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Bedrock Geology of the Cape Ann Area, Massachusetts

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ILLUSTRATIONS

BEDROCK GEOLOGY OF THE

CAPE ANN AREA, MASSACHUSETTS

Covering the Georgetown, Salem, Ipswich, Marblehead North, Marblehead South, Gloucester, and Rockport 7.5 minute Quadrangles with map, scale 1:62,500

William H. Dennen

1978

1.0 INTRODUCTION

1.1 Location and Previous Work

The Cape Ann area lies on the eastern shore of Massachusetts and is covered by the Georgetown, Salem, Marblehead North, Marblehead South, Gloucester, and Rockport 7.5 minute series quadrangles. This area is dominated by igneous rocks of the Cape Ann Plutonic Series intruded into an igneous and metamorphic complex and the whole transected by numerous faults.

Rocks of part or all of the area have been previously described by Shaler (1889), Washington (1898, 1899), Sears (1905), Clapp (1910, 1921), Emerson (1917), Warren and McKinstry (1924), La Forge (1932), Toulmin (1960, 1964), Bell and Dennen (1972), Bell and others (1973), Norton (1974, 1975), Norton and others (1975), Dennen (1975a, 1975b, 1975c, 1975d), Bell and Alvord (1976), and Barosh and others (1977).

Surficial deposits of the Ipswich and northwest corner of the Marblehead North Quadrangle were mapped by Sammel (1962) and Sammel and others (1966), the Marblehead North quadrangle by Carnevale (1976), and surficial coastal geology and glacial features from Annisquam Harbor north were described by Chute and Nichols (1941).

Geophysical investigations in the area include total intensity aeromagnetic Geophysical Investigations Maps GP-710, 718, 719, 722, 723, and 724 (1970), gravity and magnetic studies by Joyner (1963), Bromery (1967), Kane, Yellin and others (1972), and Kane, Simmons and others (1972). Pertinent interpretations of geophysical data include studies by Barosh and others (1974) and Ballard and Uchupi (1972).

1.2 Physiographic Features

The Cape Ann area is situated on the northeastern Massachusetts coast within the Seaboard Lowland section of the New England Physiographic Province as described by Fenneman (1938). Here the sloping margin of the peneplaned New England Upland bedrock surface passes seaward into the Atlantic beneath a veneer of unconsolidated Pleistocene and Holocene sediments.

The present shoreline results from late Tertiary (?) submergence of a stream-dissected topography having 15-60 meters of relief, which was later over-ridden by Pleistocene glaciers. The ice sheet, moving approximately S40°E into the ocean, smoothed the surface by planation and deposition of ground moraine and outwash deposits forming a smooth and gently sloping surface. Complex shifting of ocean level through Pleistocene time stabilized in a stand slightly below the present level, and in the past few thousand years a rise of perhaps 10 meters has taken place. Holocene deposition has formed a seaward barrier beach north of Cape Ann comprised of beach and dune sands on Plum Island and Castle Neck which is backed by a wide area of salt marsh.

The veneer of glacial deposits over dissected bedrock consists of ground moraine, which may range upward to 15 meters in thickness, a variety of outwash deposits including kames, kame terraces and fine sediments of glaciofluvial and glaciomarine origin, and numerous drumlins of roughly oval plan rising to 65 meters or more.

The present bedrock surface is irregular with a maximum relief in excess of 60 m. Outcrop varies from very good to very poor depending on glacial cover and bedrock type; granite and dioritic rocks and granitoid gneisses being typically well exposed on rounded and knobby hills and along the southern coast.

The drainage throughout the area is sluggish with many small estuaries reaching inland. The low relief and gradient of the bedrock surfaces coupled with glacial mantling has resulted in numerous areas of seasonal or permanent swampland.

2.0 STRUCTURAL FEATURES

2.1 Faults

The Cape Ann area is within the imbricate thrust fault zone of eastern Massachusetts (Bell, 1967; Skehan, 1968; Barosh and others, 1974) with the principal faults being northeast-trending high-angle thrusts, west over east, usually having a large dextral strike component. The dominant feature of the area is the presence of large fault-bounded blocks of contracting lithologies and metamorphic grade. Figure 1 shows the faults bounding the principal lithologic groupings which are composed of:

- I diorite and metavolcanic rocks
- II unmetamorphosed volcanic and sedimentary rocks of the Newbury Complex
- III metamorphosed diorite, granodiorite and mafic volcanic rocks
- IV unmetamorphosed granite and dioritic rocks of the Cape Ann Pluton and related salic volcanics.

The larger faults are generally not exposed but their traces are usually marked by topographic lineaments, in many places the sites of streams and swamps. Other criteria used to identify faults are metamorphic contrast, offset contacts, truncated foliation or bedding, gouge, cataclastic and breccia zones, hydrothermal alteration, and interpretation of aeromagnetic maps.

It should be noted that all available evidence indicates that these faults are brittle fractures without associated flowage such

