-	-
0.26	1.37	1.43	5.18	0.05		
0.313	0.83	0.86	0.52	ND	ND	70
0.845	1.20	2.70	5.10	ND	210	225
0.030	5.30	3.70	1.70	ND	ND	980
0.890	2.80	1.80	12.60	0.28	ND	275
0.114	0.760	2.62	1.0	ND	ND	-
0.148	4.30	4.30	20.0	ND	1.8%	645

ND = not detected
\- = not analyzed

$\frac{Zn + Pb}{Cu} = 15.73$

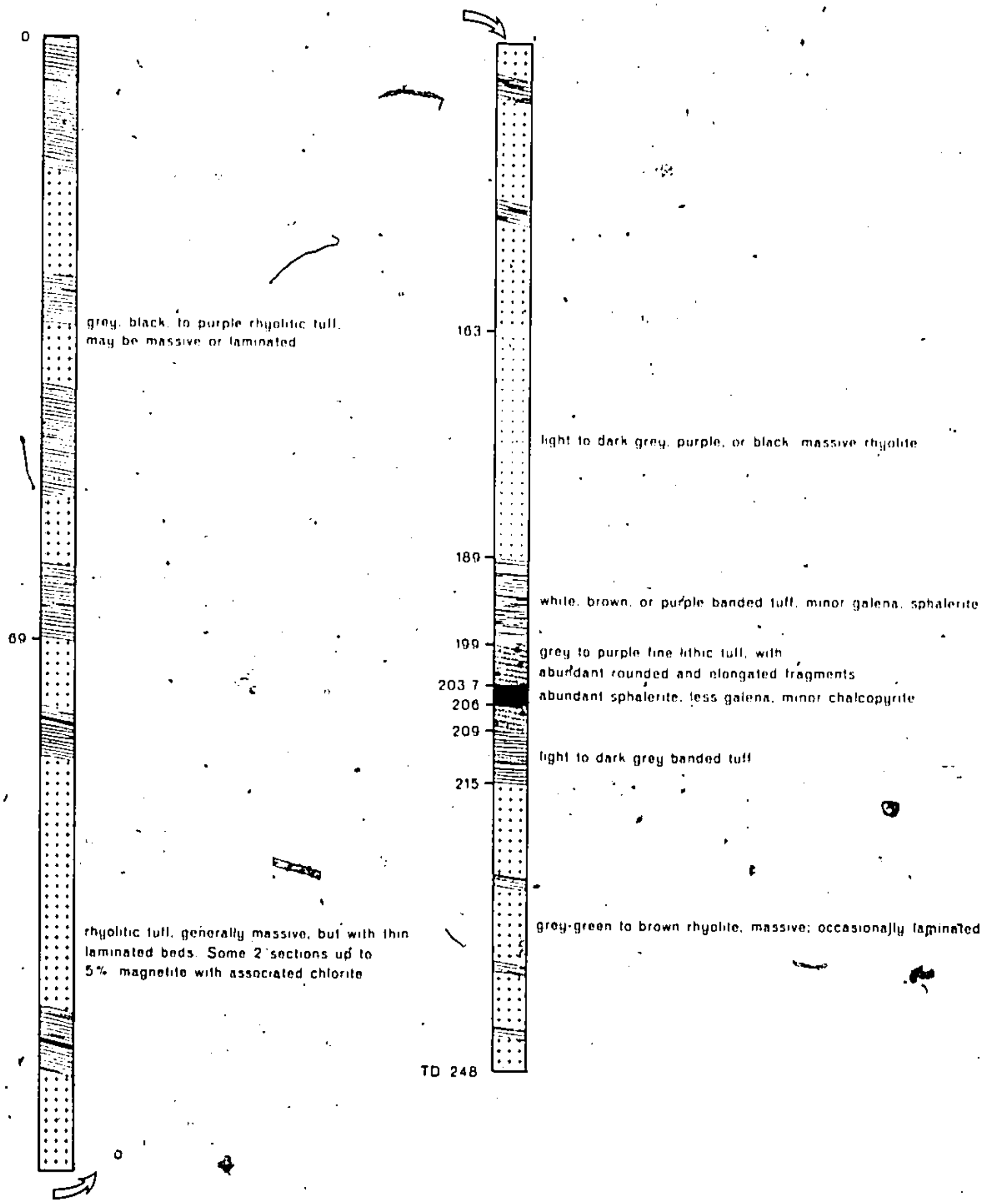
*Analysis reported by Young (1962)

Figure 17

Graphic log. Diamond Drill Hole He-64-3. Hercules Mine

Penobscot, Maine

inclination. -45°. bearing 110°. total depth 248. Ax wireline



North Castine - Emerson Prospect

These old occurrences are located on the west side of the Bagaduce River, about 2 km northeast of Castine, Maine, in Castine Township (Fig. 3). A flooded two-compartment shaft is 10 meters inland from high tide at North Castine (Emmons, 1910). The shaft was sunk in medium-grained volcanic breccia consisting of rounded to subrounded pyroclasts of devitrified rhyolite in a fine-grained dark green matrix, with fragments elongated parallel to foliation. Disseminated sulfide and quartz-sulfide veinlets transect this breccia, and judging from scattered dump material, were abundant enough to warrant interest. In addition, some boulders of bedded sulfide minerals are present, consisting of pyrite, sphalerite, galena, and minor chalcopyrite. An exploration drill hole by Denison Mines, Ltd. in 1964 penetrated fine tuffs with interbedded black graphitic shales (Fig. 18).

TABLE 8

Metal Content of Selected Samples from North Castine - Emerson Prospect

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
*0.163	6.4	10.5	4.6	0.13	-	-
0.028	0.32	1.4	0.55	ND	195	-
0.340	1.1	0.696	12.3	4.2	450	150
0.099	1.5	3.1	1.0	0.35	ND	ND
0.039	0.46	0.450	9.3	ND	480	180

ND = not detected
\- = not analyzed

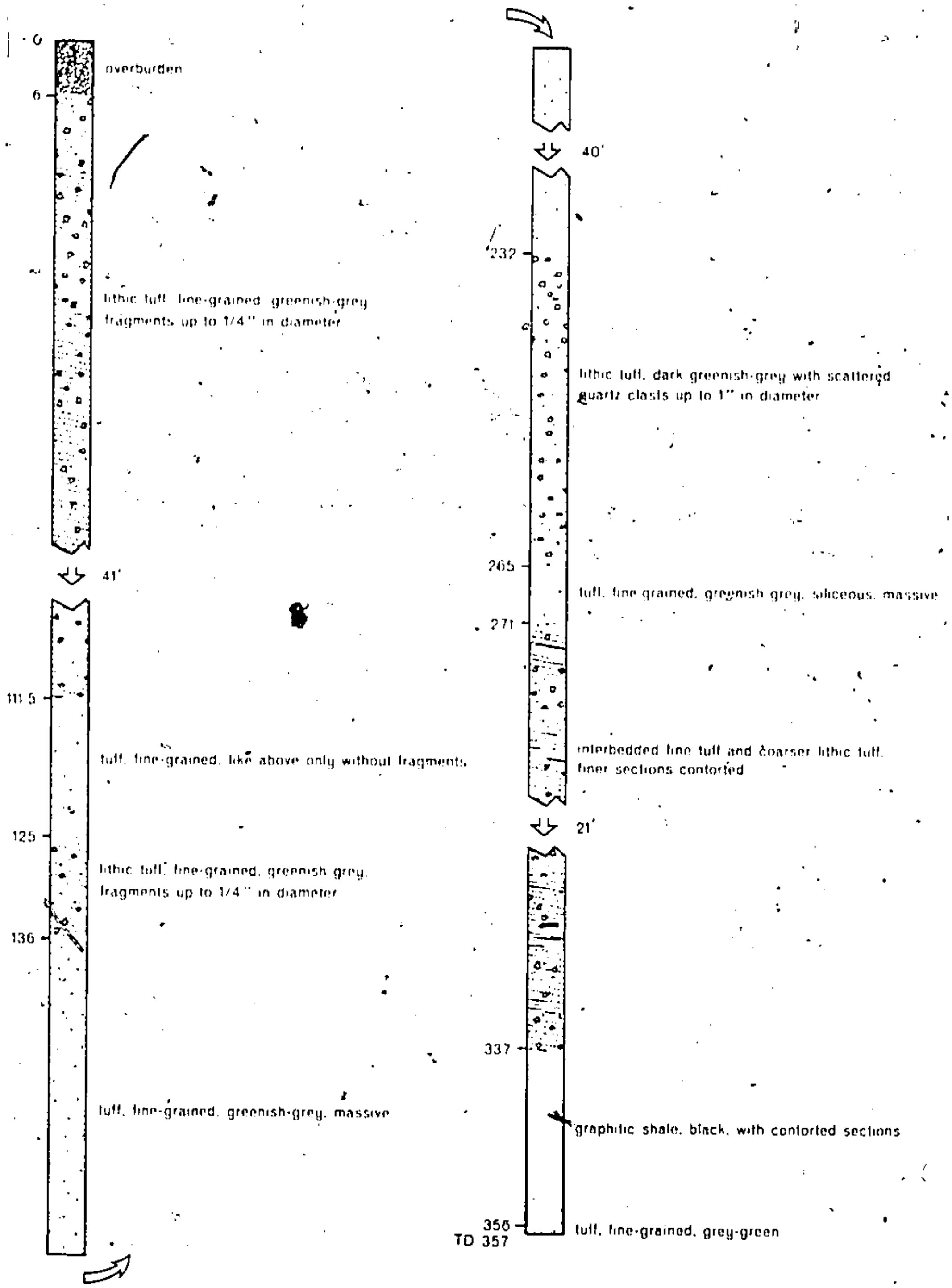
$$\frac{Zn + Pb}{Cu} = 38.75$$

*Analysis reported by Young (1962)

Figure 18

Graphic log, Diamond Drill Hole E-1, North Castine-Emerson Prospect
Castine, Maine

inclination: -45°, bearing 300°, total depth 357', Ax wireline



Jones, or Jones-Dodge Prospects

A series of sulfide mineral showings, old prospects, and one abandoned shaft occurs along the south shore of Bagaduce Narrows in Brooksville Township (Fig. 3). The shaft is surrounded by a waste dump containing andesitic tuff and rhyolite breccia fragments in sufficient number to suggest several tens of meters of underground workings. The rock sequence along the south side of the Narrows consists of rhyolitic to dacitic tuffaceous beds, minor volcanogenic sedimentary beds, and mafic tuffs or thin mafic flows. Numerous lithofacies changes occur in the 1 kilometer of section which is nearly continuously exposed, and the rocks are mostly within the cordierite isograd of the Sedgwick or South Penobscot pluton, except on the west, where they are within the biotite isograd. Associated with rhyolitic to dacitic tuffs, and commonly occurring along a contact between felsic tuffs and more mafic rocks, are stockwork and disseminated occurrences of sulfide minerals, mostly pyrite, with galena and sphalerite. A prospect pit 150 meters east of the shaft exposes a breccia of devitrified rhyolite pyroclasts intensely veined by a quartz-sulfide stockwork. Fine-grained galena and sphalerite fill in between fragments, and are locally massive, although not bedded (Plate 14A). The rhyolite breccia is finer grained, although similar to those formed on Cape Rosier during phreatomagmatic explosion of rhyolite domes. A hole drilled to test size and grade of this sulfide mineral occurrence was not encouraging (Cheney, 1969).

TABLE 9

Metal Content of Selected Samples from
Jones - Dodge Prospects

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
*0.289	3.0	4.4	0.74	ND	550	217
*0.007	0.330	0.580	0.18	ND	ND	-
*0.384	4.5	4.6	0.39	ND	270	-
0.084	1.9	0.864	1.0	ND	250	80
0.021	0.175	0.062	1.1	ND	4850	225
0.078	0.071	0.205	0.09	ND	310	ND

$$\frac{Zn + Pb}{Cu} \quad \bar{x} \quad 24$$

ND = not detected
\- = not analyzed

* Samples from blasted prospect pit

The Eggemoggin Mine

The Eggemoggin mine is in Brooksville Township, about 1200 meters northwest of the footings for the Deer Isle Bridge, on the north shore of Eggemoggin Reach (Fig. 3). The mine is completely overgrown, and was nearly so 70 years ago when Emmons (1910) reported two shafts in devitrified rhyolite. The shafts are enclosed and now provide fresh water to a nearby summer camp. Abundant sulfide-bearing boulders are strewn along the high tide line, and are very siliceous and fine-grained rhyolite. Silica and sulfide-bearing veinlets occur as a dense, anastomosing network (Plate 14B), which terminates, so far as can be ascertained, at the site of the old shafts. Rare boulders of near-massive sulfide minerals suggest that the stockwork of veinlets was overlain

PLATE 14

Ore and Enclosing Rocks at Jones - Dodge, Eggemoggin, and Deer Isle Prospects

A. Silicified rhyolite fragment surrounded by fine-grained mixture of galena and sphalerite. Sample collected from ore pile near small devitrified rhyolite body at Jones Prospect.

B. Quartz-sulfide veinlets in rhyolitic tuff, 100 meters northwest of Eggemoggin shaft. Hammer length is 34 cm.

C. Coarse polymictic agglomerate, 200 meters northwest of Eggemoggin shaft. Hammer length is 34 cm.

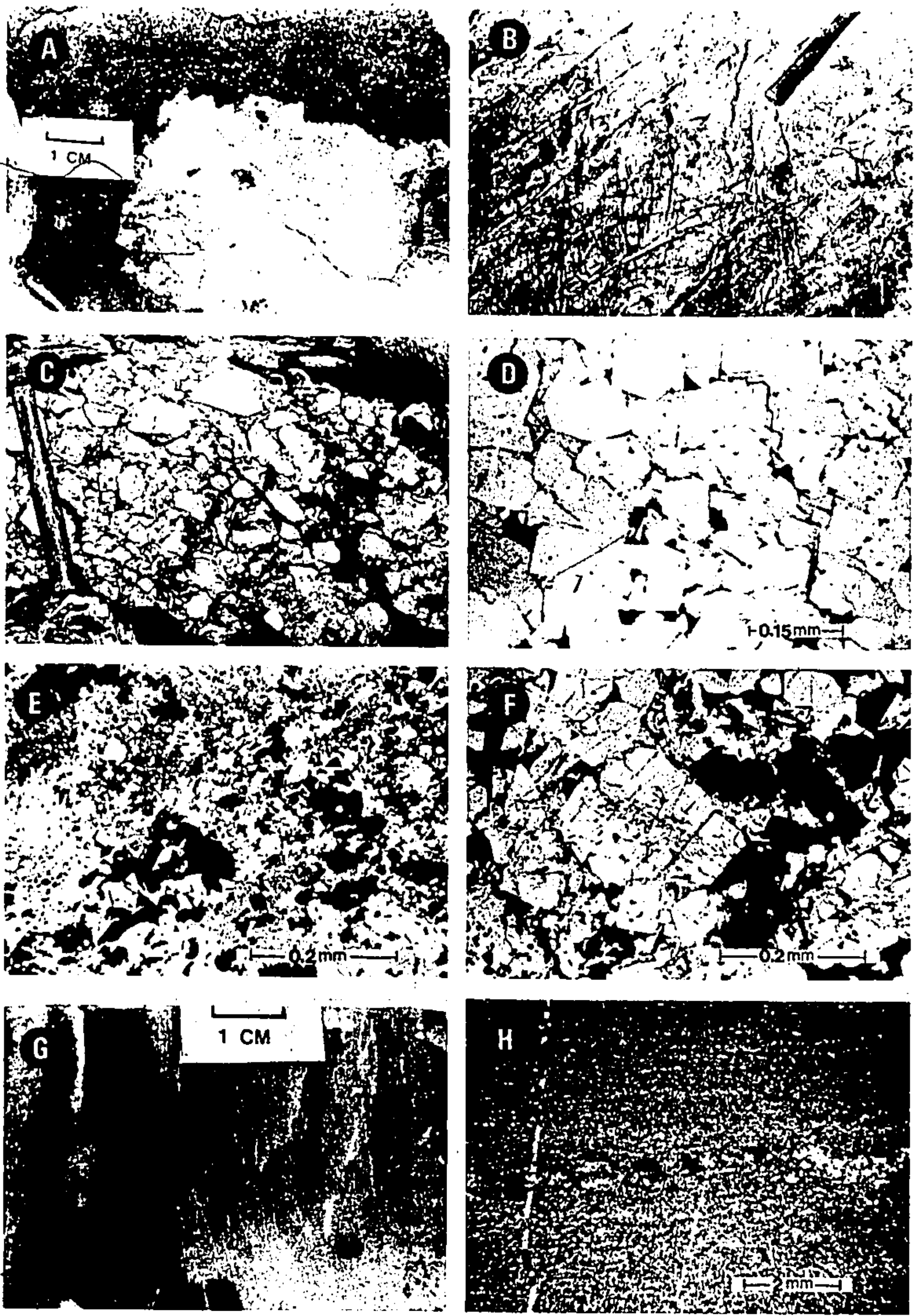
D. Euhedral pyrite crystals, surrounded by fine-grained galena. Eggemoggin mine, collected from waste dump.

E. Sphalerite (dark grey), chalcopyrite, and pyrrhotite (latter two are light grey and not distinguishable in photomicrograph) intermixed with silicate gangue (black). Deer Isle Mine, collected on dump.

F. Galena and chalcopyrite (not distinguishable) around euhedral, shattered pyrite crystal. Deer Isle Mine, collected on dump.

G. Laminated, fine-grained albite-quartz rock, collected on dump of Deer Isle Mine.

H. Albite-quartz rock of G, with sulfides in silica band and in later cross-cutting veinlets. Deer Isle mine, collected on dump.


A
1 CM
B
C
D
0.15mm
E
0.2mm
F
0.2mm
G
1 CM
H
2 mm

by massive ore in the manner described at many volcanogenic massive sulfide deposits (Sangster, 1972; Sangster and Scott, 1976). About 100 meters to the northwest is a coarse polymictic breccia (Plate 14C), consisting of rounded to partially flattened clasts of aphanitic rhyolite, clasts of intermediate composition, and mafic clasts. The sulfide minerals include abundant arsenopyrite, with lesser chalcopyrite, sphalerite, and galena (Plate 14D). Vein assemblages in dump rocks consist of siderite and aphanitic quartz intergrown with sulfide minerals.