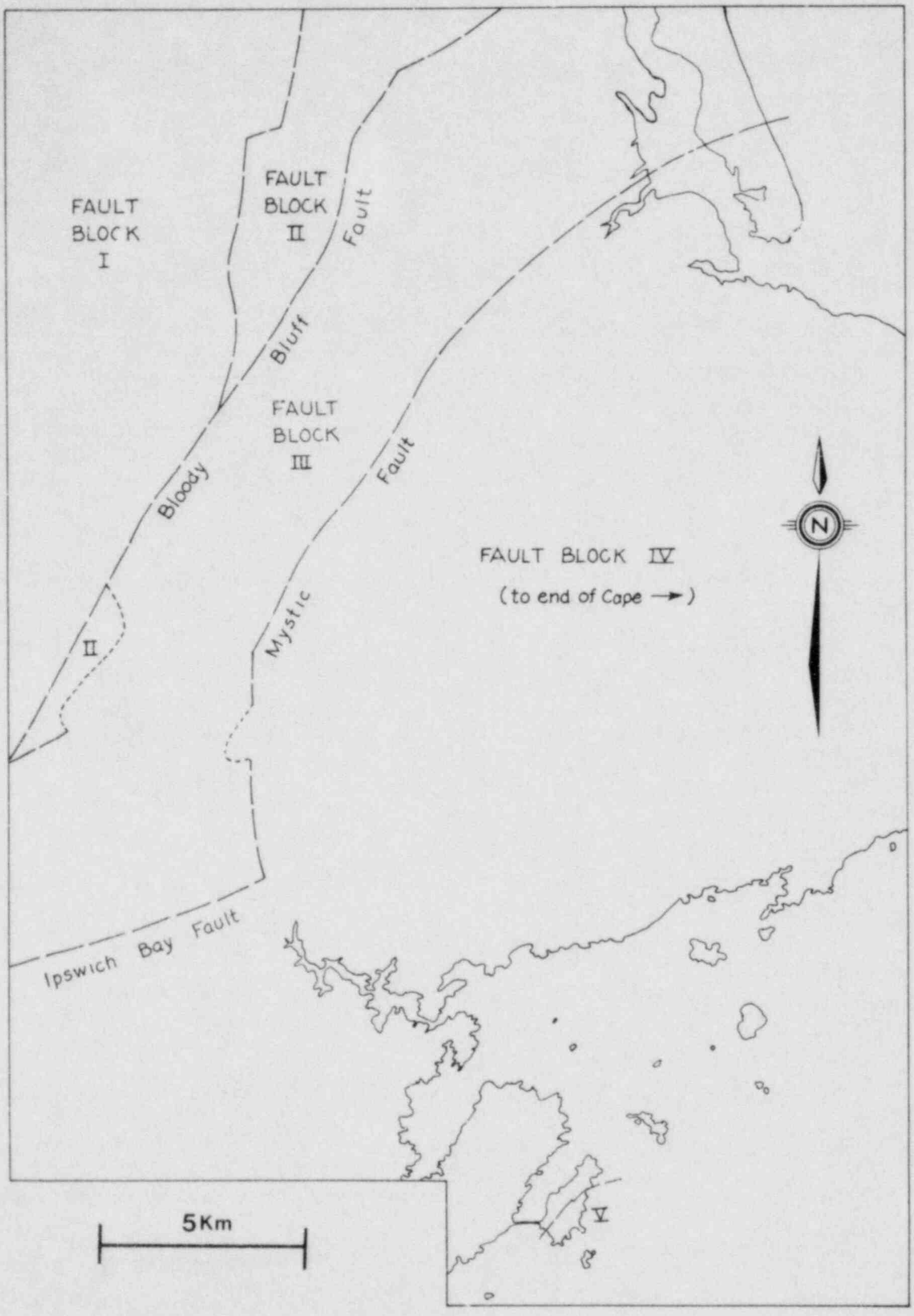

Figure 1. Map of the Cape Ann area, showing faults bounding blocks of the principal lithologic assemblages.

as is found in this imbricate zone in Connecticut.

Displacements on the larger faults are not known but must be large, perhaps measured in many kilometers, to bring the various lithologies into juxtaposition.

Minor faults that reflect internal adjustments of the thrust sheets are abundant and can be seen on almost any substantial bedrock exposure. Displacements range from inches to hundreds of feet. Throughout most of the area lack of outcrop precludes mapping of minor faults, but significant patterns can be demonstrated in localities of abundant outcrop. Many minor faults trend northwest, dip at high angles, and indicate northeastward movement that is consistent with the transport direction of the thrust sheets. Other minor faults trend east, dip at high angles and seem to indicate mainly vertical adjustments.

Zartman (1972), based on his radiometric dating of various intrusive events, concludes that " . . . juxtaposing of formerly separate tectonic elements probably took place during the Acadian orogeny, with some further adjustments occurring in late Paleozoic time." However, a younger age for the faulting appears more likely based on geologic information from other areas. Faults of the imbricate zone displace stratified rocks of Pennsylvanian age in the Narragansett Basin of Rhode Island and stratified rocks of Triassic age in the Bay of Fundy area, New Brunswick. They are covered by undisturbed stratified rocks of Lower Cretaceous age on the Atlantic Coastal Plain. The faulting thus probably occurred either intermittently or more or less continuously from Permian to Jurassic time.

There is no evidence of latest movement on these faults within the map area. Rare tiny displacements of glaciated pavement may record either adjustment to minor tectonism or glacial unloading.

2.2 Folds

Folds are not significant in the Cape Ann area. Stratified rocks usually dip at high angles and are portions of homoclinal sequences within thrust plates.

Division of the salic phases of the Cape Ann Pluton on the basis of their modal quartz content yields a series of bands geometrically equivalent to folds. The pattern suggests a major synform plunging to the northeast, but is more probably the result of fractional crystal settling from a subhorizontally spreading magma between an irregular floor and roof rather than tectonically caused.

2.3 Jointing

Joints arising from pure extensional stress are recognized by their undulatory surfaces and, except for common subhorizontal sheeting and a few relief cracks related to blasting, are quite rare. Most of the joints observed are the clastic response to shear stress and show planar surfaces which are often shear-feathered, faintly striated, or slickensided. Many joints are also, in detail, surfaces which step across closely-spaced en-echelon fractures lying a few degrees from the joint plane.

Since the joints mainly represent a shearing failure in response to the applied stress field, the directions of least and greatest principal stress should bisect the dihedral angles between conjugate joint pairs rather than be normal and parallel to the strike of the joint. Dike emplacement is presumably controlled by extensional movement and, when the dikes are emplaced contemporaneously with the formation of joints, their strike normal should mark the direction of least principal stress. In the absence of contemporaneous diking, the direction of least principal stress is probably the bisector of the obtuse dihedral angle of the conjugate set.