TABLE 10

Metal Content of Selected Samples from
Eggemoggin Prospect

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
0.100	0.3	0.4	0.1	0.01	-	-

- = not analyzed

$$\frac{Zn + Pb}{Cu} = 7$$

The Tapley Mine

The Tapley mine is in Brooksville Township, about 1½ km east of state route 175. Several open cuts surround a flooded two-compartment shaft which is 80 feet deep, with 200 feet of drifts (Emmons, 1910) exploring an andesitic tuff. The old workings are well within the cordierite isograd of the Sedgwick Granite to the east, and porphyroblastic cordierite and stellar bundles of anthophyllite are intergrown with magnetite, pyrrhotite, and pyrite. Bedded massive sulfide minerals have not been reported at Tapley, nor are any visible on the large dumps. Base metal sulfide minerals are confined to stockwork vein systems, and where sufficiently abundant were mined. Chalcopyrite and pyrite are prevalent, and sphalerite and galena are completely absent. Away from the mine site the distinctive, mottled cordierite-anthophyllite hornfels is traceable for 200 meters south, where it is obscured by swamp cover. It continues north for at least 8 kilometers, although it probably is not a continuous unit for the entire distance. Several prospects and old workings are within this rock unit, and wherever examined it contains specks and streaks of sulfide minerals, and generally graphite or magnetite. In West Brooksville, beyond the thermal aureole of plutonic bodies, it is a chlorite-actinolite schist, with specks of magnetite and pyrite.

TABLE 11

Metal Content of Selected Samples from Tapley Mine

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
2.184	0.00	t	0.3	0.005	–	–
0.449	0.006	0.010	0.08	ND	ND	–
0.473	0.006	0.012	0.06	ND	ND	–
0.737	0.007	0.011	0.06	ND	ND	–
4.20	0.016	0.068	23.0	0.25	ND	2220
0.669	0.005	0.011	0.20	0.03	ND	290
4.60	0.026	0.054	0.87	0.16	ND	10
4.70	0.016	0.047	1.30	0.006	ND	735
5.60	0.014	0.065	1.80	0.10	ND	620

t = trace
ND = not detected
– = not analyzed

The Shepardson Prospect

This short shaft is 425 meters northwest of the Tapley shaft, and is within the same cordierite-anthophyllite hornfels, although here granoblastic texture is more prominent. Dump rocks have sulfide minerals as disseminations throughout, and also in veins and stringers. Layered sulfide minerals occur as random, thin, (< 4 cm) and discontinuous bands of chalcopyrite and pyrrhotite parallel to faint compositional layering, overprinted by growth of large porphyroblasts of cordierite attributable to thermal metamorphism.

TABLE 12

Metal Content of Selected Samples from Shepardson Prospect

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As	ppm Sb
0.178	0.008	0.041	ND	ND	ND	–
0.313	0.010	0.033	0.07	ND	ND	–
0.096	0.010	0.027	0.05	ND	ND	ND
0.013	0.006	0.011	0.05	ND	2650	ND
0.181	0.011	0.063	0.07	ND	–	–
0.241	0.010	0.046	0.06	ND	–	–

ND = not detected
– = not analyzed

The Highland Prospect

In Penobscot Township, north of state route 199, and 8½ kilometers northwest of the Hercules mine, a 90 foot shaft explored a hornfels similar to that at Tapley. As seen on the dumps, the rock type is a cordierite-anthophyllite hornfels, although not as coarse-grained as at Tapley, and with a greater ratio of anthophyllite to cordierite. Extensive exploration drilling by Denison Mines, Ltd. in the mid 1960's suggests lithology equivalent to that of Hercules mine, with fine-grained fragmental rocks intercalated with shaly beds and laminated tuffs. Sulfide minerals occur as disseminations and as veins within the hornfels; massive ore, however, is unknown (Young, 1962).

TABLE 13

Metal Content of Selected Samples from Highland Prospect

%Cu	%Pb	%Zn	o/t Ag	o/t Au	ppm As.	ppm Sb
0.424	0.004	0.017	0.06	ND	ND	-
1.40	0.007	0.033	0.14	ND	ND	-

ND = not detected
- = not analyzed

TABLE 14

Element Ratios of Selected Ores from Sulfide Mineral Occurrences in the Castine Formation

	$\frac{Zn + Pb}{Cu}$
Penobscot Mine	5
Leach Occurrence	5
Hercules Mine	16
North Castine - Emerson	39
Jones - Dodge	24
Eggemoggin Mine	7

Relationships between Sulfide Deposits and Volcanic Stratigraphy

Base metal sulfide occurrences have a consistent relationship to the volcanic stratigraphy of Cape Rosier, and throughout Brooksville Township. Where mines and occurrences are plotted against this stratigraphy (Fig. 3), nearly all are in rhyolitic or upper parts of basalt to rhyolite cycles. Excluding mere showings, layered stratabound sulfide minerals are related spatially to silicic rhyolite domes, as at the Penobscot mine, or to silicic, fine-grained rhyolitic tuffs, as at the Hercules and North Castine-Emerson showings. Proximity of coarse felsic fragmental rocks is almost axiomatic. This relationship between stratigraphic height in a volcanic sequence, coarse felsic pyroclastic rocks, and massive, bedded sulfide minerals is known, and has been thoroughly documented from other regions within rock sequences ranging in age from earliest Precambrian to Tertiary (Sangster, 1972; Sangster and Scott, 1976; Sato, 1974; Franklin, 1976; Spence and de Rosen-Spence, 1976).

Element ratios (Table 14) for analyzed samples from mines and prospects have significant differences. The Penobscot mine and Leach occurrence, within the coarse volcanic assemblage of Cape Rosier, are dominantly copper and zinc rich. Deposits contained within finer-grained volcanic rocks interbedded with reworked volcanic sediment, such as at North Castine-Emerson and Hercules, have considerable enrichment in both lead and zinc relative to copper, and relative to deposits within volcanic centers. Furthermore, the latter type tend to be thinner, but more areally extensive or stratiform, without the pod-like or lenticular geometry of sulfide bodies typified by the Penobscot mine. Although not well-represented in the Castine succession, showings such as the Eggemoggin mine have metal ratios and shapes between Penobscot and Hercules, and appear to be a transitional type. Occurrences such as Highland and Tapley, although contained within fine-grained volcanic and volcanic-derived sedimentary rocks, are not comparable to deposits like Hercules or North Castine-Emerson. Presumably, if layered sulfide minerals did occur above stockworks of sulfide minerals at Tapley, form and metal ratios would be similar to those at Hercules and equivalent deposits because the enclosing rocks are equivalent. The same is true of the Shepardson and Highland prospects.

Stratabound sulfide deposits occur within volcanic rocks accumulated near focused explosive volcanism, and also within volcanic rocks derived from, but some distance from the volcanic focus. Deposits within both the proximal and distal environments have identifiable features that are characteristic and definitive of relative position in the depositional continuum between volcanic center and marginal basin.

Chapter Five

The Ellsworth Formation

Definition and General Geology

Smith and others (1907, p. 1) defined Ellsworth Schist as,

> ". . . highly metamorphic argillaceous sedimentary rocks, prevailingly greenish gray in color, and locally much injected with quartz. They are named from the city of Ellsworth, . . ., near which locality occur abundant exposures typical of the formation."

They considered the Ellsworth Formation to be of Precambrian age, and the oldest rock unit in the region because of more apparent deformation within it than within volcanic rocks of the Castine Formation, or other rock units about nearby Penobscot Bay. Later workers have concurred with the relative stratigraphy proposed by Smith and others (1907), although no consensus exists as to the actual age of the Formation.

Within the area of this study Ellsworth Formation is the dominant layered rock in the Blue Hill quadrangle, east of and flanking the dominantly volcanic rocks of the Castine Formation (Fig. 2). In the Castine quadrangle, Ellsworth Formation is exposed only in the east, although intercalated volcanic and sedimentary rocks on Deer Isle and other islands in Penobscot Bay are considered time equivalent with Ellsworth Formation (Brookins and others, 1973). Volcanic rocks mapped as Ellsworth Formation along Eggemoggin Reach (Wingard, 1961) were mapped as Castine Formation by Smith and others (1907) and Emmons (1910), and because they are not distinguishable from the volcanic rocks of Cape Rosier, herein are considered part of the Castine Formation also.

The characteristic and most widespread lithology within the Ellsworth Formation is a thinly laminated quartz, chlorite, sericite, phyllite, with micaceous minerals defining a well-developed foliation (Plate 15A). Lithic tuffs, graywackes, and subordinate thin flows of basaltic to dacitic composition also occur. There is an overall increase in grain size and proportion of volcanic component within the Ellsworth Formation from east to west. Within the city of Ellsworth, thin-bedded phyllite lacks clasts of volcanic rocks, and volcaniclastic texture and intercalated extrusive rocks are rare. In contrast, west of Blue Hill and in the east part of the Castine quadrangle, volcanic clasts are prominent and there are numerous intercalated tuffs and flows.

Mineral assemblages are characteristic of regional greenschist facies metamorphism, although extensive thermal metamorphic overprinting has taken place near intrusive rocks such as the Sedgwick pluton. Near Blue Hill and within the vicinity of the Blue Hill mine, Ellsworth Formation is impure to pure quartzite, interbedded with about equal volumes of more mafic tuffaceous and pelitic rocks. This distinction between pelites and quartzites becomes less well-defined to the east, and cannot be made 3 kilometers east of Blue Hill.

Phyllite

The prominent and distinctive lithology of the Ellsworth

Formation is what Smith and others (1907) called the Ellsworth Schist (Plates 15A, 15B). It is ~~a~~ ribbon-like, laminated, quartz, chlorite, muscovite phyllite, locally feldspathic, with accessory apatite, epidote, calcite, magnetite, pyrite, and talc. Individual quartz laminae are generally 2-4 mm thick, but can be 10 cm thick, or mere hair-like bands less than 0.1 mm thick. Micaceous layers, usually less than 1 mm thick, separate silica-rich bands and are marked by preferred orientation of sericite or chlorite. Within thermal aureoles of plutons, biotite, chlorite, and epidote predominate, with quartz, andalusite, cordierite, garnet, and sillimanite reported (Jones, 1967). In many localities the foliation in the rock is intensely contorted (Plates 15C, 15D), and wavelengths of minor folds range from millimeters to several meters. Foliation is always parallel or subparallel to compositional layering, even in contorted beds (Plates 15G, 15H).

Quartzite

Although silica is invariably present, rocks with a preponderance of quartz are found only in the vicinity of Second Pond. Three prominent siliceous horizons and many minor siliceous beds, locally biotitic or sulfidic, strike east and dip moderately south. Such siliceous beds host all sulfide occurrences near Blue Hill, including the Blue Hill and Douglas mines. These rock units were noted by Earl (1950), and were described as quartzites by Jones (1967) and later by Cheney (1969). Silica-rich bands are separated by biotite, muscovite, or biotite-muscovite-amphibole layers, which also

PLATE 15

Lithology, Macroscopic, and Microscopic Structure of the Ellsworth Formation

A. Slab of typical Ellsworth Formation; wavelength of prominent folds is about 5 cm. Dark bands are silica and chlorite; light bands are sericite. Scale indicator (partly obscured) is 2 cm long. Sample collected near city of Ellsworth.

B. Close-up of slab in A. Bar is 2 cm long.

C. Contorted Ellsworth Formation typical of exposures along the Bagaduce River Narrows. Light bands are quartz with lesser feldspar; dark bands are biotite with lesser cordierite and andalusite.

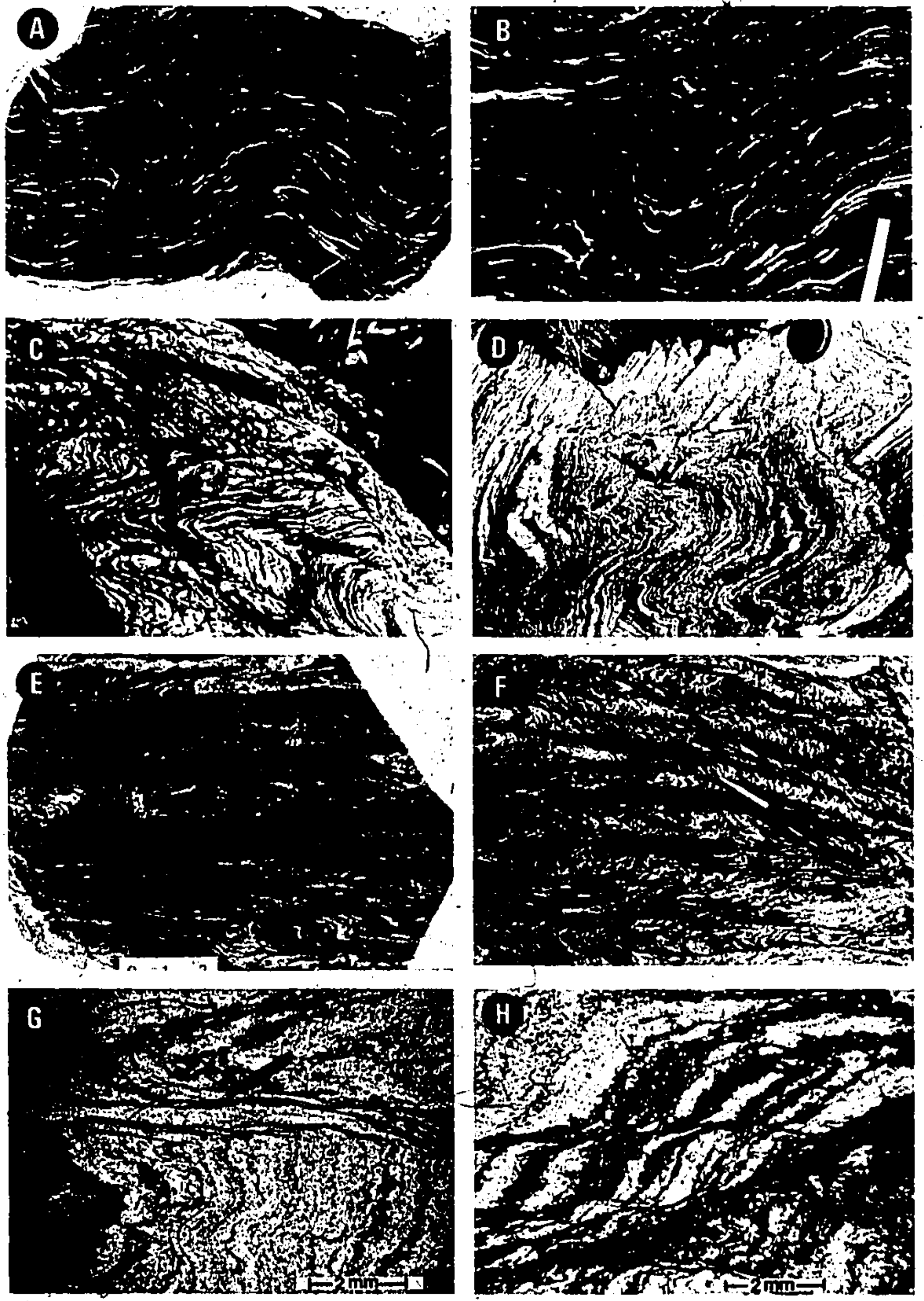
D. More finely laminated than in C; similar mineralogy; lens cap is 5.3 cm.

E. Asymmetric folds with planar interlayers. Light bands are quartz and feldspar, minor sericite; dark bands are biotite and andalusite. Bar is 2 cm long. Sample collected at Bagaduce River Narrows.

F. Similar to E; contorted layers separated by planar features. Pencil is 14 cm long.

G. Photomicrograph of thin section cut from rock in E. Note finely laminated quartz-biotite layers and absence of axial planar features. Plane light.

H. Photomicrograph of thin section cut from rock in F. Finely laminated quartz-biotite bands cut by crenulation cleavage. Plane light.


A
B
C
D
E
F
G
H
2 mm
2mm

impart a foliation. Near the Sedgwick pluton the rock has sillimanite, andalusite, cordierite, microcline, and anthophyllite, in addition to micas and quartz. Pyrite is ubiquitous as disseminations, massive seams, and lenses several centimeters to a few meters thick, and averages 1-5% of the rock. Sulfide content promotes rust-brown weathered surfaces of limonite and goethite.

Basaltic to Dacitic Extrusive Rocks

Within terrain mapped as Ellsworth Formation (Cheney, 1969; Stewart and Wones, 1974)(Figure 3) minor thin flows and tuffs of basaltic to dacitic composition have been described (Jones, 1967). These occur predominantly in a zone separating the Castine and Ellsworth Formations, trending generally north near the boundary between the Castine and Blue Hill quadrangles. Massive flows with blocky or rubbly weathered surfaces, and foliated tuffs and tuffwackes are included. These rocks are indistinguishable in hand specimen and thin section from rocks of equivalent composition or texture within the Castine Formation. Cheney (1969) concluded that distinction is possible because volcanic rocks of the Castine are massive, while those of the Ellsworth are foliated. The progression from dominantly massive to dominantly foliated occurs as the transition from Castine Formation to Ellsworth Formation.

Petrochemistry

Published analyses of rocks of the Ellsworth Formation (Gillson and Williams, 1929), 5 analyses obtained from Kerr-american, Inc., and one analysis made during this study, are between 61 and 75 percent silica (Table 15). Silica contents as low as the basalts (Table 2) or as high as the rhyolites (Table 4) of the Castine Formation are lacking, and average values for the well-laminated quartz-biotite or quartz-chlorite phyllite are between 60 and 70 percent silica. However, all samples are alumina-rich, and over the range of silica contents given for the Ellsworth Formation, corresponding rocks in the Castine Formation have less alumina. Calculations of normative mineralogy for the Ellsworth rocks (Appendix 2) invariably have corundum, which is rare in the Castine Formation. Thus, the comment by Stewart and Wones (1974, p. 236) that,

> ". . . bulk compositions (of the Ellsworth Formation) are not as aluminous as is common in the Castine volcanics."

is invalid.

Structure

As in the Castine Formation, geopetal features such as scour and fill structures, minor cross-bedding, and occasional graded bedding, indicate the section is not overturned. Dips of compositional layers are moderate to gentle, although with various orientations. Broad antiformal and synformal warps with wavelengths of several kilometers have been de-

Table 15: Whole Rock Analyses, Ellsworth Formation Phyllite and Quartzite

	A	B	C	D	E	F	G	H
SiO_2	67.60	70.20	65.02	63.66	69.99	74.49	63.61	61.74
TiO_2	0.499	0.30	0.79	0.52	0.34	0.26	1.64	1.05
Al_2O_3	16.27	15.99	17.78	17.21	14.70	13.73	16.89	17.74
Fe_2O_3	4.30	1.09	2.21	1.74	0.93	1.57	2.59	5.76
FeO	-	2.20	4.17	2.86	2.09	3.46	4.20	5.52
MnO	0.077	0.20	0.45	0.14	0.11	0.09	0.16	0.15
MgO	1.17	3.60	3.71	6.74	9.70	2.02	2.80	2.34
CaO	0.674	0.87	0.72	3.51	0.16	0.26	2.40	0.44
Na_2O	8.18	2.74	3.13	1.65	0.09	1.19	2.22	1.19
K_2O	0.93	2.28	2.01	1.96	1.89	2.92	3.08	3.83
P_2O_5	0.207	-	-	-	-	-	0.40	0.26

Totals recalculated to 100%.

Analysis A by radio frequency induction coupled plasma emission spectroscopy, at Barringer Research, Limited, Toronto, Ontario.
Analyses B through F by J. Descarreux for Kerramerican, Inc.
Analyses G and H by Gillson and Williams (1929).

Sample A collected 2 miles west of Ellsworth on state highway #172.
Sample B: Biotite Quartzite, diamond drill hole 74-83, 1578 to 1592 feet.
Sample C: Banded Quartzite, diamond drill hole 74-8, 1596 to 1618 feet.
Sample D: Banded Quartzite, diamond drill hole 74-8, 1497 to 1562 feet.
Sample E: Quartzite, diamond drill hole 75-23, 454 to 471 feet.
Sample F: Pond Quartzite, diamond drill hole 74-8, 1449 to 1497 feet.
Sample G: Average of 3 samples; not contact metamorphosed.
Sample H: Average of 5 samples; within thermal aureole of Sedgwick Pluton. Locations for G and H not given.

-scribed (Jones, 1967; Cheney, 1969), and steep dips occur around the Sedgwick pluton.

The most obvious structural features are small-scale folds, present at virtually all localities (Plates 15A through 15H). These range in wavelength from fractions of millimeters (Plates 15G, 15H), to several centimeters (Plate 15D), and axes have slight preferred orientation, although in most instances lack symmetry (Plates 15C, 15E). In many localities disturbed beds are enveloped by planar, undisturbed horizons of similar mineralogy (Plates 15E, 15F). Nowhere has axial planar cleavage been observed in minor folds, despite Jones' contention to the opposite. Small lithic clasts and minor breccia beds of coarse to fine volcanic debris, locally prominent, are undeformed. Micaceous minerals are aligned parallel to compositional layering, and maintain this orientation even where wrapped around noses of minor folds.

The prominent foliation in the Ellsworth Formation is interpreted as inherited primary depositional alignment of abundant clay minerals, possibly volcanic ash, intercalated with laminae which are silica-rich, feldspathic, or both. Regional metamorphism to the greenschist facies, preceded by diagenesis, enhanced this planar structure by recrystallization of originally minute crystallites. The general orientation and style of structures in the Ellsworth Formation are analogous to those developed in comparable rock types of the Castine Formation, including fine tuffs, jasper bands, and fine volcanic sediment. Departures from homoclinal orientation are attributable to injection of plutonic rocks with attendant deformation near contacts, and broad flexing of the depositional basin during isostatic readjustments. Asymmetry of minor fold axes and juxtaposition of contorted layers against noncontorted are considered characteristic features of soft-sediment, and not hard-rock, deformation.

Chapter 6

Base Metal Sulfide Deposits in the Ellsworth Formation

The Blue Hill Mine

History and Production

Interest in base metal mining near the town of Blue Hill began with discovery of spectacular azurite and malachite-bearing gossans in the vicinity of Second Pond in the early 1880's (Paul Tapley, personal communication, 1975). Early production from the many small mines included more than 2,000,000 pounds of copper from the Douglas mine between 1878 and 1884 (Rand, 1957). The area was inactive from 1887 until 1917, when, during peak prices for metals, American Smelting and Refining Company produced an unrecorded amount of copper concentrates from a 125 ton-per-day mill at the Douglas mine. Production was curtailed in 1918.

Interest in the properties has waxed and waned with metal prices, and the inability to define large ore reserves in the numerous small workings and prospects, indicated by the proliferation of names and localities tabulated by Young (1962) and Rand (1957). Kerramerican, Inc. has been the sole producer of zinc and copper from underground operations south of and beneath Second Pond, 3 kilometers southwest of Blue Hill (Figure 3). Delineation of sufficient ore reserves to warrant development of the present workings began in 1957 with drilling by Northern Pyrites, Ltd., a wholly-owned subsidiary of Texas Gulf Sulfur. This failed to outline an ore body and the site was dormant until Denison Mines, Ltd. ac-

-quired an interest in the property from Black Hawk Mining Company, and undertook more exploratory drilling leading to discovery of additional reserves. A shaft was sunk during 1964-65 to a depth of 698 feet, with 3 development levels and 10,000 feet of lateral workings. Engineering and economic factors forced curtailment of this work in 1967, prior to any production. In 1970, Kerr-Addison Mines, Ltd. entered a joint venture agreement with Black Hawk Mining, and through the subsidiary Kerramerican, Inc., undertook additional diamond drilling to define more accurately grade and form of ore. A 15 degree decline was driven to intersect the ore, and trackless underground mining methods were initiated. A second decline was driven in 1975 to intersect ore beneath Second Pond, and north of then-existing development. As of June, 1976, Kerramerican, Inc., has milled 793,260 tons containing 7.35% zinc, 0.89% copper, and 0.35% lead, with recoverable silver. With the exhaustion of reserves and a decreasing trend in copper and zinc prices, Kerramerican, Inc., ceased production and placed the mine and mill on a care and maintenance basis on October 15, 1977.

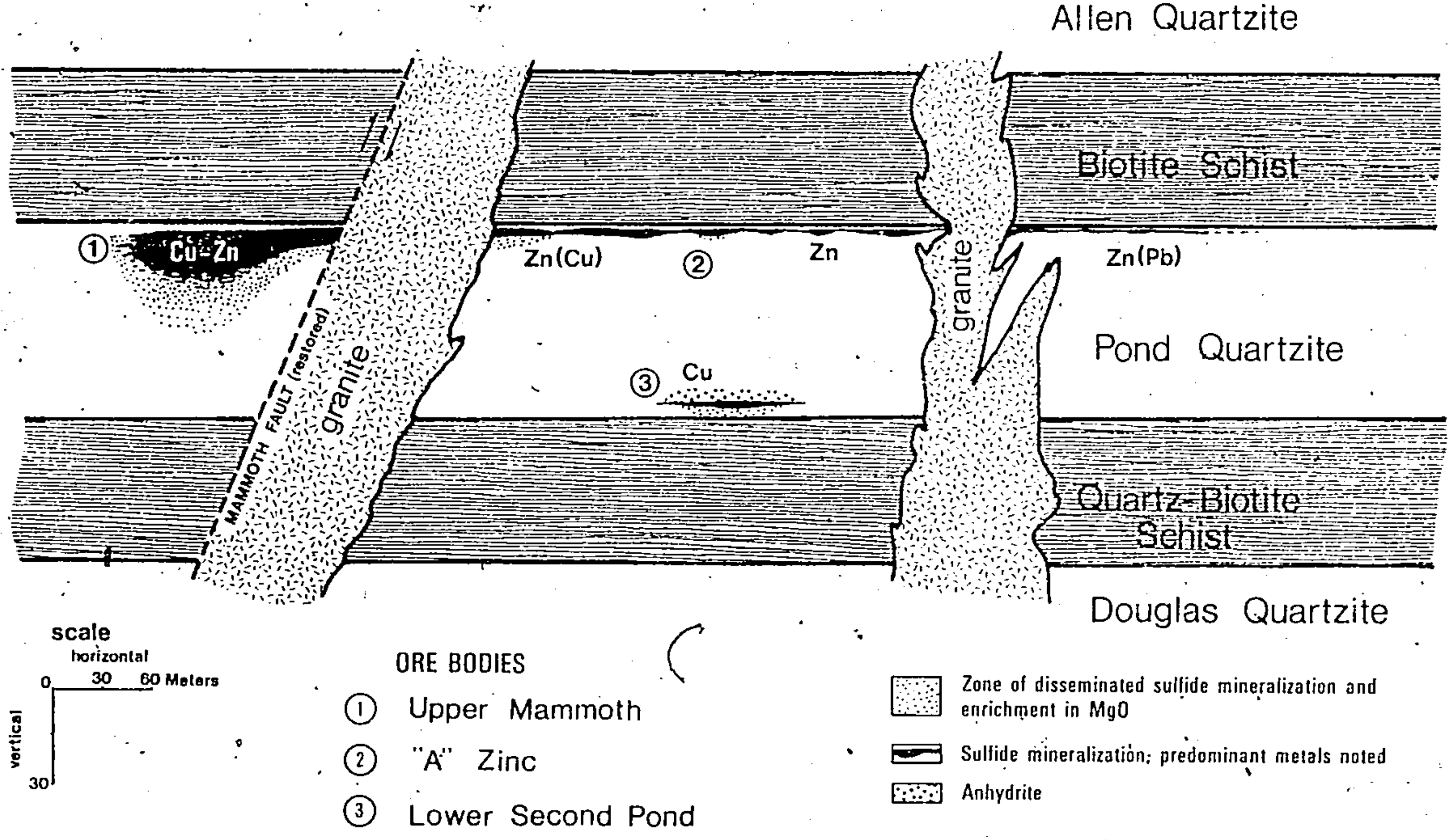
Mine Geology

The Blue Hill mine occurs within a quartzitic unit of the Ellsworth Formation (Plate 16B), within which ore zones are stratabound and broadly stratiform (Fig. 19). This quartzite is from 50 to 120 meters thick, and is enclosed by thin-bedded to massive biotite-rich rocks. The sequence

Figure 19

GENERALIZED EAST–WEST GEOLOGIC CROSS–SECTION, LOOKING NORTH, BLUE HILL MINE

Modified from a drawing by J. A. Pearson, 1977



strikes east, and on average dips 30 degrees south. Development of biotite, cordierite, andalusite, muscovite, anthophyllite, polygonization of quartz grains, and triple point textures in sulfide minerals (Plate 17D), are attributable to contact metamorphism by the Sedgwick pluton (Fig. 3). In addition to quartzite and granofels, quartz-magnetite iron fromation, minor intermediate tuffs, diabase dikes and sills, and irregular gabbro bodies all occur on the mine property. Granitic dikes and sheets derived from the Sedgwick pluton transect the mine sequence, and some pass through bodies of massive sulfide (Plate 16A).

Ore horizons at the Blue Hill mine are localized along the contact between Pond Quartzite footwall, and Biotite Schist hangingwall (Fig. 19), with smaller base metal sulfide concentrations and subeconomic disseminated sulfide minerals scattered throughout the quartzite. Economically significant base metal sulfide accumulations have two modes of occurrence:

1. Within the Upper Mammoth ore body (Fig. 19), sphalerite, chalcopyrite, and pyrrhotite occur as irregular-shaped pods of near-massive sulfide, minor stockwork veins, and most commonly as disseminated sulfide grains or streaks. The sulfide minerals are enveloped by, and intergrown with, magnesian anthophyllite, phlogopite, manganiferous tourmaline, and lesser cordierite. The Upper Mammoth is not a discrete ore body or series of individual bodies, but rather its boundaries are assay-defined. It extends away from the Biotite

Schist contact into footwall quartzite as a zone of magnesium and boron-rich rocks with variable sulfide content, and gradually merges with surrounding quartzite. Most production has come from the upper parts of the zone, closest to the hanging wall contact, where disseminated and minor podlike sulfide bodies were sufficiently numerous to constitute ore. The average of Zn to Cu is about 1:1 (J. A. Pearson, personal communication, 1977).

2. Within the "A" Zinc ore body and its unnamed strike extension on the east, and the underlying Lower Second Pond ore body, sphalerite, chalcopyrite, galena, pyrrhotite, pyrite occur in discrete bands which are stratabound and stratiform (Fig. 19). Contacts between ore and wall rocks are sharp, except along the footwall quartzite at the west edge of the body, where anthophyllite and tourmaline are intergrown with disseminated and banded sulfide minerals. Zn to Cu varies from about 8:1 at "A" Zinc, to probably more than 10:1 on the east, with lead at a maximum of 0.5% on the east (J. A. Pearson, personal communication, 1977). The Lower Second Pond ore body consisted of banded chalcopyrite and pyrrhotite, with minor sphalerite. Other sulfide masses in Pond Quartzite were mined by Kerramerican, but are too far from the line of section to be included in Figure 19. All were discrete bodies of banded sulfides, and most were either copper-rich or zinc-rich. The Carlton ore zone, downdip (south) of the extant workings, has not been mined, but diamond drill hole data indicate nearly 1,000,000 tons of

10% combined Cu-Zn ore. It occurs at approximately the same stratigraphic level as the Lower Second Pond ore zone.

Petrologic and Mineralogic Studies, Blue Hill Mine

The three quartzites of the Blue Hill mine sequence are grey or white, but weather brown because of sulfide mineral content. Typical modes (Table 16) have quartz and biotite as essential minerals, with accessory pyrite, andalusite, cordierite, muscovite, amphibole, and minor magnetite. Oriented micas define a poor to well-developed foliation, depending upon their volume relative to massive quartzite. Locally, sulfide minerals are major components of the rock, and in such instances surround rounded, equidimensional quartz grains (Plate 16B). Size of quartz grains varies, ranging from extremely fine-grained to coarse ragged growths. In many thin sections optically continuous cordierite, with abundant apatite inclusions, conforms with foliation (Plate 16C). Also, thin quartz bands are simply layers of quartz grains one grain thick (Plate 16D). Elsewhere, apparent individual quartz grains merge gradationally with neighboring grains (Plate 16E). Massive quartzite with coarse grains in angular or mosaic-like orientation are interbedded with laminated quartz-biotite or quartz-cordierite rocks. Triple-point 120° grain boundaries are common. Rhythmically alternating quartz and biotite bands, occasionally with magnetite or pyrite laminae, occur in all three quartzites.

Magnesia-rich rocks (Table 15), often containing more than 20% MgO, envelope the Upper Mammoth zone, occur beneath

TABLE 16

Modes of Quartzites near Blue Hill

	A	B	C	D.	E	F	G
Plagioclase	4	5	20	2	1	7	1
Microcline	20					25	50
Quartz	73	93	75	51	65	60	34
Chlorite	tr	tr	4				4
Muscovite	1	1	1	5	4	3	1
Biotite	2	2	tr	5	30	4	2
Sillimanite				2	1		
Andalusite						tr	3
Cordierite				30			1
Actinolite							4
Sulfides				2		tr	tr
Zircon		tr	tr	tr	tr	tr	[illegible]

Sample locations given in Cheney (1969); Data modified from that of Jones (1967) and Cheney (1969).

PLATE 16

Microscopic Features of Pond Quartzite and Related Rocks of the Blue Hill Mine

A. Massive sphalerite from "A" Zinc orebody, intruded by granitic dike bearing xenoliths of partly digested Ellsworth Formation.

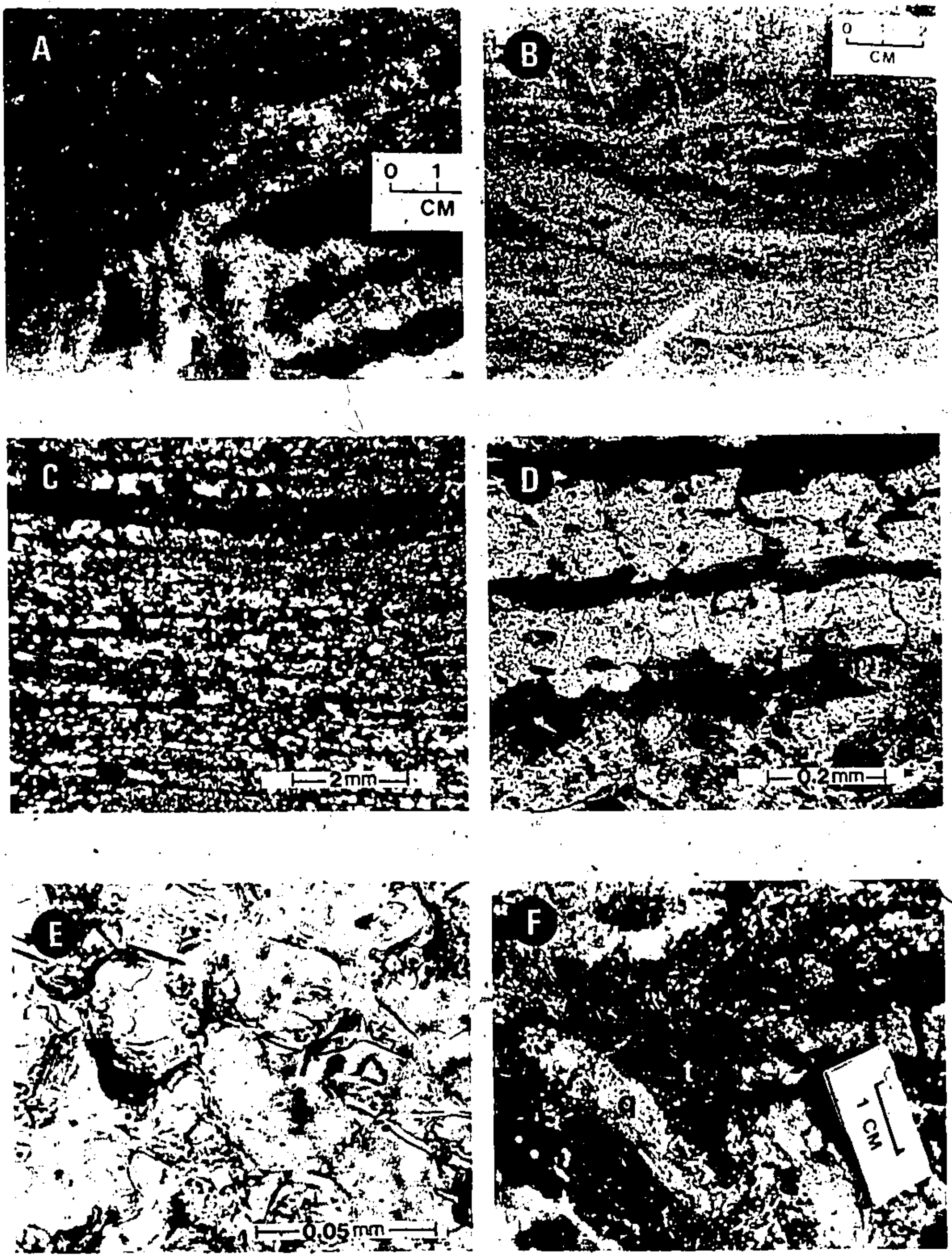
B. Pond Quartzite; bands of pyrrhotite and chalcopyrite surrounding spherical grains of quartz.