An intensive study has been made of the jointing in the salic phases of the Cape Ann Plutonic Series in part of fault block IV (Figure 1). The attitude, surface characteristics, and general features of about 400(individual joints were noted and the data used to develop a partial analysis of the orientation of the stress field in this area with time.

To facilitate this study, fault block IV was subdivided into 7 fault-bounded units, (Figure 2) which are dominated by relatively undisturbed rocks (or uniformly disturbed rocks in the case of the Annisquam imbricate zone). Strips lying within 1 km. of the bounding faults were considered separately.

The orientation of the least principal stress during consolidation is approximately known from the strong preferred orientation of mafic dikes, (Figure 3) which were emplaced contemporaneously with the last intrusive movements of the magma (see 3.2.2.3.4). Jointing consistent with this stress field is seen in joints which, in general, have surfaces mineralized with hornblende, are butt or offset joints of limited strike length, and dip at less than 75°. The horizontal projection of the greatest and leas principal stress directions at this time is shown in Figure 4a.

Post-consolidation jointing in response to regional tectonic events is represented by a second set of joints characterized by extensive strike length (master joints), steep dips, and often having associated minor cataclasis, shearing, or stepped surfaces. The orientation of the stress field at this time had been rotated

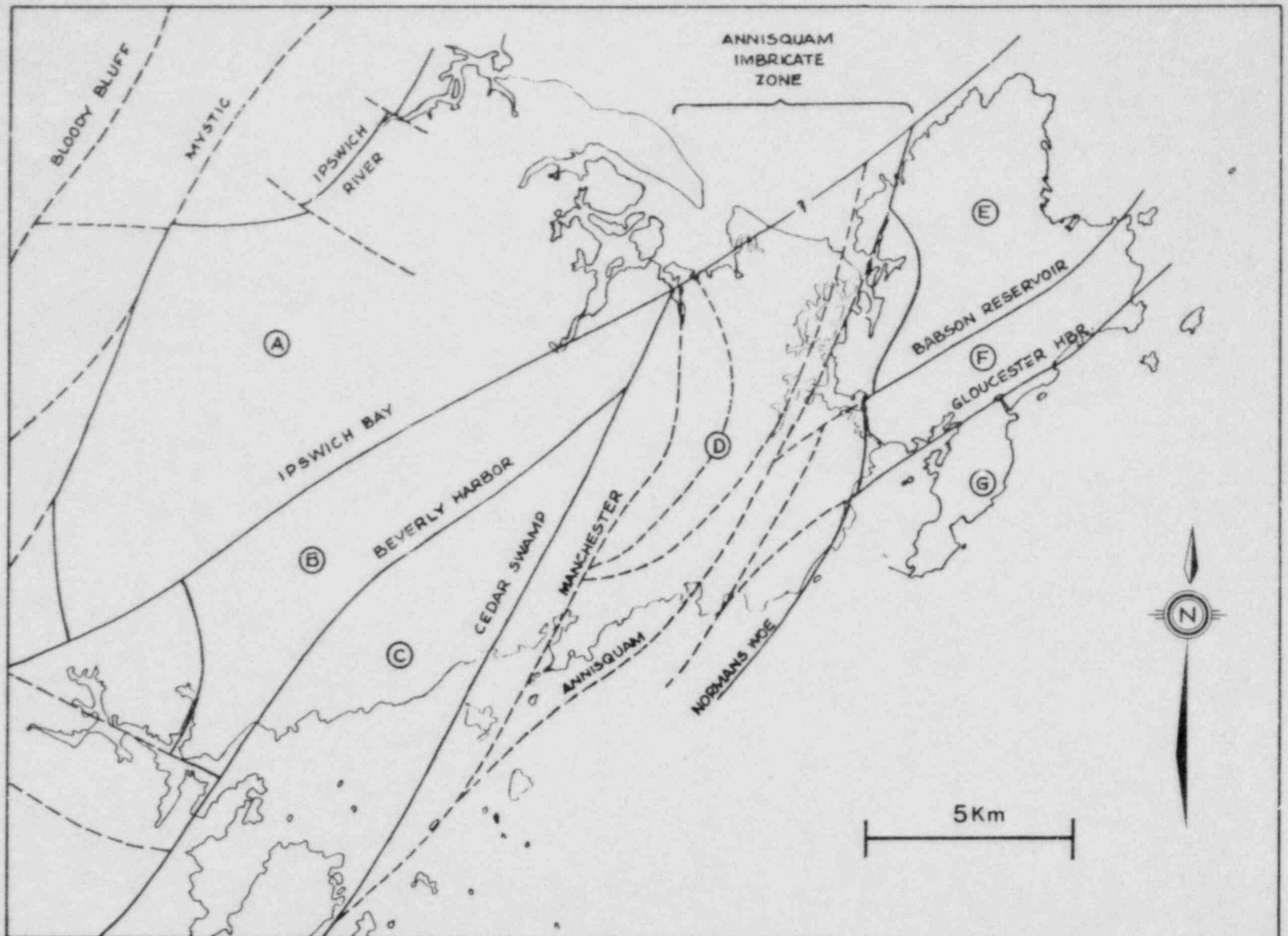

Figure 2. Map of the eastern part of the Cape Ann area, showing the principal faults. The circled letters designate fault blocks.

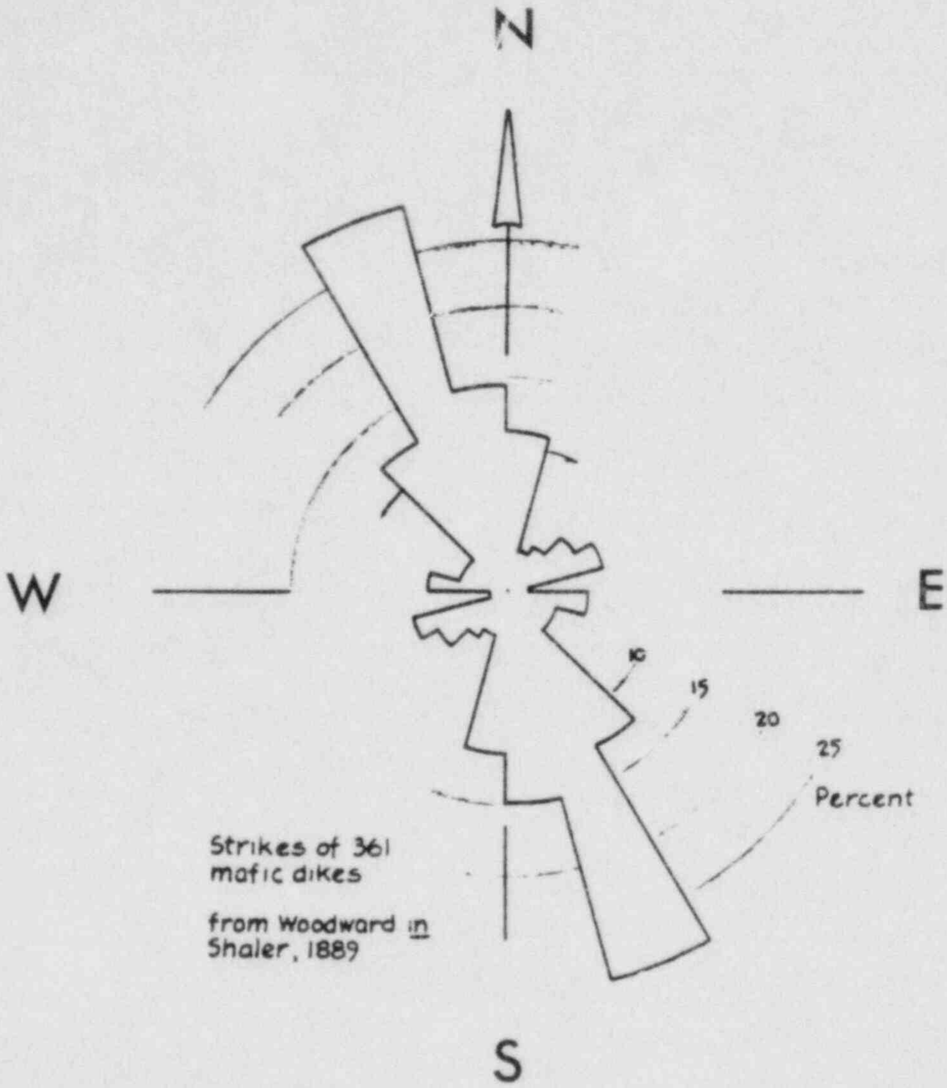

Figure 3. Diagram showing the orientation of mafic dikes on Cape Ann.

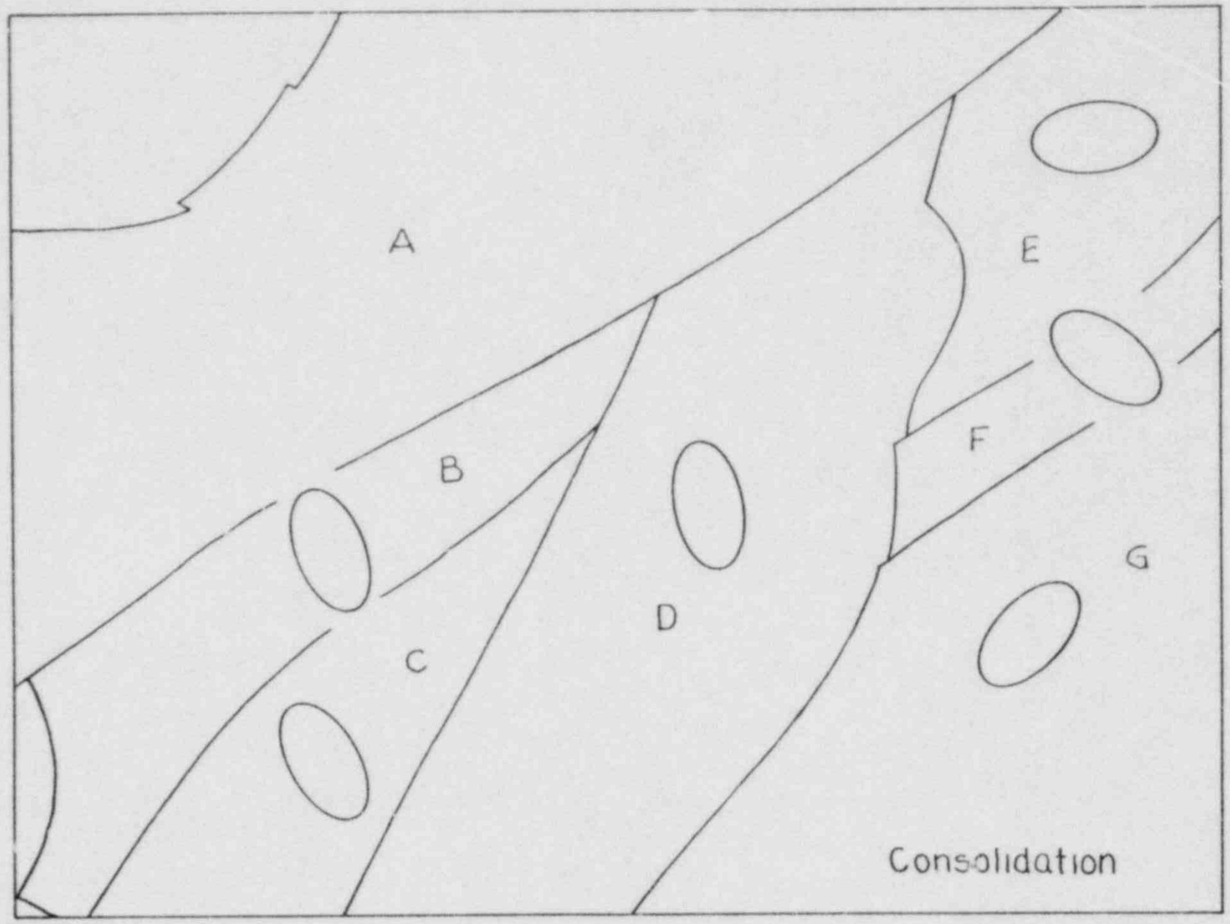

Figure 4a. Map of the Cape Ann area, showing the horizontal projection of the greatest and least principal stress, calculated from joint data, during the consolidation of mafic dikes. Letters refer to fault blocks shown on Figure 2.