C. Pond Quartzite; finely laminated variety from exploration diamond drill hole southwest of Second Pond. Optically continuous cordierite (dark bands) with quartz-rich bands bearing sulfides. Biotite helps define foliation; crossed nicols.

D. Quartz bands, each composed of tabular quartz grains equal to the band thickness, with much included apatite. Biotite with minor amphibole define foliation; plane light.

E. Detail of granular quartz growths of C above. Note poor definition of grain boundaries and unusual grain shapes; plane light.

F. Sheaves of Mn-rich tourmaline (tsilaisite) with intergrown pyrrhotite, chalcopyrite, and quartz vein. Collected on Blue Hill dump.


A
0 1
CM
B
0 1 2
CM
C
2mm
D
0.2mm
E
0.05mm
F
t
a
1 CM

the "A" Zinc zone (Fig. 19), and are also sporadically distributed throughout Pond Quartzite. They are granoblastic intergrowths of cordierite, magnesian anthophyllite, phlogopite, and titaniferous biotite, with or without sulfide minerals. Quartz-tsilaisite (i.e., manganiferous tourmaline) veinlets occur in these magnesian rocks, and commonly chalcopyrite and pyrrhotite are intimately intergrown with tourmaline (Plate 16F).

A small body of anhydrite occurs in the Lower Second Pond copper zone (J. A. Pearson, personal communication, 1977). It is stratigraphically above sulfide-bearing horizons (Fig. 19) and less extensive than these horizons in plan view. A few pieces available for study are random prisms of anhydrite with disseminated euhedral specks of dark blue corundum.

Sulfide Mineralogy

Sphalerite, chalcopyrite, galena, pyrite, and pyrrhotite are by far the most common sulfide minerals at Blue Hill, although minor tetrahedrite, boulangerite, safflorite, pyrargyrite, arsenopyrite, molybdenite, marcasite, gudmundite, and native silver have been described (Petruk and Owens, 1964). Like the ores at Penobscot, individual sulfide laminae can range from minutely thin bands to massive seams or pods tens of centimeters thick. Within parts of the "A" Zinc zone, thicker than average layers of sphalerite with unusually large grain size occur.

Sphalerite is dark brown to black, with mosaic textured aggregates of anhedral individual crystals up to 1 cm in di-

-ameter, although 1 mm is average. In some areas of the mine multiple twinned crystals are common, with bent or kinked twin lamellae. Exsolution of chalcopyrite blebs within sphalerite is widespread and well-developed (Plate 17A), and intergrowths between sphalerite and other sulfide minerals are abundant (Plate 17B). Magnesian rocks beneath the Upper Mammoth zone have sphalerite as subhedral to anhedral, or rarely euhedral, disseminated grains, intergrown with other sulfide minerals or with phlogopite, anthophyllite, or biotite (Plate 17F).

Pyrrhotite and pyrite both occur, although the former is far more common. Pyrrhotite is intergrown with sphalerite and chalcopyrite within ore zones, but most pyrrhotite and pyrite are in uneconomic sulfide-bearing zones within Pond Quartzite. Nearly massive anhedral aggregates of pyrrhotite in places contain irregular patches of slightly anisotropic pyrite (Plate 17C). Triple point 120° grain boundaries are exceptionally well-developed in pyrrhotite (Plate 17D).

Chalcopyrite, pyrite, and pyrrhotite commonly occur together, and especially so as layered sulfide in Pond Quartzite. In many instances rounded to irregular quartz grains are surrounded by ragged patches of pyrrhotite and chalcopyrite (Plate 17E), with minor pyrite or galena. Chalcopyrite is present within magnesian rocks as streaks and blebs, and as irregular fillings between radiating tourmaline crystals. Galena also occurs as disseminated blebs and euhedra within

PLATE 17

Photomicrographs of Ore Assemblages, Blue Hill Mine

A. Oriented exsolution blebs of chalcopyrite in sphalerite, with nearby, ragged, anhedral pyrrhotite (po) containing inclusions of silicates and sphalerite; plane light.

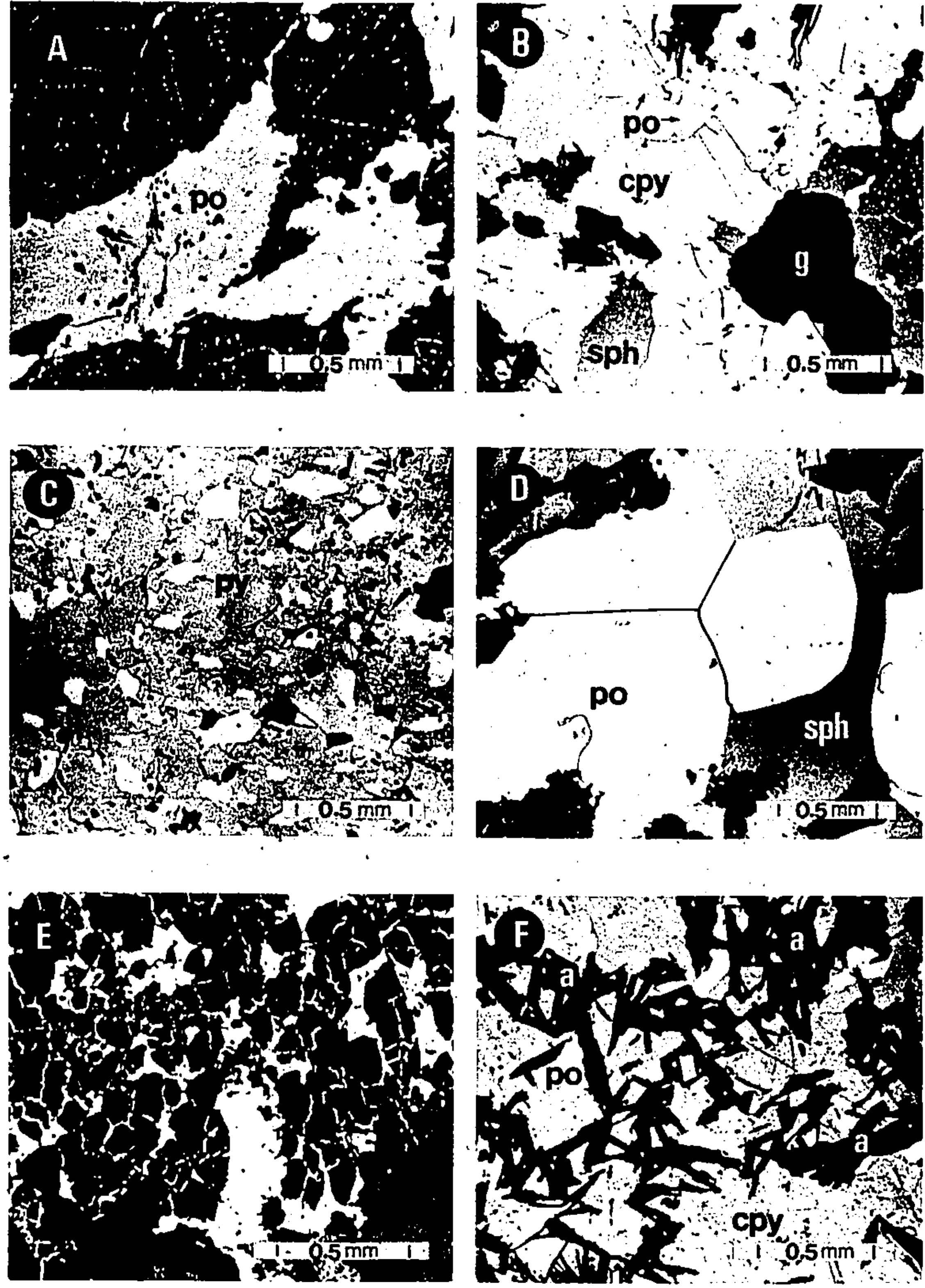
B. Euhedral pyrrhotite grains (po) surrounded by anhedral masses of chalcopyrite (cpy), with nearby patches of sphalerite (sph) and unidentified gangue (g); plane light.

C. Massive polycrystalline pyrrhotite around anhedral grains of slightly anisotropic pyrite, which at the scale of the section are in optical continuity; crossed nicols.

D. Triple point boundary boundary between three pyrrhotite crystals (po; grain boundaries accented with inked lines) surrounded by structureless sphalerite; plane light.

E. Ragged to subrounded grains of quartz surrounded by chalcopyrite and pyrrhotite (not distinguishable); plane light.

F. Granoblastic intergrowth of chalcopyrite (cpy), pyrrhotite (po), anthophyllite ([illegible]), with minor phlogopite; plane light.


A
po
0.5 mm
B
po
cpy
g
sph
0.5 mm
C
py
0.5 mm
D
po
sph
0.5 mm
E
0.5 mm
F
a
a
po
a
cpy
0.5 mm

magnesian rocks, and as small grains within concentrations of sphalerite and chalcopyrite. Some coarsely crystalline galena occurs sporadically in the Lower Second Pond zone.

The Deer Isle Mine

A house has been constructed over the abandoned shaft of the Deer Isle mine, located at tidewater on a prominent point in northwest Deer Isle (Fig. 3). The rock sequence is thinly bedded sedimentary rocks of volcanic derivation, considered Castine Formation by Smith and others (1907) and later by Emmons (1910), but redefined by Stewart (1956) as equivalent to Ellsworth Formation. Judging from meager specimens on an overgrown dump, and prior descriptions (Emmons, 1910), the ores were rich in zinc and lead, with lesser chalcopyrite and pyrite (Plates 14E, 14F). The sulfide minerals were associated with a very thinly layered microcrystalline rock consisting of albite and minor quartz, with streaks of magnetite, stilpnomelane, and pyrite (Plates 14G, 14H). The stilpnomelane and clusters of porphyroblastic actinolite have developed in the rocks because of proximity to the Deer Isle Granite. Fractured pyrite healed by chalcopyrite (Plate 14F), and deformed cleavage lamellae in galena, probably also are attributable to contact metamorphic effects.

The Douglas Mine

The abandoned workings of the Douglas mine are on the north shore of Second Pond (Fig. 3), about 600 meters from the Blue Hill mine. Chalcopyrite and pyrrhotite are strata-

-bound within the Douglas Quartzite (Fig. 20), which is about 50 meters stratigraphically below the Pond Quartzite, and underlying the Biotite Schist. Copper showings were discovered as early as 1868, and American Smelting and Refining Company produced at least 2,000,000 pounds of copper (Rand, 1957). Zoning, grade, and relationships with country rocks are unknown, but samples of copper-rich quartzite collected near an open stope closely resemble quartzite ores of the Pond Quartzite.

Other Occurrences

Rand (1957) and Young (1962) have tabulated and located the numerous prospect pits and abandoned mines in the Blue Hill area. The majority are within a 1 kilometer radius of Second Pond, and most are in the overlying Allen Quartzite (Fig. 19). Most of those in Pond Quartzite are surface projections of sulfide minerals mined underground by Kerramerican. In addition, both authors locate old workings in Ellsworth Formation east of Second Pond, along the shoreline south of Blue Hill Harbor, and farther south on Blue Hill Neck. The largest of these generally contained several tons of massive sulfide, usually pyrrhotitic, within Siliceous Ellsworth Formation similar to the mine quartzites, although not continuous with them. Silica content and size of sulfide mineral occurrences decrease with distance from the vicinity of Second Pond. Showings along the shoreline 5 kilometers from Second Pond are within typical Ellsworth Formation; that is, chloritic phyllite. Such showings consist of stratabound streaks and small pods of sulfide minerals.

Genesis of Sulfide Deposits in the Ellsworth Formation

Discussion

In subaqueous volcanic-sedimentary successions, compositional variations in volcanic products at the volcanic centers are manifested in the sediment accumulated in a flanking basin. Volcanic material supplied to that basin from multiple sources is homogenized by processes of sedimentation, and the rocks become flyschoid facies (Sangster and Scott, 1976). It also appears likely that brines charged with silica and metals and like those outlined as important for genesis of massive sulfide at volcanic centers, are deposited in this basin. These exhalations can add chemical sediment and hence a departure from the generally monotonous sequence of flysch sedimentation. Such a model accounts for quartzites and attendant base metal sulfide bodies of the Blue Hill deposits. This is attractive because it unifies all data into a simple, single model, as outlined below.

The Genetic Model

Brines were discharged in a broad transitional zone between volcanic rocks and volcaniclastic sediments. At times the brines were silica-rich, and at times metal-rich, and three quartzites are interpreted as chemical sedimentary horizons. Nearest the brine discharge site quartzites are purest silica, and thickest. Influx of fine ash from the central volcanic provenance of the Castine Formation made pelitic layers within the siliceous chemical sediments. Decreasing concentration of silica away from the brine discharge site, combined with an increasing component of detritus, produced localized quartzites within the Ellsworth Formation. Major episodic periods of brine discharge are represented by the three main quartzite horizons at the Blue Hill mine, with intervening periods of quiescence and clastic basinal sedimentation. Short-lived episodes of exhalation produced the thin siliceous bands within Biotite Schist and mafic rocks underlying Pond Quartzite (Fig. 19). Size and grade of sulfide deposits in this succession are functions of brine chemistry (Large, 1977), duration of brine discharge, and ambient conditions at the site of emission. Passageways through which brines migrated to the sea floor are zones enriched in volatile constituents such as halogens, boron, and water, as well as magnesium and manganese. The Mg-rich rocks enveloping the Upper Mammoth zone are attributed to such processes. In brief, massive base metal sulfide accumulation occurred in the area of discharge because:

1. Temperature of the brine was reduced through contact with seawater so that metal ions became insoluble, and;
2. Changes in brine chemistry were induced through mixing with seawater, involving changes in pH and Eh conditions, so that metal ions became insoluble.

Lateral and vertical zoning within the ore bodies of the Blue Hill mine, common in many occurrences, (Sangster, 1972;

Sangster and Scott, 1976; Large, 1977), reflect such changing conditions. Infilling of local depressions on the depositional surface by dense precipitated sulfide minerals made pods of uneven thicknesses.

Subsequent intrusion of the Sedgwick pluton induced textural changes in the stratigraphic succession. Contact metamorphic minerals grew within pelitic and siliceous horizons according to the compositions of the individual horizons. Thus, the former discharge zone contains Mg-rich anthophyllite, tourmaline, Ti-rich biotite, and phlogopite. Continuous chert horizons were broken into irregular grains bounded by polygonal cracks, although optically continuous bands were in some instances preserved, and some minute laminae were broken into layers one grain thick. Within pelitic horizons biotite, andalusite, cordierite, and amphibole grew in granoblastic habit, although in many instances preserving mimetically the original layered fabric inherited from early compactional alignment of sheet silicates. Sulfide minerals were annealed, with increase in grain size, exsolution of incompatible phases during retrograde cooling, and twinning of pyrrhotite and sphalerite.

Chapter 7

Re-Evaluation of Castine - Ellsworth Relationships

Investigations into the nature of stratabound ore deposits in the east Penobscot Bay region suggest there is a continuum in which copper-zinc deposits formed at volcanic centers give way to deposits of zinc and copper with or without lead in flanking basins. The transition from the Penobscot mine, through Hercules, to the Blue Hill mine exemplifies this transition. This series suggests that the Castine and Ellsworth Formations are merely proximal and distal manifestations of the same volcanism, and as such are time equivalent and lithologically transitional with one another.

To further investigate this possibility, field mapping was undertaken at several critical localities and on various scales. Two of the critical exposures where Castine Formation is in inferred unconformable contact with Ellsworth Formation were remapped at one inch equals ten feet (Fig. 20). The first locality is stop 9 of the New England Intercollegiate Geology Conference field trip B-7 (Stewart and Wones, 1974). The second, necessitating two separate map segments, is one kilometer west-northwest of stop 9 across the Bagaduce River (Figs. 21-23).