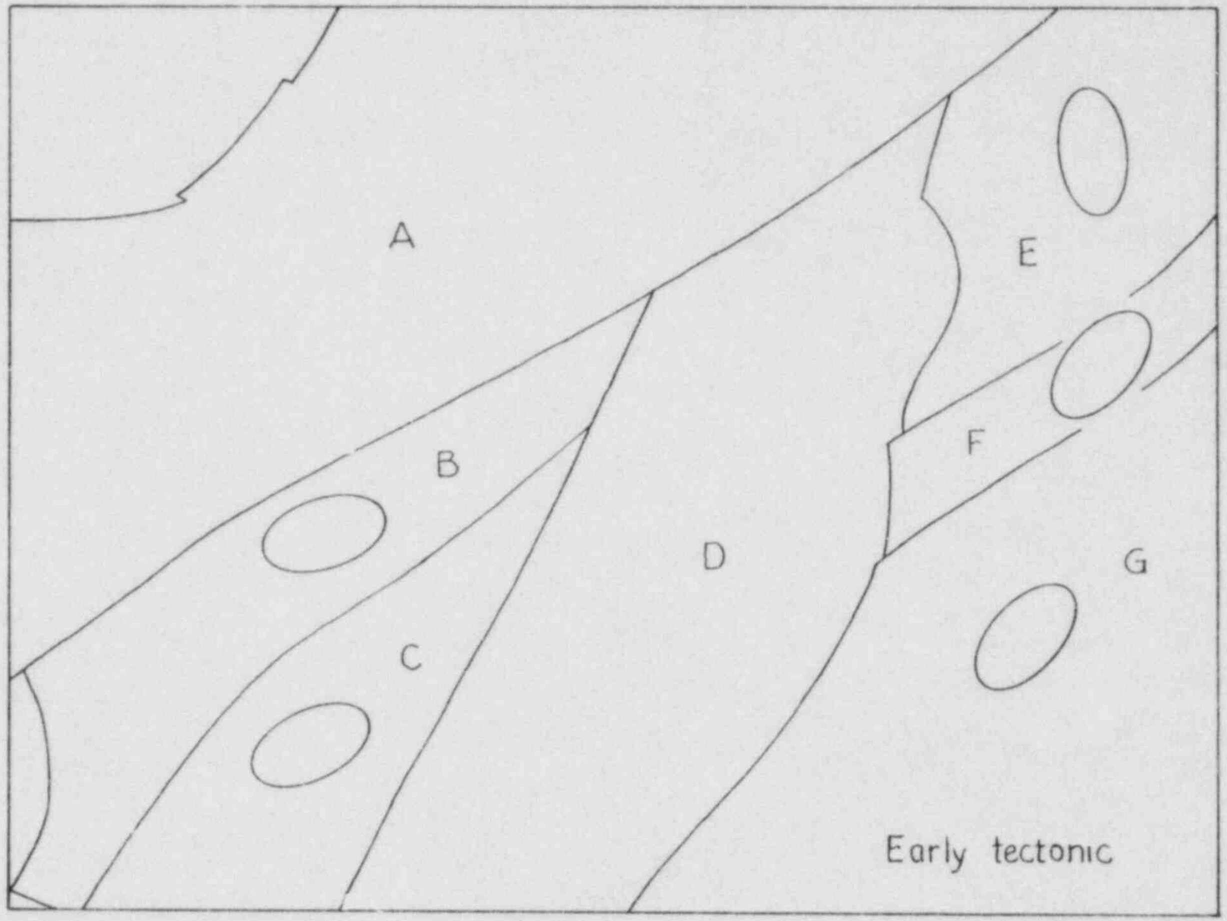

Figure 4b. Map of the Cape Ann area, showing the horizontal projection of the greatest and least principal stress, calculated from joint data, during early regional tectonic events. Letters refer to fault bounded blocks shown on Figure 2.

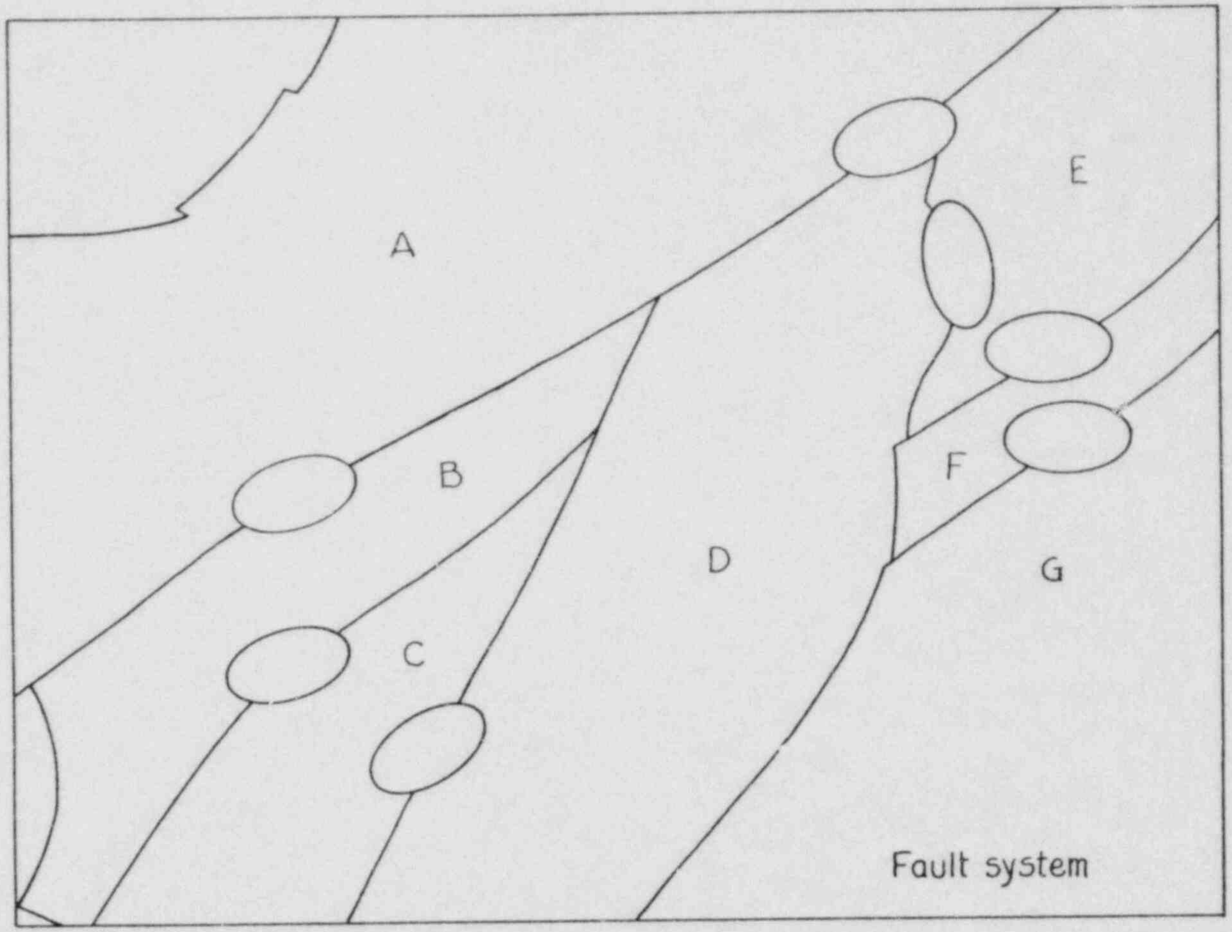

Figure 4c. Map of the Cape Ann area showing the horizontal projection of the greatest and least principal stress, calculated from joint data associated with the regional faulting. Letters refer to fault blocks shown on Figure 2.

and was as shown in Figure 4b.

Further change in orientation of the stress field is seen in the attitude of jointing associated with the regional faulting. This is the last period of joint development and has overprinted and masked the earlier episodes. (Figure 4c).

Some indication of the present day stress field is given by the orientation of relief cracks associated with highway and quarry blasting. Unfortunately, the number of such observations is limited but the available data suggests the least principal stress to be very slightly to the east of north, (Figure 5).

The rotation of the stress field on Cape Ann through time is shown by Figure 6 in which the polar projections of the intermediate principal stress (σ_2) to the lower hemisphere of an equal-area net are plotted. Positions are shown for early consolidation jointing, later tectonically induced jointing, and the stress field which caused the faulting.

Sheeting is widely developed in granitic rocks of the Cape Ann Plutonic Series, but has not been included in the preceding analysis. Typically the sheeting dips seaward and defines a rough dome.

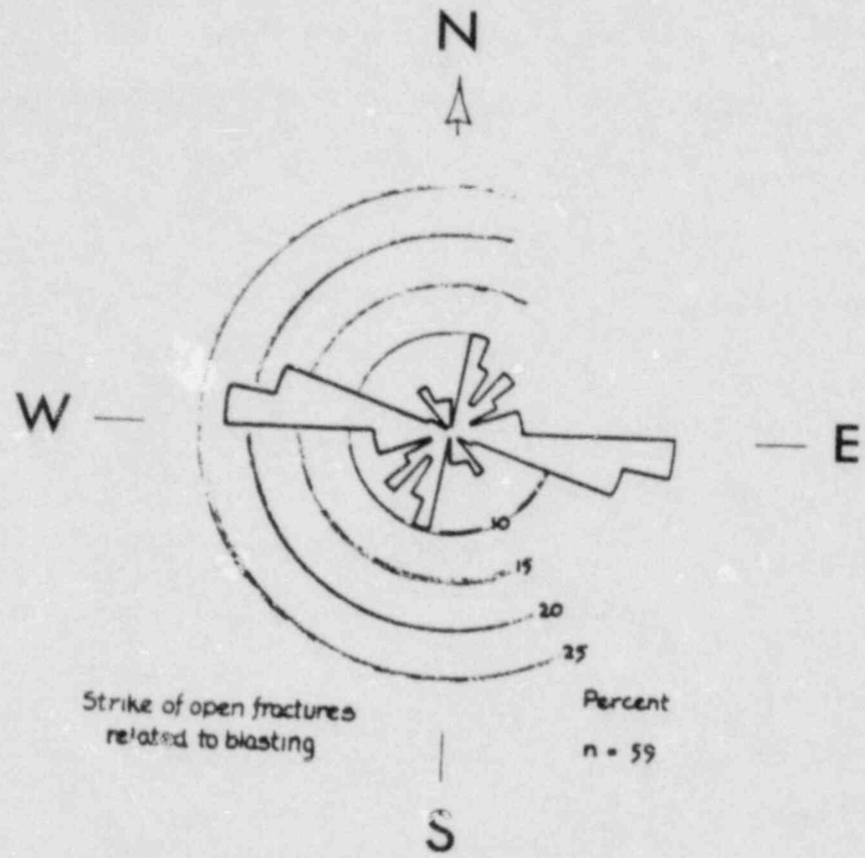

Figure 5. Diagram showing the orientation of relief cracks associated with highway and quarry blasting on Cape Ann.