Wingard (1958) first described coarse clastic rock at Stop 9 as a conglomerate at the base of the Castine Formation, developed by erosion of already existing Ellsworth Formation and incorporation into basal flow units. This coarse clastic

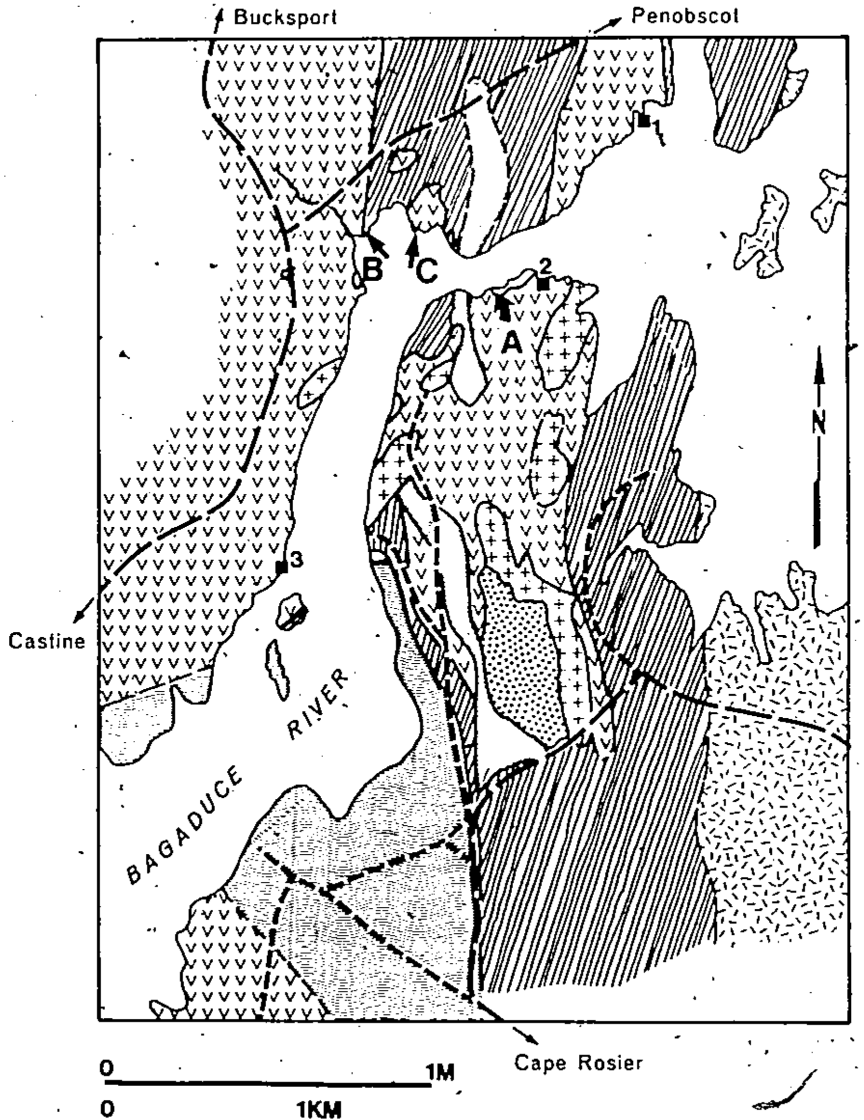
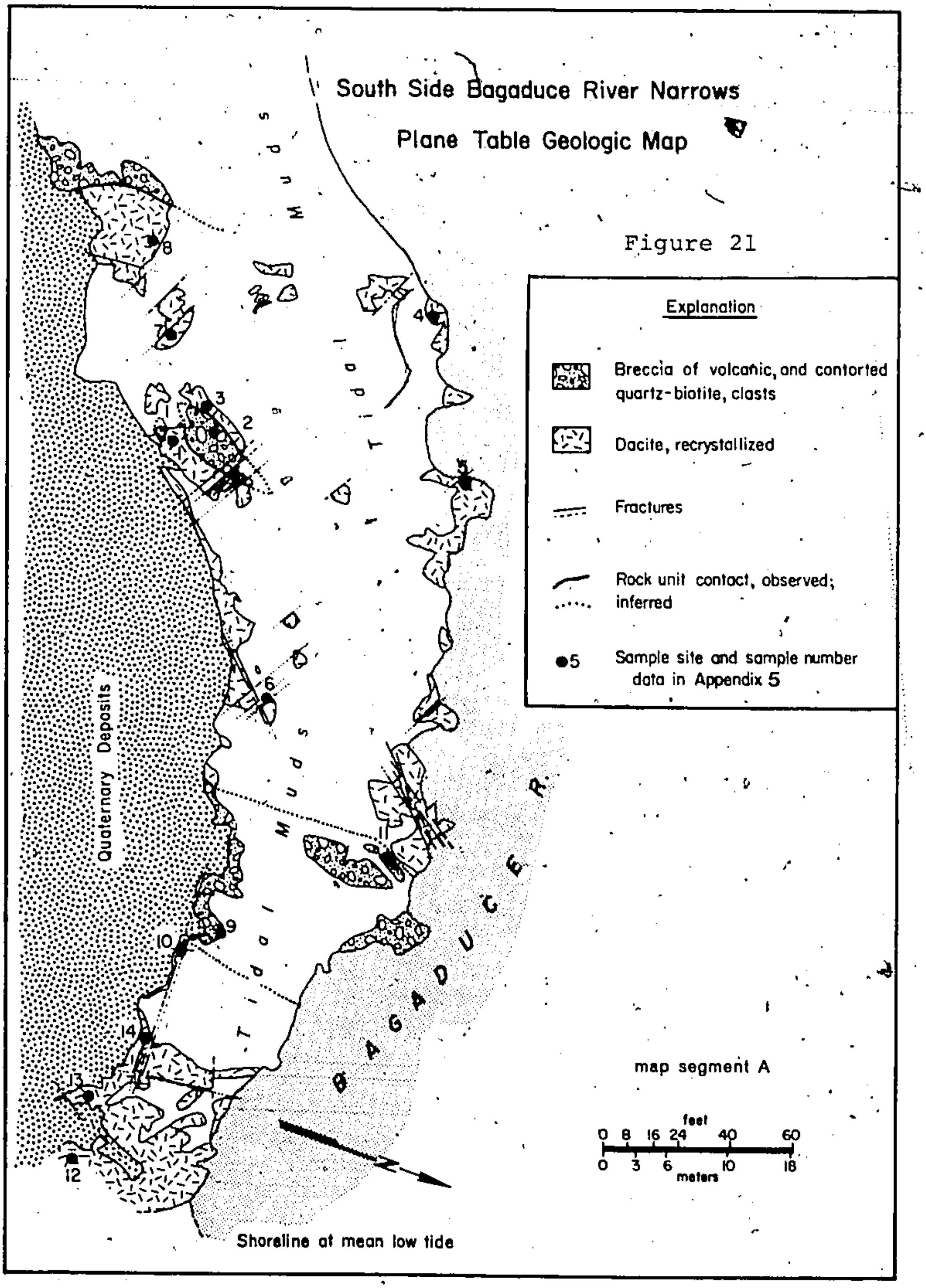


Figure 20
Location Geologic Map for Detailed Mapping Localities, North and South Sides Bagaduce River Narrows, Brooksville, Maine
after Stewart and Wones (1974)

▨	South Penobscot pluton
▨	Ellsworth Formation
☐	Penobscot Formation
▨	Castine Formation, undifferentiated
▨	Rhyolite and rhyolite porphyry
▨	Diabase, diorite, andesite
☐	Foliated amphibolite
———	Contact, dashed where inferred
— · —	Primary road
- - -	Secondary road
↖A	Location of detailed map segment
■1	Hercules mine
2	Jones-Dodge prospect
3	North Castine-Emerson prospect



South Side Bagaduce River Narrows

Plane Table Geologic Map

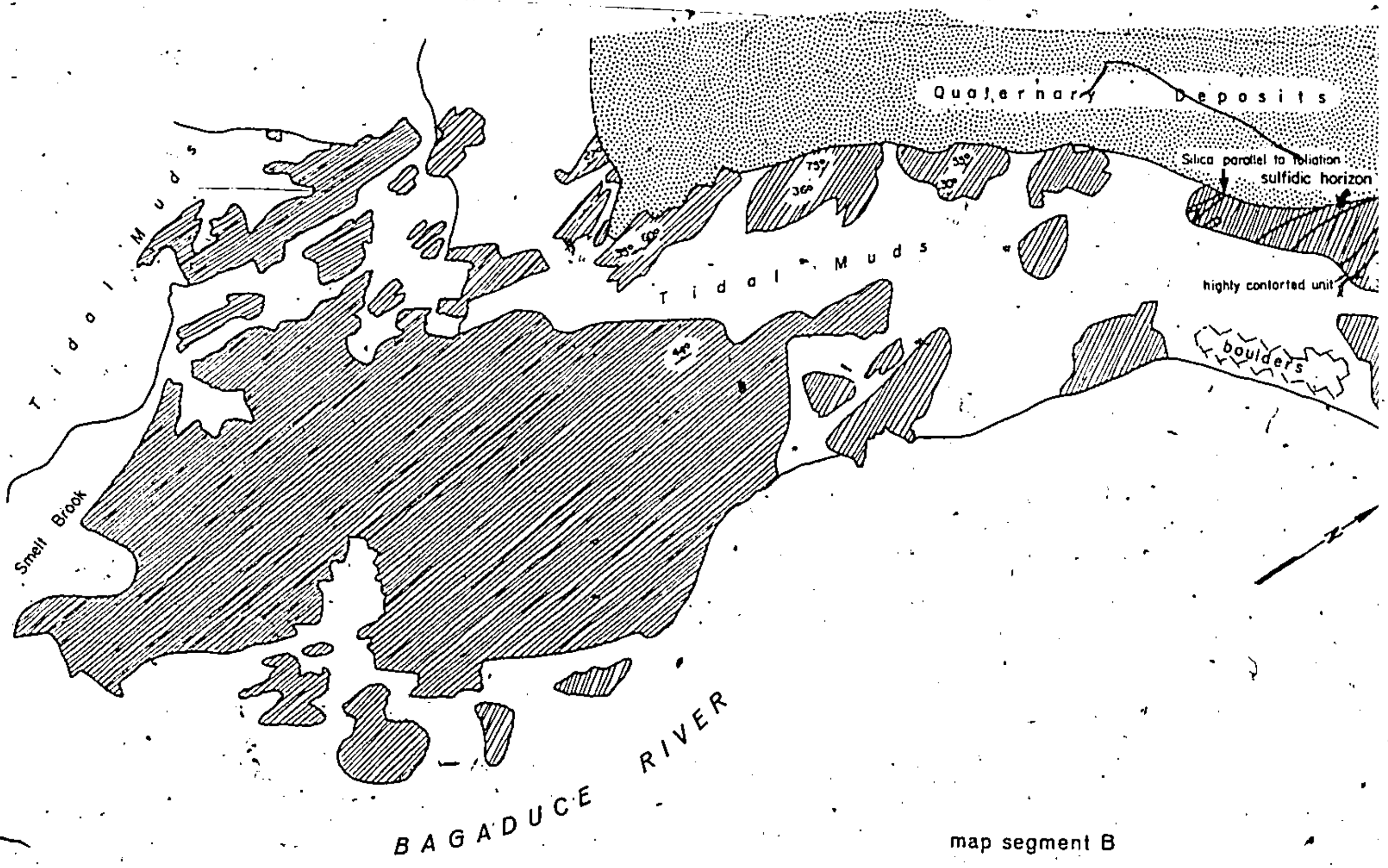
Figure 21

rock consists of angular, randomly oriented phyllite fragments, clasts of rhyolitic to dacitic volcanic rocks, and bent and broken feldspar crystals. Field relationships shown by detailed mapping at Stop 9 lead to re-interpretation of this rock as an intraformational conglomerate, full of immature clasts, which is repeated as three distinct and mappable horizons within the local sequence of Castine volcanic rocks (Fig. 21). The nature of the clasts in these horizons, and the presence of three mappable units, indicate that the rock is neither basal conglomerate nor fanglomerate, but rather a series of volcanic mudslides or similarly derived mass flowage deposit, derived from some nearby volcanic edifice.

At the second locality rock types of the Castine and Ellsworth Formations are in apparent fault contact (Figs. 22 and 23). Ellsworth Formation here is finely banded metasedimentary rocks which are highly contorted and exhibit preferred orientation of layer silicate minerals. Principal mesoscopic structures are crenulation folds and kink bands with varied geometry and disposition, characteristic of deformation in mechanically anisotropic rock (Cobbold and others, 1971). Intraformational conglomerates within this buckled rock contain boulders and cobbles of Ellsworth Formation, and at one locality, volcanic clasts indistinguishable from rocks of the Castine Formation. Folds within individual boulders are misoriented with respect to folds in neighboring boulders and in adjacent phyllites.

Well-bedded and finely laminated tuffaceous horizons

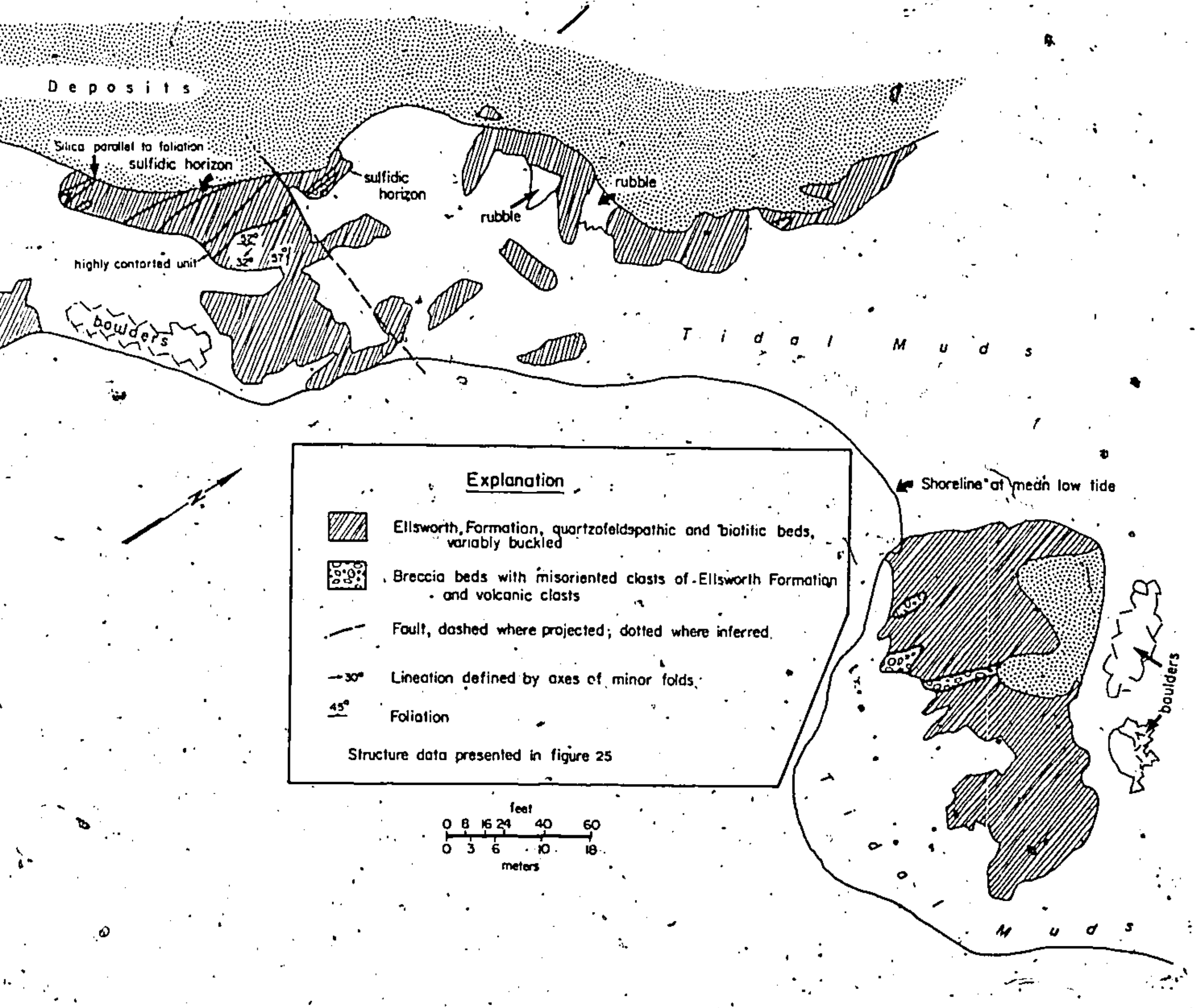
North Side Bagaduce River Narrow
Plane Table Geologic Map



map segment B

e Bagaduce River Narrows
Table Geologic Map

Figure 22



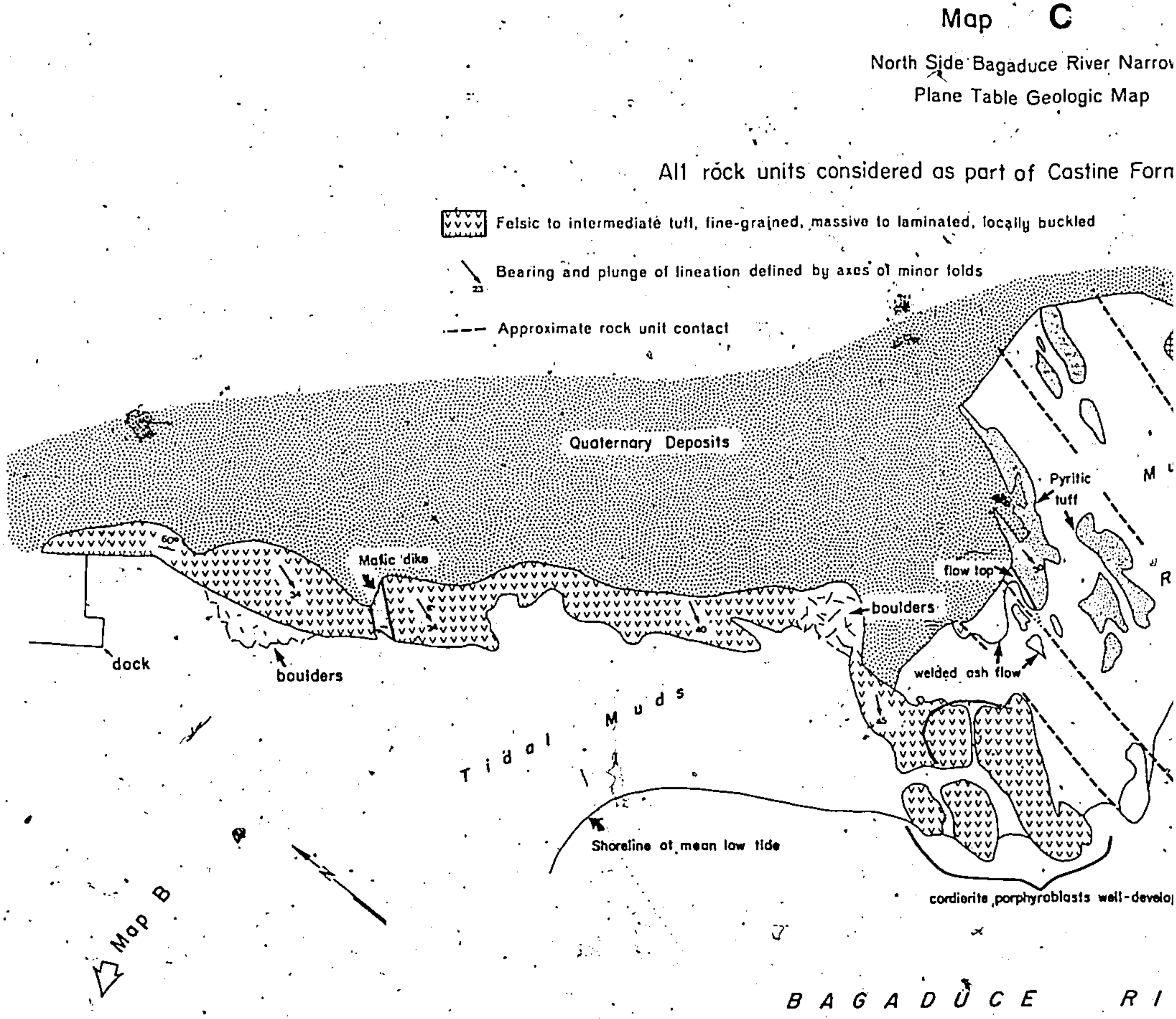

Map C
North Side Bagaduce River Narro
Plane Table Geologic Map
All rock units considered as part of Castine For
Felsic to intermediate tuff, fine-grained, massive to laminated, locally buckled
Bearing and plunge of lineation defined by axes of minor folds
23
Approximate rock unit contact
Quaternary Deposits
Pyritic tuff
flow top
Mafic dike
boulders
boulders
dock
welded ash flow
Tidal Muds
Shoreline at mean low tide
cordierite porphyroblasts well-develo
Map B
N
BAGADUCE RI
M
R
60
34
34
40
45