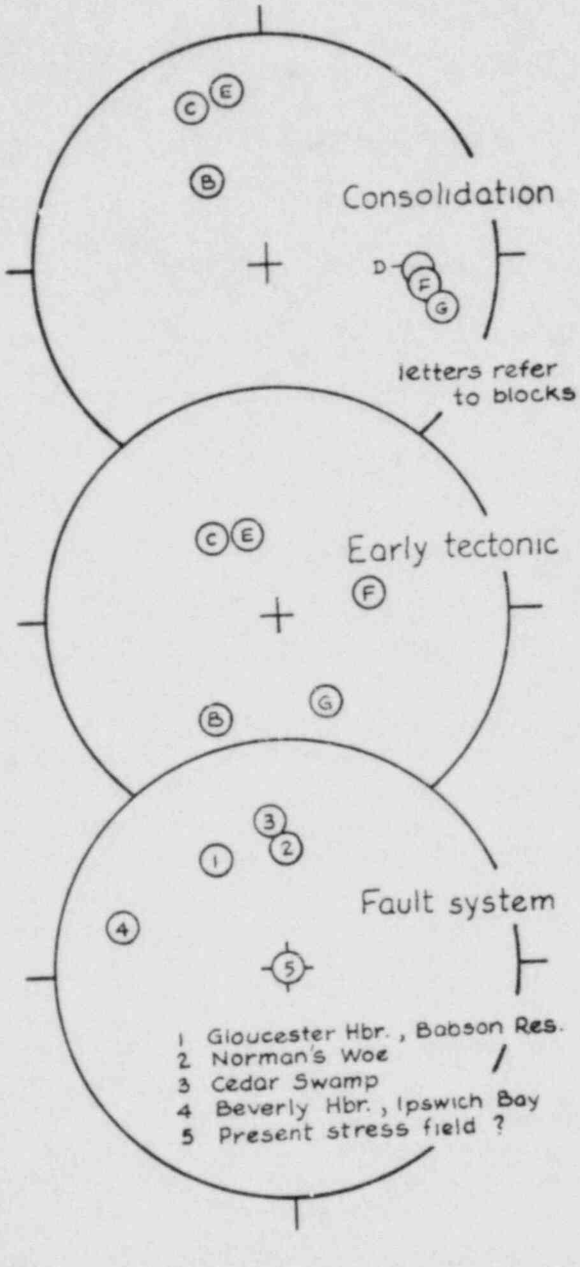

Figure 6. Diagram showing polar projections of the intermediate stress to the lower hemisphere of an equal area net for jointing related to consolidation, early tectonic and fault effects. (Figs. 4a, 4b, and 4c).

3.0 STRATIGRAPHY

3.1 Stratified or layered rocks

3.1.1 Pre-Silurian rocks

3.1.1.1 Middlesex Fells Volcanic Complex

Mafic metavolcanic deposits, of late Precambrian (?) age, are the oldest bedrock exposed in the Cape Ann area and have been correlated by Bell and Alvord (1976) with the mafic upper part of the Precambrian (?) Blackstone Series of Rhode Island as described by Woodworth in Shaler and others (1899) and Quinn and others (1949-1968). The Middlesex Fells Volcanic Complex was formerly included as a unit in the Marlboro Formation of Emerson (1917) and La Forge (1932) but, following Bell and Alvord (1976), these rocks are older than rocks in the type locality of the Marlboro Formation. The Complex is a typical volcanic pile composed of lentils of flow rocks, coarse pyroclastic deposits, and fine-grained tuffs which have undergone both prograde and retrograde metamorphism.

According to Bell and others (1973) and Dennen (1975c), these mafic metavolcanic rocks occur as a homoclinal sequence in the central and northern portions of fault block III (Figure 1) in the Ipswich, Georgetown, and Salem quadrangles and in several xenolithic masses in fault block IV. Although their outcrops are mostly small and scattered, they furnished large amounts of debris to the glacial drift which allows the extent of their bedrock area to be determined. The lower part of the sequence consisted mostly of interlayered ash-fall tuffs and flow rocks, including a pillow lava zone near the base. The middle part consisted mainly of pyroclastic material interlayered with minor flow rock and ash fall tuff. The upper part was mainly ash fall tuff and fine pyroclastic deposits enclosing thin lenses of flow rocks. The composition seems to have been predominantly basaltic although parts may have been andesitic. The upper part includes thin lenses of meta-andesite or metadacite. Both upper and lower parts of the sequence are cut out by intrusive rock and faults. Lack of exposure and dilation by intrusive rock prohibits accurate estimates of thickness, but probably 1500 meters of the sequence of metavolcanic rocks exist in the Cape Ann area.

After deposition, these volcanic rocks were regionally metamorphosed to amphibolite facies and later, except for isolated occurrences, underwent retrograde changes by two periods of hydrothermal alteration. In the metamorphism, the mafic constituents were converted mainly to hornblende, but in some beds or layers small quantities of biotite were formed.

An early period of pervasive hydrothermal alteration, perhaps associated with emplacement of the Topsfield Granodiorite and the diorite of Rowley, almost completely converted hornblende and biotite to chlorite and saussuritized feldspars with the production of much epidote. During a later, post-faulting, hydrothermal episode carbonate minerals, pyrite, and specular hematite were deposited in fractures. These episodes of alteration almost completely eliminated bedding, foliation and textural features so attitudes on most outcrops are indeterminate. These rocks today are typically hard, flinty, dark greenish-grey metavolcanics which are fine-grained, massive, and have closely-spaced polyhedral jointing. Thin-section petrography reveals former textures, mineralogy and history.