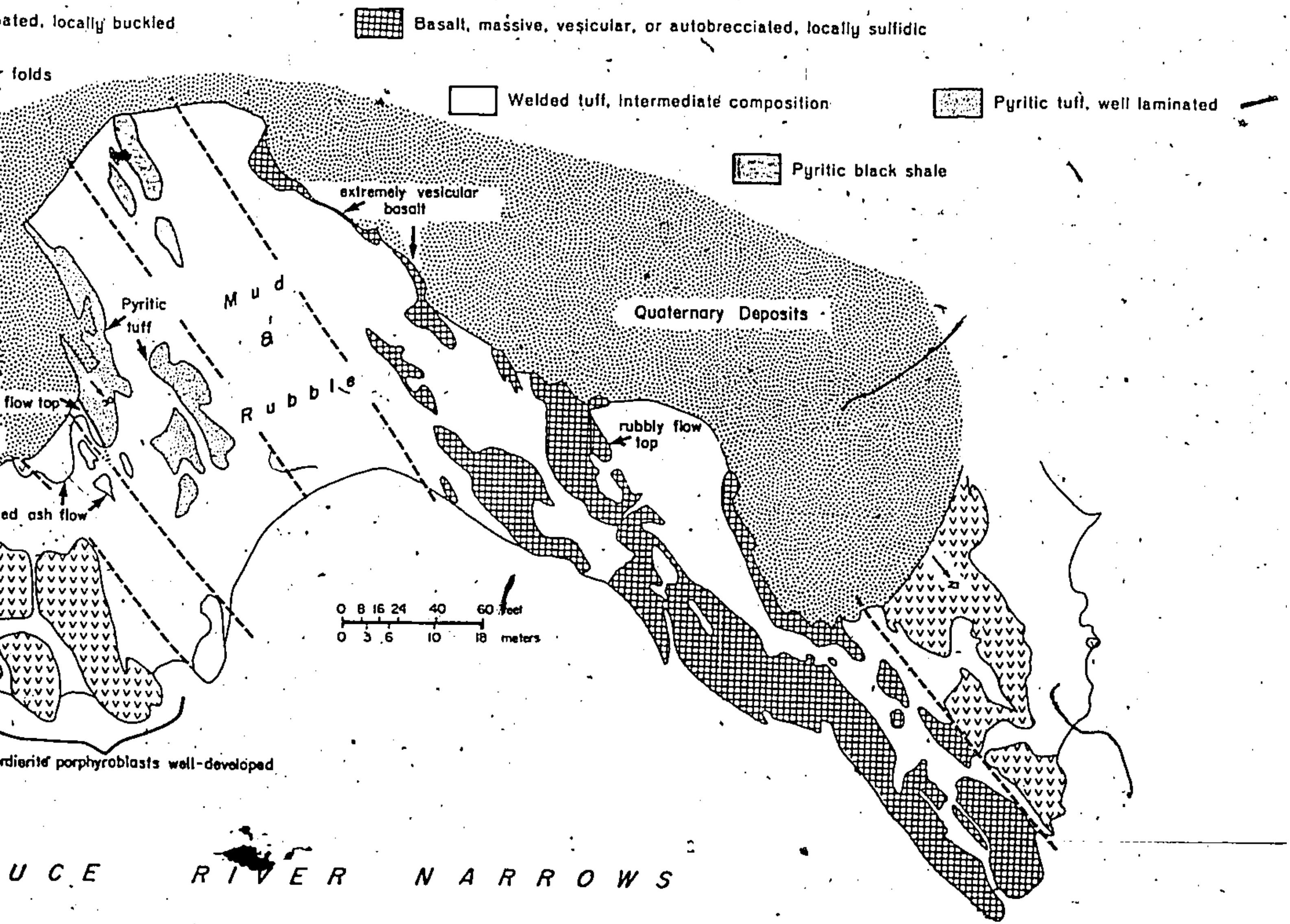
Figure 23

Map C

Side Bagaduce River Narrows

ane Table Geologic Map

as part of Castine Formation by Cheney (1967) and Stewart and Wones (1974)



mapped as Castine Formation (Wingard, 1961; Cheney, 1969; Stewart and Wones, 1974) are juxtaposed against Ellsworth Formation in this second area. Crenulation folds and kink bands are ubiquitous in these rocks, as in adjacent Ellsworth Formation. Axes of minor folds in rocks of both formations plot within the same field (Fig. 24). Furthermore, there is no evidence of refolding of structures in Ellsworth Formation, which should be apparent if both formations were deformed subsequent to a previous deformation of Ellsworth. The contention by Stewart and Wones (1974, p. 237) that rocks of the Castine Formation

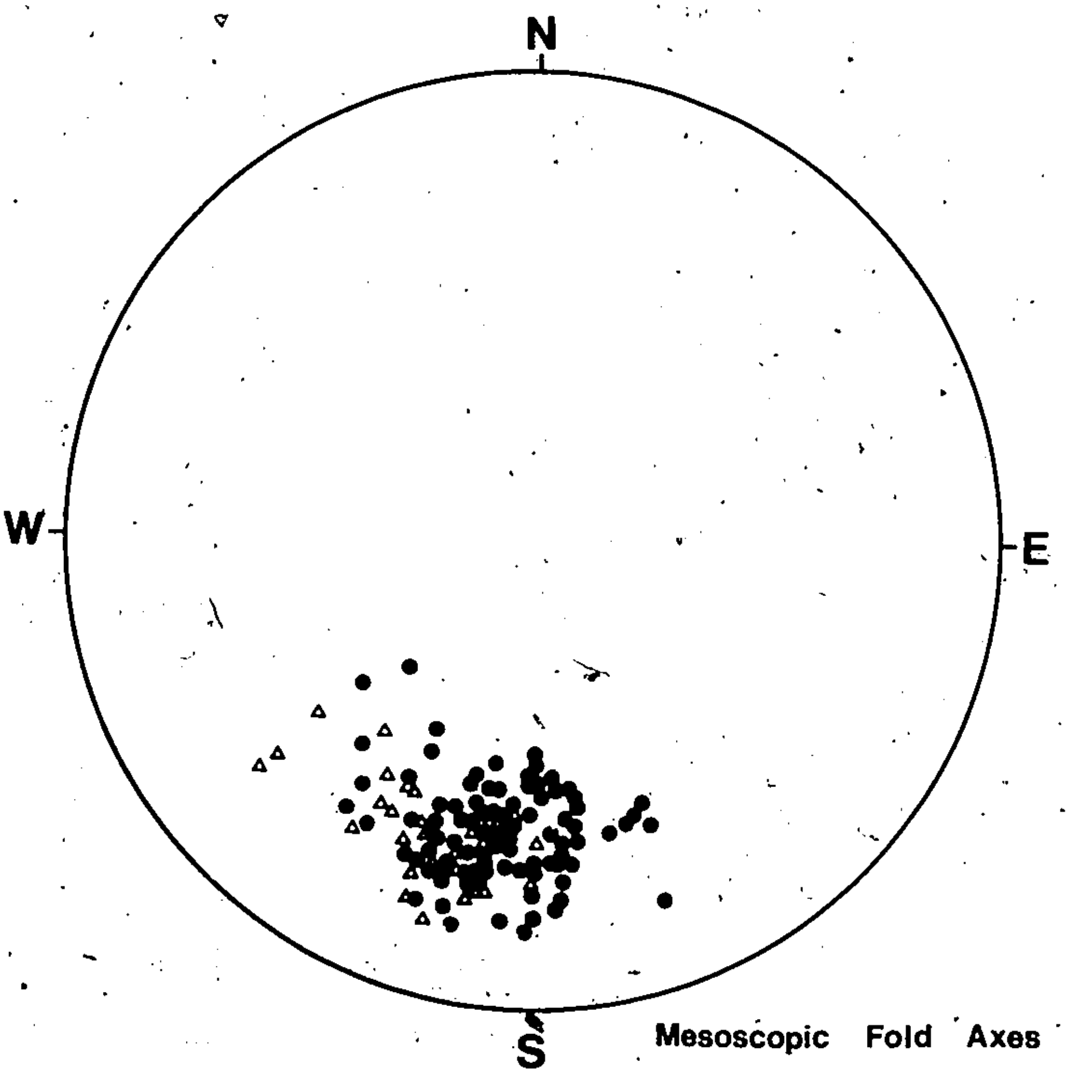
> ". . . are distinct from Ellsworth rocks, because, though foliated, they lack the lineations of the multiply deformed Ellsworth, . . ."

cannot be held correct when structures in mechanically equivalent lithologies are compared.

In conjunction with analyses of mesoscopic structures, microstructures of folds in several rock types were also studied. Sericite and chlorite of greenschist metamorphic facies mimetically overgrow previously folded bedding, and now define the dominant mesoscopic fabric. Minor folds are without axial surface cleavage, in that layer silicate minerals of metamorphic origin do not have axial surface orientation, but rather remain parallel to primary layering. These structural and metamorphic relationships indicate that greenschist metamorphism is post-folding of the Ellsworth Formation.

FIGURE 24

Structure Data
North Side Bagaduce River Narrows



Mesoscopic Fold Axes

● **ELLSWORTH**

△ **CASTINE**

equal area projection, lower hemisphere

Ubiquitous fracturing along hinges of crenulation folds and kinks, coupled with microfracturing of clasts and pebbles of volcanic rock, is consistent with deformation under conditions of low temperature and low effective confining stress (Cobbold and others, 1971). Conversely, absence of optical features associated with dislocation creep in quartz (White, 1973), and of pressure solution fabrics in crenulation folds (Ramsay, 1967, p. 179; Williams, 1972) argue against deformation at elevated temperatures during metamorphism. Considerations of microstructures and post-depositional mimetic textures at the two localities along the Bagaduce River Narrows indicate folding of Castine and Ellsworth Formations took place prior to metamorphism, and presumably was accomplished by gravitational sliding off a subaqueous edifice.

Isotopic Studies

Brookins (1976) obtained a 510 ± 10 m.y. isochron age for Ellsworth Formation in the general vicinity of Ellsworth. This age is considerably older than the 395 to 424 m.y. ages established for the duration of Castine volcanism (Brookins, 1976), which also are in agreement with the paleontologic dating (Brookins and others, 1973). However, lead isotopic data for galena separates from the Penobscot, Hercules, and Blue Hill mines all have essentially the same ratios (Table 17), and model lead and isochron ages for all three galena separates are equivalent to the generally accepted ages for the Castine Formation. Moreover, the equivalence of lead

Table 17

Lead Isotope Data

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Penobscot mine	18.029	15.591	37.844
Hercules mine	18.079	15.609	37.919
Blue Hill mine	18.072	15.612	37.920
Silver Wave, Acton*	18.458	15.640	38.346

Penobscot sample collected from underground workings in 1970 by R. W. Hutchinson, and consisted of rhyolite veined by sphalerite and galena veinlets

Hercules sample collected from waste dump around Hercules shaft in 1976, and consisted of near massive sphalerite and galena with lesser pyrrhotite and chalcopyrite.

Blue Hill data from sample collected by Dr. B. Doe, as is galena from Devonian fracture filling Silver Wave deposit.

Data were obtained at the United States Geological Survey, Branch of Isotope Geology, by the triple filament, thermal emission technique, and should be within 0.1% of absolute (B. Doe, personal communication).

<u>Age computations</u> (B. Doe, personal communication)

	Isochron age	$^{208}Pb/^{204}Pb$ model age
Penobscot	425 my	425 my
Hercules	425 my	385 my
Blue Hill	425 my	385 my

*Silver Wave is a Devonian fracture filling, York Co., Maine isotopic ratios for all three suggests a broadly coeval origin for the leads, and therefore for the enclosing strata; or at least closer in time than Siluro-Devonian versus Cambro-Ordovician. Resolution of these apparently contradictory data probably is in the time-transgressive nature of the Ellsworth Formation. Alternatively, the suitability of regionally metamorphosed pelitic and volcaniclastic rocks for rubidium-strontium dating may also be questioned.

The interpreted tectono-stratigraphic relationships between the Castine, Ellsworth and Penobscot Formations are envisaged as representing development of a volcanic island in an existing flysch basin, with persistence of the basin beyond the life span of active volcanism. Thus, volcanic sediments derived from Castine Formation were volumetrically important only adjacent to the volcanic accumulation, and for a limited time interval.

Chapter 8

Conclusions

1. The Castine Formation is a differentiated sequence of volcanic rocks with minor intercalated volcanogenic sediment. Mafic, intermediate, and felsic rock types are equally represented on Cape Rosier, and mafic rocks are dominant in south Penobscot Bay. Cyclicity in volcanic products is evident on Cape Rosier, where mafic rocks are overlain by successively more felsic rocks, culminating in felsic fragmentals and dacite, rhyodacite, and rhyolite lava domes. East of Cape Rosier the Castine succession becomes finer grained, with an increase in tuffs, fine fragmental, and volcanogenic sedimentary rocks. There is a corresponding absence of lava domes, coarse breccias, and thick, massive flow units.

2. Base metal sulfide occurrences on Cape Rosier are localized in the felsic parts of volcanic cycles, and bedded massive sulfide bodies are associated with rhyolite domes which were intruded into a shallow water environment. Ore genesis involved phreatomagmatic explosions related to dome emplacement. Meteoric brines circulated through shattered domes and derived explosion breccias, with subsequent precipitation of complex chemical sedimentary horizons which include massive sulfide. The Penobscot copper-zinc deposit is the type example of deposits formed in this environment, and closely resembles Kuroko deposits in the Green Tuff region of Japan. Deposits of this type in southeast coastal Maine are primarily copper and zinc. Sulfide mineral occurrences

east of Cape Rosier, in the finer grained, more sedimentary part of the Castine Formation, are associated with felsic tuffs, are more stratiform than those on Cape Rosier, and have greater zinc and lead relative to copper. The Hercules and North Castine-Emerson deposits are examples.

3. The Ellsworth Formation flanks the Castine Formation, and consists of sedimentary rocks of obvious volcanic derivation, with minor flows and tuffs. The Ellsworth Formation is demonstrably richer in volcanic component on the west, and in the vicinity of Bagaduce Narrows characteristic Ellsworth Formation and fine-grained Castine Formation are in contact. Contorted clasts of Ellsworth Formation are contained within volcanic breccias typical of the Castine succession. Elsewhere the contact appears transitional, and at some localities the two formations may be in fault contact.

4. Ore deposits in the Ellsworth Formation are stratiform and enriched in zinc and lead relative to those in the Castine Formation. The Blue Hill mine of Kerramerican is typical, and is believed to have formed through exhalative brine discharge processes analogous to those proposed for the Penobscot mine.

5. The continuum represented by changing form and metal assemblage in proceeding from base metal deposits in the Castine Formation to those in the Ellsworth Formation is viewed as the progression from proximal volcanic environment to distal flanking basin receiving volcanic sediment.

6. Detailed remapping of critical exposures where

Ellsworth and Castine rocks are in contact reveals a normal stratigraphic succession, and not a basal Castine conglomerate deposited on a previously metamorphosed Ellsworth terrane, as earlier described (Wingard, 1958; 1961; Stewart and Wones, 1974). Deformation occurred prior to greenschist facies metamorphism, and therefore is penedepositional, and probably of soft-sediment origin. Comparison reveals that structures in mechanically equivalent rock masses, whether in Castine or in Ellsworth Formations, are identical. Furthermore, similar orientations of minor structural elements in both formations suggests that whatever processes produced these structures occurred in both at the same time. Therefore, age distinctions based upon differing structural orientations and elements are invalid. It is concluded that at the Bagaduce River Narrows locality, long considered a critical location in establishing the younger Castine and older Ellsworth age relationships, these two rock series are time equivalent.

Radiometric age determinations for samples of Ellsworth Formation collected near Ellsworth yield significantly older ages than those determined for the Castine Formation lavas on Cape Rosier. Lead isotopic data for galena separates from the Penobscot and Hercules deposits within the Castine Formation, and the Blue Hill mine within the Ellsworth Formation, indicate, however, that the ore leads are coeval. The syngenetic nature of the deposits dictates the time equivalence of their enclosing rocks. Assuming reliability in the two iso-

-topic dating methods, the differing Ellsworth ages are resolvable if the Ellsworth Formation is considered time-transgressive.

APPENDIX 1

LOCATIONS AND BRIEF DESCRIPTIONS OF SAMPLES ANALYZED FOR TABLES 2, 3, 4, 5

UTM designation refers to coordinates on Universal Transverse Mercator Grid.

Exact Locations for all samples collected during this study are on file in the Geology Department thesis collection at the University of Western Ontario.

Column 1: Field designation, as shown on maps in thesis collection
Column 2: Letter designation in appropriate table
Column 3: UTM coordinates
Column 4: Brief petrologic description

Table 2

1	2	3	4
Ca-7	A	4910.8/514.3	Basalt; dense, massive, chloritic; traces pyrite.
Ca-38	B	4908.1/514.2	Basaltic agglomerate; variable fragment sizes and shapes, but all basaltic; matrix chloritic and foliated, originally glassy.
Ca-137	C	4910.6/518.2	Basalt; massive with scoriaceous flow top, chloritic.
Ca-149	D	4911.7/519.5	Gabbro; massive, coarse-grained, structureless; large pyroxene crystals altered to chlorite.
Ca-226	E	4911.9/518.0	Basalt; highly amygdaloidal with calcite and quartz fillings; much groundmass chlorite.
Ca-326	F	4894.3/518.4	Basalt; massive, structureless, chloritic, fine-grained.

1	2	3	4
Conpil	G	4908.4/520.4	Basalt; pillowed and amygdaloidal with relict glassy rims and concentric flowage structures. Incipient growth of granoblastic biotite due to proximity of Sedgwick Granite. Much groundmass biotite.
Bh-26	H	4909.7/520.7	Basalt, dense, structureless; much granoblastic biotite growing in groundmass at expense of earlier greenschist facies chlorite.
Cordant	I	4912.6/520.6	Cordierite-Anthophyllite Granofels; Biotite Schist unit at Blue Hill mine.
Gabbro	J	4912.6/520.6	Gabbro; Blue Hill mine, collected and analyzed by Dr. J. Descarreux for Kerramerican, Inc.
PM-15-O	K	4910.2/515.2	Diorite; dike or flow at south edge of Penobscot open pit. Well-developed diabasic texture; feldspar altered to epidote and chlorite; pyroxene altered to chlorite. 1-3% magnetite.
*	L	*	Typical High Alumina Basalt (Carmichael and others, 1974, p.33).

Table 3

Ca-104	A	4908.3/518.2	Fragmental; weathered surfaces shows rounded fragments of variable size and composition. Fresh surface green, chloritic.
Ca-139	B	4910.5/518.1	Crystal Tuff; finely laminated, potassium feldspar crystals aligned parallel to foliation; matrix all chlorite.

1	2	3	4
Ca-184	C	4910.4/519.5	Latite; flow, massive, abundant potassium feldspar phenocrysts in chlorite/sericite matrix.
Ca-208	D	4911.6/515.4	Lithic-Crystal Tuff; lapilli-sized rounded fragments of variable composition, with quartz phenocrysts. Matrix of finely laminated chlorite wraps around clasts and phenocrysts.
Ca-209	E	4911.8/515.9	Latite; flow, massive; potassium feldspar phenocrysts in aphanitic groundmass containing granoblastic biotite. Blocky weathering, 2-3% disseminated pyrite.
Ca-195	F	4909.2/519.1	Dacite or Rhyolite; black; scattered potassium feldspar phenocrysts; blocky weathering; 5% disseminated pyrite and also in hairline veinlets.
Ca-213	G	4912.6/516.6	Fragmental; siliceous, flow-banded pyroclasts in chloritic matrix.
Ca-227	H	4911.7/518/4	Dacitic or Latitic Flow; autobrecciated; angular fragments with little or no matrix.
SSB-5	I	4918.9/519.4	Crystal Tuff; thoroughly recrystallized due to South Penobscot Pluton. Much granoblastic biotite and potassium feldspar porphyroblasts.

Table 4

Ca-33	A	4907.5/513.9	Dacite or Rhyolite Porphyry; 3-5 mm albitic plagioclase phenocrysts in trachytic alignment; probably silicified.

1	2	3	4
Ca-54	B	4906.6/515/6	Rhyolite; lava dome, sparse potassium feldspar phenocrysts in dense, aphanitic, black, massive rhyolite.
Ca-70	C	4906.7/516.7	Rhyolite; lava dome as above; 3% disseminated pyrite.
Ca-91	D	4907.3/517.2	Rhyolite; lava dome as above; extremely fractured, black, pyritic; probably devitrified glass.
Ca-106	E	4908.8/518.1	Rhyolite, lava dome as above; probably silicified.
Ca-168	F	4908.8/519.1	Fragmental; siliceous flow-banded pyroclasts with minor chloritic matrix; probably silicified.
Ca-173	G	4911.0/516.8	Rhyolite; black, dense, probably devitrified glass; quartz veinlets have bleached selvages.
Ca-210	H	4912.1/516.1	Dacite; blocky weathering, dense, massive, minor potassium feldspar phenocrysts.
Ca-215	I	4912.7/517.4	Dacite; dark grey, silicic, probably devitrified glass, minor potassium feldspar phenocrysts.
Ca-246	J	4913.9/518.3	Rhyolite; autobrecciated, healed with younger silica and localized patches of pyrite.
151-1	K	4910.7/517.4	Rhyolite; dense, black, silicified in places, and with as much as 5% pyrite.
151-2	L	4921.5/520.2	Rhyolite; dense, dark grey to black, weathers into columns or slabs. Rare 2-5 mm randomly oriented to slightly trachytic potassium felspar phenocrysts, minor pyrite.
151-3	M	4921.4/519.3	Rhyolite, as in L; massive weathering.

1	2	3	4
152-1	N	4912.7/520.1	Rhyolite; brecciated, abundant dissemations and veins of pyrite, minor potassium feldspar phenocrysts.

Table 5

Dome 1	A	*Penobscot mine	Rhyolite; black, devoid of phenocrysts, columnar jointing; southeast corner of rhyolite dome.
Dome A	B		Like A, above
Dome B	C		Rhyolite, as above, with minor quartz veining. Refer to Plate 9B.
Dome C	D		Rhyolite,as above; intensely veined and silicified. Refer to Plate 9C.
Dome D	E		Refer to Plate 9D.
Dome D½	F		Rhyolite, as in Plate 9D, only slightly more disrupted and with slightly more matrix.
Dome E	G		Rhyolite Breccia; matrix and fragments difficult to distinguish, although disruption and fragmentation has occurred. Refer to Plate 9E.
Dome F	H		Rhyolite Breccia; Clasts of bleached and rounded rhyolite suspended in fine-grained albite-chlorite-sericite matrix. Refer to Plate 9F.
F-Matrix	I		Albite-chlorite-sericite matrix of Dome F, above.
Goose Pond	J		Fragmental; polymictic agglomerate, clasts of volcanic rocks, volcaniclastic rocks, and leuogranite

1	2	3	4
Goose Pond (cont'd)	J	*Penobscot Mine	cobbles in heterogeneous groundmass of fine ash and comminuted fragments. Minor sulfide minerals, occasionally occuring as fragments within the fragmental. Refer to Plate 8F.
PM-15-O	K		Same as in Table 2, analysis K.
Goose Pond	L		Fragmental; textural variety of sample J above. Refer to Plate 8F.
D-Ditch	M		Crystal Tuff alternating with Ferruginous Chert. Refer to Plate 8G.
Talc-CO_3	N		Talc Carbonate Rock from within mine sequence. Refer to Plate 8C.

*All samples collected at the Penobscot mine are from large waste dumps at the south of the mine property, except A and B, collected in situ on the margin of the rhyolite dome, and M, collected at the Drainage Ditch near Weir Cove.

APPENDIX 2

CIPW NORMATIVE MINERALOGY

CIPW Norms for Analyses in Table 2: Basalt and Andesite

	A	B	C	D	E	F	G	H	I	J	K	L
Q	-	-	-	-	-	-	-	-	20.88	-	-	-
or	12.59	42.95	16.41	13.29	12.97	24.74	15.11	11.21	9.25	9.24	15.51	6.56
ab	22.91	7.02	4.80	35.38	44.97	23.00	19.95	5.92	23.40	21.83	14.78	23.38
an	17.01	12.96	12.35	14.95	16.56	18.98	13.44	25.58	0.16	33.49	26.03	36.97
ne	12.71	10.39	28.06	-	-	3.99	15.18	-	-	-	7.31	-
di	4.14	-	27.49	14.46	-	11.74	22.19	3.20	-	19.70	18.33	15.23
hy	-	-	-	-	13.48	-	-	32.05	25.03	15.75	-	-
ol	23.46	12.86	0.11	8.87	1.08	8.42	-	15.21	-	2.53	11.35	20.55
mt	4.06	4.90	5.50	4.67	5.39	4.79	4.34	4.00	6.21	3.53	3.86	1.39
il	2.43	3.39	4.32	3.21	4.17	3.40	3.07	2.35	5.23	2.93	2.18	1.67
c	-	4.83	-	-	0.39	-	-	-	7.83	-	-	-
wo	-	-	-	-	-	-	5.85	-	-	-	-	-
ap	0.70	0.76	0.97	0.63	0.99	0.94	0.67	0.47	1.98	-	0.65	0.17

CIPW Norms for Analyses in Table 3: Intermediate Rocks

	A	B	C	D	E	F	G	H	I
Q	35.41	19.79	41.20	6.79	15.63	6.95	30.73	4.25	4.36
or	17.22	27.66	14.03	47.73	30.80	12.45	14.26	6.84	21.35
ab	28.91	31.18	23.48	14.95	40.62	66.25	39.14	76.65	61.13
an	2.23	4.20	1.84	1.42	1.77	-	0.46	2.71	1.94
di	-	-	-	-	-	1.88	-	-	-
hy	7.93	6.74	12.48	16.83	6.04	5.57	8.51	5.46	5.91
c	5.78	6.05	4.21	9.19	1.65	-	3.99	0.57	1.26
ac	-	-	-	-	-	4.18	-	-	-
mt	0.00	2.19	2.43	2.58	2.73	0.36	2.50	2.77	2.33
il	0.26	1.06	0.33	0.51	0.73	0.35	0.40	0.76	0.84
hm	1.95	0.35	-	-	-	-	-	-	-
ap	0.00	0.47	0.00	-	-	-	-	-	0.48

CIPW Norms for Analyses in Table 4: Rhyolite and Rhyodacite

	A	B	C	D	E	F	G	H	I	J
Q	18.58	33.31	40.27	41.59	48.34	29.82	33.16	19.81	34.96	32.12
or	39.99	44.23	36.50	35.67	2.43	14.85	23.45	13.45	10.71	5.36
ab	21.47	16.89	19.55	12.34	43.44	49.33	40.43	58.07	49.41	50.96
an	0.00	0.47	0.40	1.81	0.88	2.06	-	-	0.35	-
di	-	-	-	-	-	-	-	0.20	-	0.38
hy	8.06	1.62	1.03	3.71	2.77	1.08	.83	5.08	1.67	4.04
c	7.75	1.42	0.21	1.97	0.91	0.60	-	-	0.18	-
mt	2.93	-	-	2.50	-	-	0.00	1.83	2.41	-
il	0.97	0.16	0.09	0.41	0.65	.07	-	0.37	0.30	0.32
hm	-	1.74	1.75	-	1.65	1.87	1.47	-	-	-
ac	-	-	-	-	-	-	.77	1.21	-	4.87
ap	0.45	-0.00	-	-	-	-	-	-	-	-

CIPW Norms for Analyses in Table 5: Common Rock Types at the Penobscot Mine.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Q	30.40	24.55	21.61	36.40	22.51	32.58	28.38	41.20	41.53	46.20	0.00	34.58	24.88	-
or	27.29	28.06	42.83	0.88	5.16	4.48	5.58	4.29	29.35	8.49	15.51	14.08	5.83	-
ab	37.30	43.25	31.50	53.49	67.08	57.83	37.85	37.96	9.67	16.68	14.78	24.11	52.63	-
an	0.74	-	-	-	-	-	-	1.20	1.33	2.02	26.03	2.88	1.26	-
ne	-	-	-	-	-	-	-	-	-	-	7.31	-	-	-
di	-	0.29	0.34	7.90	2.28	1.34	1.26	-	-	-	18.33	-	-	-
hy	3.17	3.17	3.43	-	1.51	3.54	5.82	12.80	14.63	20.06	0.00	15.97	10.56	-
ns	-	0.68	0.29	1.23	1.45	0.23	1.11	-	-	-	11.35	-	-	-
mt	-	-	-	-	-	-	-	-	-	-	3.86	2.86	2.55	-
il	0.42	-	-	-	-	-	-	-	-	-	2.18	0.93	0.52	-
c	0.16	-	-	-	-	-	-	2.54	3.48	6.56	-	4.53	1.76	-
wo	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ap	0.02	-	-	-	-	-	-	-	-	-	0.65	-	-	-

CIPW Norms for Analyses in Table 15: Phyllite and Quartzite

	A	B	C	D	E	F	G	H
Q	-	37.41	29.59	27.48	46.19	50.63	29.27	34.67
or	-	13.50	11.87	14.60	11.17	17.27	18.20	22.60
ab	-	23.20	26.51	13.99	0.80	10.08	18.76	10.08
an	-	4.33	3.58	17.43	0.77	1.28	9.33	0.49
hy	-	11.98	14.61	20.02	26.85	9.83	10.14	9.75
mt	-	1.58	3.20	2.52	1.36	2.28	3.75	8.35
il	-	0.57	1.51	0.98	0.65	0.49	3.12	-
c	-	7.42	9.14	5.97	12.21	8.13	6.49	11.45
ap	-	-	-	-	-	-	0.95	0.62

APPENDIX 3

Rock Names Corresponding to Numbered Fields in Figures 5A, 7A, 8A, 9A (after Streckeisen, 1971)

1. Silexite
2. Alkali Rhyolite
3A. Rhyolite
3B. Rhyodacite
4. Dacite
5. Quartz-Andesite
6. Alkali Quartz-Trachyte
6'. Feldspathoid-bearing Alkali Trachyte
7. Quartz-Trachyte
7'. Feldspathoid-bearing Trachyte
8. Quartz-Latite
8'. Feldspathoid-bearing Latite
9. Quartz-Latite-Andesite, or Latite-Basalt
9'. Feldspathoid-bearing Latite-Andesite, or Latite-Basalt
10. Quartz Andesite
10'. Aklali Andesite, Alkali Basalt
11. Phonolite
12. Tephritic Phonolite
13. Phonolitic Tephrite
14. Tephrite

APPENDIX 4

Modal Mineralogy for selected samples of diamond drill core from hole 72-83

Sample Interval	Albitic Plag.	Quartz	Chlorite	Epidote	Sericite	K-Spar	Calcite	Sphene	Sulfides	Biotite	Clinopyroxene	Apatite	Amphibole	Access.
4	80	12	6	½	1	-	tr	3/4	-	-	-	-	-	-
36	78	12	8	-	1	-	-	3/4	½py	-	-	-	-	-
42	35	15	6	½	12	25	-	1	-	4	-	½	-	-
46	40	18	12	-	21	8	-	3/4	tr sph	-	-	½	-	-
47	72	8	9	-	10	-	3/4	-	-	-	-	½	-	-
52	42	21	7	-	11	18	-	1	tr sph	-	-	-	-	-
60	24	1	6	18	12	-	5	2	½ po	-	-	½	31	-
63	33	-	8	11	4	-	6	1½	½ po	-	-	-	36	-
72	14	7	16	22	-	-	9	1½	½ po	-	4	½	26	-
77	11	-	16	22	18	-	-	1½	½ py	-	12	1	28	-
80	24	6	2	-	53	13	-	1	½ po	-	-	-	-	-
93.5	43	37	4	-	15	-	-	3/4	-	-	-	½		-
94	48	41	7	1	-	2	-	½	-	-	-	tr	-	-
101	21	3	5	1½	69	-	-	½	-	-	-	tr	-	-
116	52	42	2	-	3	-	-	½	½ py	-	-	½	-	-
118	74	22	2	-	1	-	-	½	tr	-	-	½	-	-
132	65	32	1	-	½	-	tr	1	-	-	-	½	-	-
142	37	2	18	4	2	-	15	3	-	-	-	-	19	-
162	46	4	23	1	22	1	-	3	-	-	-	tr	-	-
180	47	3	-	23	24	tr	-	2	-	-	-	½	-	½
190	41	2	-	23	28	-	-	1½	-	3	-	½	-	½
198	29	3	-	-	6	43	5	11	tr py	-	-	-	3	-
213	59	8	-	22	7	-	-	3	tr py	-	-	-	-	tr
218	19	½	-	23	5	18	4	2	½ po	-	-	-	28	tr
220	16	-	-	23	7	16	3	3	½ po	-	-	-	31	-
223	18	tr	-	22	9	13	2	1½	½ po	-	-	-	34	-
224	12	tr	-	26	11	17	3	1½	½ po	-	-	-	29	-
226	14	-	-	24	9	12	3	2	tr	-	-	-	36	-
227	14	-	-	24	9	12	3	2	tr	-	-	-	16	-
229	14	3	-	41	5	11	6	2½	1½ po	-	-	-	16	-
230	-	2	-	23	-	2	3	1	1 po	-	-	-	68	-
230.5	-	6	-	75	-	-	½	3	3 cpy 1 py ½ sph	-	-	-	11	-
232.5	-	6	-	-	15	-	52	-	5 py 3 sph ½ po	-	-	-	18	-
234	-	½	-	-	24	-	66	-	5 sph 2 py ½ gn	-	-	-	2	-
234.6	-	5	-	1½	77	-	6	-	4 py ½ gn	-	-	-	3	-

									1 py ½ sph					
232.5	-	6	-	-	15	-	52	-	5 py 3 sph ½ po	-	-	-	18	-
234	-	½	-	-	24	-	66	-	5 sph 2 py ¼ gn	-	-	-	2	-
234.6	-	5	-	1½	77	-	6	-	4 py ¼ gn 3 sph	-	-	-	3	-
235	-	-	-	-	13	-	83	-	3 py 1 sph	-	-	-	-	-
237.9	-	5	-	-	72	-	8	-	6 py 3 sph tr gn	-	-	-	6	-
238	-	6	-	-	62	-	11	-	6 sph 8 cpy 1½ py	-	-	-	5	-
239	-	33	-	-	52	-	8	-	4 cpy 2 sph	-	-	-	-	-
240	29	26	39	-	1	-	3	1½	-	-	-	tr	-	tr
241	-	41	42	-	16	-	-	½	-	-	-	tr	-	tr
241.5	-	18	38	½	39	-	-	4	½ py	-	-	-	-	tr
242.3	-	29	3	1	65	-	-	-	1 py	-	-	-	-	tr
243	-	27	31	-	39	-	-	½	2 py	-	-	-	-	tr
243.9	-	26	38	½	32	-	-	1	2 py	-	-	tr	-	-
245	-	32	-	½	62	-	-	1	4 py	-	-	-	-	-
246	-	32	8	½	53	-	-	1½	5 py	-	-	-	-	tr
247	-	38	4	½	50	-	-	1	6 py	-	-	-	-	tr
249	-	44	3	tr	43	-	-	½	9 py	-	-	tr	-	-
250	-	39	½	½	47	-	-	1½	6 cpy 5 py ¼ sph	-	-	-	-	-
250.2	-	36	-	3/4	53	-	-	½	2 cpy 6 py ½ sph	-	-	-	-	-
254	-	68	2½	1	21	-	-	½	4 py 3 cpy	-	-	-	-	-
255	-	68	½	1	25	-	-	½	5 py tr sph	-	-	-	-	-
256.5	-	31	3	1	56	-	-	-	2 cpy 1 sph 5 py	-	-	-	-	tr
259	-	73	2½	½	23	-	-	½	½ py	-	-	-	-	tr
264	3	34	57	tr	3	-	-	½	1½ py ¼ sph	-	-	tr	-	-
267	-	48	16	½	33	-	-	½	1½ py ¼ sph	-	-	-	-	tr
272	-	66	11	-	22	-	-	½	tr sph	-	-	-	-	tr

Total Depth = 272 feet

cpy = chalcopyrite; sph = sphalerite; py = pyrite; gn = galena; tr = trace

Amphibole = uralite; clinopyroxene = augite and minor pigeonite, usually persisting as cores within chlorite and uralite

Data through the courtesy of Dr. S. A. Williams, Phelps Dodge Corporation, Douglas, Arizona.

APPENDIX 5

Descriptions of Samples shown in Figure 21;
South Side Bagaduce River Narrows, Plane Table Locality

Sample Number	Description
1	Quartz - potassium feldspar porphyry. Euhedral to subhedral sanidine phenocrysts; quartz phenocrysts rounded and partly resorbed; minor, randomly oriented biotite.
2	Polymictic fragmental; fragment types include: 1. contorted, well laminated quartz-biotite rock; appears identical to ribbony Ellsworth Formation. 2. rounded leucogranite cobbles 3. various intermediate volcanic rocks; crystal and lithic tuffs; aphanitic felsite, keratophyre. Matrix consists of rounded and broken albitic plagioclase laths, much chlorite and sericite, and comminuted volcanic clasts.
3	Like sample number 4.
4	Mafic tuff. Much wispy biotite interstitial to fragments of intermediate volcanic rock; potassium feldspar and quartz phenocrysts in matrix.
5	Mafic tuff, like sample number 4.
6	Dacite porphyry, like sample number 1.
7	Intermediate tuff; silicified; potassium feldspar and quartz phenocrysts; 2-3% disseminated euhedral pyrite.
8	Dacite, autobrecciated; equal amounts of potassium feldspar and quartz as phenocrysts. Groundmass of sericite, chlorite, biotite.
9	Intermediate flow, probably dacitic; massive; grades into conglomeratic rock of Stop 9 (Stewart and Wones, 1974).
10	Mafic tuff; minor 2-5 cm interbeds of felsic tuff. Much biotite, amphibole, 1% disseminated pyrite.
11	Polymictic fragmental, as in sample number 2.

APPENDIX 5 continued

Sample Number	Description
12	Intermediate tuff; biotite rich, sanidine phenocrysts, lenses of polymictic fragmentals up to 5 cm in thickness.
13	Like sample number 12, slightly more biotitic.
14	Like sample numbers 12 and 13; weathered surface has retrograded cordierite and andalusite porphyroblasts.

APPENDIX 6

Analytical Procedures

X-Ray Fluorescence

Samples were crushed in a jaw crusher, divided, and pulverized for 30 seconds in a Bleuler Mill. Pressed powder pellets and fused discs were made for each sample according to the method of Norrish and Chappell (1967) and Norrish and Hutton (1969), respectively. Analyses were determined by a Philips 4500 automated X-ray fluorescence spectrometer at the University of Western Ontario, and compositions were obtained using a program developed by Norrish and Hutton (1969), processed by a Cyber 73 computer. A second program computed CIPW normative mineralogy. Chemical data thus obtained are considered good approximations of the real compositions of analyzed samples, and precision and accuracy were monitored periodically by analyzing samples of known composition.

Radio Frequency Induction Coupled Plasma Arc Spectroscopy

A portion of the sample was weighed out and treated with concentrated HF, HNO_3, and $HClO_4$. The mixture was refluxed for a few hours, then evaporated to dryness. The residue was taken up in 0.5N HCl and diluted to volume.

A 32 channel Applied Research Laboratories induction coupled plasma QA-137 optical emission spectrometer is used for the analysis. The emission source is an argon plasma produced by 1600 watts of radio-frequency power supplied to a two-turn induction coil. Temperatures in the plasma are in the range of 10,000^{o}K (compared to an oxy-acetylene flame at around 3,000^{o}K). The sample is injected into this plasma as an aerosol where it it atomized and subsequently yields intense emission spectra characteristic of the sample atoms present.

The direct reader is a Paschen mount polychromator with a primary entrance slit of 12μm. Radiation characteristic of the elements analysed are focused on the 50μm secondary slits appropriately spaced on the focal curve. The corresponding photomultipliers receive the optical signals, amplify them and transmit the transduced electrical signal to the readout console. The spectrometer is interfaced to a Hewlett-Packard Model 9830 programmable calculator.

Stock solutions for the preparation of multi-element standards are made from Johnson Matthey Specpure or Analar grade reagents. The range of concentration per element (typically 3 to 4 orders of magnitude beyond the detection limit) is designed to cover that normally expected in the samples being analyzed. Samples that exceed the calibration range are diluted 1:10 or 1:100 and re-analyzed by the instrument.

The instrument is calibrated at the start of each working period using a series of multi-element standard solutions. A linear regression least-squares parabolic curve is applied by the calculator which is coupled to a Hewlett-Packard Thermoprinter 9866. The calibration coefficients are regularly updated throughout a working period by aspiration of standard solutions when standards demonstrate deviation from control. Approximately one minute is required for the complete analysis of one sample. The thermal printer outputs in ppm of the analyte in solution. Data is stored in standard-size cassettes. Software developed by Barringer Research is used for further data reduction and data listing.

For geological materials the following detection limits are realized by the Multi-Element technique:

Al	5 ppm	Ni	1 ppm
As	30 ppm	P	200 ppm
Be	0.3 ppm	K	100 ppm
Ca	2 ppm	Ba	30 ppm
Cd	5 ppm	Si	20 ppm
Cr	1 ppm	Ag	5 ppm
Co	2 ppm	Na	500 ppm
Cu	1 ppm	Sr	0.1 ppm
Fe	1 ppm	Te	500 ppm
Pb	5 ppm	Ti	1 ppm
Mg	1 ppm	Zr	1 ppm
Mn	1 ppm	V	1 ppm
Mo	8 ppm	Zn	1 ppm

Long term variation due to instrumentation is kept well within 5% by control checks. Total variation in solids analysis, from sample digestion to analysis by multi-element plasma emission, has been estimated from typical runs over a number of days. Precision for major elements in rock and soil samples are in the 1% to 5% range; trace elements, 3% to 9%. Certified reference materials and standards treated in the same manner as samples are run in every batch of samples to maintain accuracy.

Description of the Multielement Technique furnished by:

Romana B. Cruz
Chemist, Barringer Research Ltd.
Toronto, Canada

APPENDIX 7

GUIDEBOOK FOR FIELD TRIP IN THE CASTINE AND BLUE HILL 15 MINUTE QUADRANGLES, HANCOCK COUNTY, MAINE

Mileage	
0	Center of the town of Blue Hill. Proceed west out of town on Highway 15 (also highways 172, 175, 176).
0.6	Intersection. Continue straight ahead on Highway 15 (176) toward Brooksville.
1.7	Rusty-weathering sulfide prospect within Pond Quartzite on south side of road.
1.8	Entrance to Kerramerican (Blackhawk) mine on south side of road.
4.8	Intersection. Turn left and continue to follow Highway 15 south.
7.8	Intersection. Turn right at yield sign onto Highway 175 and drive north toward Brooksville.
8.4	Intersection. Continue straight ahead on Highway 176 east toward South Brooksville.
9.5-10.8	Road follows high ground of the Sedgwick granitic pluton which intrudes both the Castine and Ellsworth Formations.
11.1	Enter South Brooksville.
11.4	Outcrop on the right is a greenstone of the Castine Formation, contact metamorphosed by the Sedgwick pluton.
12.4	Turn left onto small asphalt raod at sign reading "Breezemere Farm".
13.1	Blacktop ends.
13.5	Turn left onto narrow gravel lane through woods. Drive slowly.
13.7	Outcrop of dome rhyolite on right side of lane.
14.5	Lane ends; pull of into parking area on right side of lane, and walk 30 meters down to Orcutt Harbor.

STOP 1: Orcutt Harbor

The outcrops are bedded crystal/lithic tuffs, hyaloclastite pillow breccia, and some intact pillows. Note the abrupt change in lithology and the variability in attitude of bedding, both characteristic of deposition of volcanic material on highly irregular terrain.

Perfectly preserved are original volcanic features, such as euhedral feldspar in tuffs, spherical vesicles, and undeformed pillows. Angular clasts in massive uncompacted rocks contrast with flattened clasts in adjacent compacted units, the latter produced by rock loading while still hot and plastic. No tectonic lineation is associated with the flattened clasts. The poor preferred shape orientation of angular clasts is an original sedimentary feature.

Some of the more siliceous tuffs are well jointed, and many of the joints are quartz-filled. Quartz veining was contemporaneous with cooling and degassing.

Return to vehicles. Turn around and retrace route to Highway 176.

16.6	Turn left onto Highway 176 east.
17.1	Intersection. Turn left (west) onto asphalt road toward Cape Rosier/Harborside.
17.2-23.6	Outcrops seen along the road are all Castine volcanic rocks.
21.2	Turn right at Rosier Grange.
23.1	Intersection in the village of Harborside. Turn right.
23.7	Pull off and park just before bridge. Walk into Maine Sea Farms and ask permission to enter site of Callahan's Penobscot Unit (The Harborside Mine).

STOP 2: The Harborside mine and Goose Falls

Enter the mine through the gate and proceed down the gravel road. At the fork bear right and walk up the ore haulage road, viewing continuous outcrop on the right.

The outcrops are black rhyolite, which has intruded coarse-to-fine lithic tuff, which can be seen in the road bed. Note that bedding in these tuffs has been rotated past vertical by the intruding rhyolite dome, and is now dipping steeply into the dome. Proceeding west, the contact between the dome and lithic tuff weaves back and forth across the road. Quartz and calcite veining are common, with lesser laumontite lined veins and cavities. Near the top of the road at the former ore pad, a diabasic dike has intruded the felsic rocks. Note that the original geometry of columnar joints remains unmodified.

Past the old mine buildings, now in use by Maine Sea Farms, remnants of 48 inch Calyx core can be examined. The rock types are highly variable, but are typical of proximal volcanic rocks. Alternating chloritic to siliceous green and purple crystal tuffs predominate, but pyroclastic rocks are also common. Note the very abrupt wedging out of layers and the strong bedding fabric in the tuffs. This compactional fabric abuts contacts with wedges of discontinuous layers, typical of the highly irregular bedding attitude in these volcanic rocks.

The bedding has been affected by kink and crenulation soft-sediment folds, the shapes of which are controlled by the strong mechanical planar anisotropy in the unconsolidated sediment. High temperature deformational features such as pressure solution and axial planar cleavage are absent, and euhedral feldspar crytals are preserved.

Return to vehicle parking area, cross the road, and examine the outcrops near the water. These rocks are Goose Pond Conglomerate, a coarse, polymictic, volcaniclastic/pyroclastic unit. It contains felsic and intermediate volcanic fragments, as well as granitic cobbles of uncertain origin.

Return to vehicles, turn around, and proceed back along the same route.

26.2 Pull off the road to the left in old driveway and park. Cross the drainage ditch near the road to get onto the northeast side of the ditch. Walk along the ditch approximately 200 yards to the last exposures.

STOP 3: Drainage Ditch

The outcrops are of finely laminated chemical sediments and crystal tuffs. The chemical sediments are ferruginous, consisting of red and purple chert of variable thickness and continuity. Most of the tuff is green with white laths of euhedral plagioclase.

Structural features include small crenulation and kink folds, the geometry of which is controlled by the mechanical properties of the strongly anisotropic sediments.

The absence of tectonic cleavage, pressure solution features, and grain-shape fabric establishes these folds as soft-sediment features. Microfaults subnormal to bedding are probably due to dewatering of the slumped units.

Return to vehicles and continue to retrace the route to Highway 176.

28.0–28.2 View rhyolite dome to the right front.

30.2 Intersection. Turn left at stop sign onto Highway 176 west. Outcrops are rhyolite.

32.6 Road takes a sharp turn to the right. Brooksville Elementary School is on the right.

33.3 Road takes a sharp turn to the right at Wescott's Store (Texaco sign). One hundred fifty meters farther, turn left into asphalt driveway, drive up to house and park (Ask permission). Walk northeast parallel to the highway 100 meters to view outcrops.

STOP 4: Wescott's Field

The exposures here are Ellsworth Schist. Most of the rocks are the "Ribbony Ellsworth" comprised of finely laminated biotite and quartz, resembling a gneiss. Other rocks are dark green to rusty-weathering actinolite schist. The general trend of the layering in the ribbony rocks, and fine layering and fabric in the actinolite schist are bedding and are conformable. Original rocks types were alternating pelitic layers and chemically precipitated silica layers for the ribbony Ellsworth, and mafic tuff for the actinolite schist. All the rocks have been thermally metamorphosed to biotite grade by the South Penobscot Pluton, one-half mile to the east.

Profuse small scale folding is ubiquitous in the ribbony Ellsworth, but is conspicuously absent in the actinolite schist. The mimetic biotite fabric in the ribbony rocks is folded around the hinges of folds, and axial planar cleavage is absent. There is no tectonic lineation. The folds in the Ellsworth are soft-sediment features, having occurred prior to the growth of metamorphic biotite. Being inherently more stable, the mafic tuff did not undergo slumping.

Return to vehicles. Turn right onto Highway 176 West, return along same route to David's Folly.

35.8 Turn right into David's Folly, drive slowly to parking area. (Be sure to ask permission). Walk west ¼ mile down to Smith Cove.

STOP 5: Smith Cove/Shepardson Brook

The outcrops at Smith Cove are conglomerate/breccia. Blocks and fragments of ribbony Ellsworth schist are welded together to produce a spectacularly photogenic outcrop. The ubiquitous folds are misoriented in adjacent blocks, proof that the folding took place prior to the deposition of the breccia. The virtual absence of matrix between blocks is indicative of plastic accomodation. Some blocks appear to grade into one another, a feature associated with soft-sediment deformation. Within blocks, planes of discontinuity between folded layers are also indicative of soft-sediment deformation.

Outcrops at the mouth of Shepardson Brook are sedimentary breccia overlying mafic volcanic rocks of the Castine Formation. These field relationships indicate that Castine volcanism was ongoing when at least some Ellsworth schist was still a soft sediment.

Return to vehicles. Turn left onto Highway 176 East and proceed.

37.1	Road turns sharply to the right at Wescott's Store.
39.1	Road takes a sharp turn to the right. Underlying bedrock here is probably Ellsworth Formation.
39.6	Cross contact zone into the South Penobscot Pluton.
41.1	North Brooksville. Turn left toward Penobscot on Highway 176 and 175.
41.4	Estuary with reversing tidal flow.
41.2	Intersection. Turn left at yield sign onto Highway 175, north toward Orland.
46.2	Junction Highway 177. Continue straight ahead on Highway 175.
47.2	Junction Highway 199. Continue straight ahead on Highway 175 and Highway 199 toward Castine.
49.3	Junction. Continue straight on Highway 199 south toward Castine.
50.7	Outcrops on right side of road are contact metamorphosed lithic tuff of the Castine Formation.
52.8	Intersection, Highway 166. Make a U turn and proceed back down hill on Highway 199. Park on right side of road at end of white highway quard posts, and walk southeast across the open field to the Bagaduce River Narrows.

<u>STOP 6</u>: North Side Bagaduce River Narrows

West of the lobster boat pier the outcrops are rib-

-bony Ellsworth Formation. The bedding is again folded into small-scale folds which are slump structures. Careful examination is necessary, but S and Z folds occur in single layers without an intervening larger fold closure. No tectonic lineation can be seen, and the mimetic mica fabric is folded around fold hinges. Discontinuities between adjacent folded units are again indicative of slumping.

Intraformational breccias, also soft-sediment features can be seen throughout the exposure. Misoriented fragments are common, but absence of differential weathering of these fragmental units, as well as their lack of continuity, rule out a tectonic origin.

East of the lobster boat pier are folded crystal and lithic tuffs of the Castine Formation. The orientation of the small-scale fold axes is essentially identical to that in the Ellsworth Formation at this locality, with a south-southwest trend and approximately 35° plunge.

Interbedded flows with rubbly flow tops, spherical vesicles, and undeformed amygdales attest to the absence of tectonic deformation in this unit which is nevertheless folded.

It is apparent that folds in both the Ellsworth and Castine formations at this locality were formed through similar processes, presumably due to slumping of unconsolidated volcanogenic sediment off a subaqueous volcanic edifice. Biotite occurs in both formations here in rocks of appropriate composition, and is mimetic.

Return to vehicles, and retrace route to Wescott's Store in West Brooksville.

68.4	Wescott's Store. Turn right onto asphalt road. Bear left at the fork remaining on asphalt road.
69.6	Road ends past Stewart camp. Park and walk north along the shore, approximately one mile until on the north end of the peninsula across the Bagaduce Narrows from STOP 6.

<u>STOP 7</u>: South Side Bagaduce River Narrows.

The outcrops are crystal and lithic tuffs of the Castine Formation, some with cordierite porphyroblasts, and ribbony Ellsworth Formation. Between the two rock types lies a polymictic volcanic breccia. Clasts include volcanic lithologies, ribbony Ellsworth and leucogranite; matrix is highly immature volcanic debris including comminuted lithic clasts and feldspar phenocrysts. Similar units are repeated several places in the local stratigraphy.

Wingard (1958, 1961) first described this coarse clastic rock as basal conglomerate, lying above an unconformity between the older, poly-deformed Ellsworth Formation, and the virtually undeformed Castine Formation. However, the immature nature of the rock, its repetition in the sequence where it is intercalated with Castine rock types, and the absence of evidence of any pre-Silurian tectonic deformation in the Ellsworth Formation, all point to a volcanic origin for the rock, therefore lacking any regional stratigraphic significance.

Return to vehicles, and retrace route to Highway 176.

70.8	Turn left onto Highway 176.
73.6	Intersection. Turn left at North Brooksville onto Highway 175 and 176.
74.4	Interseciton. Turn right onto Highway 176 toward Blue Hill.
76.6	Intersection. Turn left onto Highway 15 north toward Blue Hill.
80.1	Turn right onto gravel road.
80.4	Turn left onto rock lane leading up the hill, or park.

STOP 8: Stover Hill

Exposures here are of contorted Ellsworth Formation, which is considerably more siliceous than that seen thus far. These rocks are continuous with the Allen, Pond, and Douglas quartzites, which host the base metal mineralization at the Kerramerican mine to the west.

This outcrop is in the contact zone of the Sedgwick Granite, and numerous dikes and veins of pegmatite, aplite, and granite cut the quartzites. The profusion of quartz veins, some of which crosscut bedding, point to a metamorphic or metasomatic origin for some. However, the majority are concordant with bedding, some of which can be seen grading into the narrow siliceous bands of concordant silica, and are interpreted as bands of recrystallized chert. Oxygen isotope studies are currently underway in order to resolve this conjecture.

As in most of the ribbony Ellsworth, these rocks are folded on the small scale, and here also a mimetic biotite fabric is folded around the fold hinges. This is true in other locations as well, where even contact-metamorphic garnet is present. Careful examination will reveal inconsistent fold geometry, including S and Z asymmetric folds in single layers. Additionally, intervening larger fold structures necessary to reconcile alternation of S and Z folds are rare, and are themselves slump structures.

In spite of the numerous small scale folds, sulfide horizons can be traced along strike of the bedding for hundreds of meters. Such continuity could not exist if these rocks had been folded on a large scale.

Return to vehicles. Retrace route to Highway 15. Turn right onto Highway 15 North and proceed to Blue Hill.

End Field Trip.

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