3.1.1.2 Metavolcaniclastic rocks: According to Bell and others (1973), two units of the thick metavolcaniclastic sequence of northeastern Massachusetts that is considered to be of Pre-Silurian age (Bell and Alvord, 1976) are exposed in the Georgetown and Salem quadrangles. The Boxford Member of the Nashoba Formation, named the Boxford Formation by Castle (1965) from outcrops in that town, seemingly conformably overlies the Fish Brook Gneiss, named by Castle (1965) from outcrops near Fish Brook in Boxford. The lower part of the Fish Brook Gneiss as known from other localities to the southwest is cut out by faults and intrusive rock in the Georgetown quadrangle. Both units were deposited subaqueously in a presumably marine environment.

3.1.1.2.1 Fish Brook Gneiss: This rock is found in fault block I (Figure 1) in the western portion of the Georgetown quadrangle. It is today chiefly a light grey, leucocratic, fine-to medium-grained plagioclase-quartz-biotite gneiss which characteristically weathers pale yellow. Ferromagnesian minerals increase and the quartz content decreases upward within the unit. The protolith was partly degraded rhyodacite or dacite volcaniclastic detritus deposited as thin ripple-marked beds. Amplitudes of ripples range from 5-10 cm. in the lower part of the unit to 1-3 cm. in the upper part, and some of the upper part is devoid of ripples. Thin beds and lenses of amphibolite, biotite-hornblende-feldspar gneiss, and feldspar-biotite schist formed from mafic tuff are interspersed throughout the unit but constitute less than 5 percent of its volume. About 1500 meters of the formation is present in the Georgetown quadrangle.

3.1.1.2.2 Boxford Member of the Nashoba Formation: The Boxford Member crops out sporadically in fault block I (Figure 1) in the northwestern portion of the Georgetown and Salem quadrangles. It consists of conspicuously layered dark grey or black amphibolite and minor biotite-hornblende-feldspar and whitish to pale green calc-silicate rock. Layers range from less than a centimeter to a meter thick but mostly are less than 3 cm. thick. Intervals of this formation that are 100 meters thick are pyritiferous and weathering causes them to become heavily iron-stained. The protoliths were interlayered carbonate sediment and fine-grained mafic ash-fall tuff. The formation is about 1500 meters thick in the Georgetown quadrangle. This unit was included by Hansen (1956) together with the Fish Brook Gneiss among the lower members of the Nashoba Formation. Recent work by Bell and Alvord (1976) places the Boxford Member at the base of the Nashoba and elevates the Fish Brook Gneiss to formation status.

3.1.2 Siluro-Devonian rocks

3.1.2.1 Newbury Complex: Rocks of the Newbury Complex comprise the entire surface of fault block II (Figure 1) which is a structural remnant of a volcanic terrane. Two poorly exposed areas of these rocks are also present in fault block III in the northwestern corner of the Salem quadrangle. The stratigraphic and structural make-up of the terrane in the Georgetown quadrangle has been determined by Bell and others (1973) in part by extrapolation from exposures to the northeast in the Newburyport West and Newburyport East quadrangles and in part by examination of glacial debris. The Complex consists of at least eight stratified members and one intrusive member. Neither the upper nor the lower parts of the Complex are preserved, and the lower two members are not exposed in the Georgetown quadrangle. At a few localities, cross-bedding, graded bedding, and conglomerates derived from earlier deposits show the strata to be generally overturned to the southeast or east and thus the rocks of the Complex are progressively older in a westerly or northwesterly direction. As pieced together from several subsidiary fault blocks in the Georgetown, Newburyport West, and Newburyport East quadrangles, the stratified members aggregate at least 3650 meters and perhaps as much as 4500 meters in thickness.

These rocks are petrographically little modified from the state in which they were laid down. Devitrification of the glassy rocks, local silicification, and pervasive propylitization of the mafic rocks are modifications that might have occurred during lithification as plausibly as later. Epidote occurs generally along fractures in the more mafic rocks and quartz veins are locally abundant in all the stratified members. The Newbury Complex has not been affected by regional dynamic metamorphism.

The stratified units of the Newbury Complex exposed within the Georgetown, Salem and Ipswich quadrangles are:

limestone-shale member		$\geq$ 90 m
red mudstone member	poorly exposed	$\leq$ 230 m
siliceous siltstone unit		$\leq$ 460 m
andesite member	flows, tuffs, volcaniclastic breccia, minor water-laid conglomerate, sandstone, tuffaceous shale and fossiliferous mudstone.	$\geq$ 900 m

rhyolite unit	locally overlain by rhyolite detritus	≤ 670 m
basaltic member	massive flows with scoriaceous borders separated by thin zones of basaltic tuff or paleosoil	base not exposed

The intrusive member is fine-grained alaskite that is one of the more resistant rocks of the Newbury Complex. Outcrops occur sporadically throughout an otherwise well-ordered sequence of lithologic units but lack continuity which suggests they are near-surface intrusive phases of the Complex. These intrusions seem to be pod-form or sill-like bodies, ranging from a few to perhaps 100 meters in thickness, emplaced concordantly with the enclosing strata.

The Newbury Complex is the only unit in the Cape Ann area which is dated by fossils. A collection of shelly marine fossils from an outcrop near the intersection of the Newburyport Turnpike and Central Street in the town of Rowley was first reported by LaForge (in Emerson, 1917). A similar assemblage was found by N.P. Cuppels in an outcrop near the northeast edge of Wilson Pond, also in the town of Rowley. These fossils occur in thin calcareous mudstone zones that separate breccias and flows of the andesitic member. Remains of brachiopods, pelecypods, gastropods, ostracodes, crinoids, and trilobites have been found. Cuppels also found ostracodes to be locally abundant in the limestone-shale member. These fossils generally are considered to be of Late Silurian to Early Devonian age.

Toulmin (1964) describes the rediscovery of a fossiliferous locality containing leperditiids and other smaller ostracodes first described by Foerste (1920). The fossils occur in a thin bed of finely crystalline limestone exposed in the town of Topsfield on the east side of the small hill northwest of Old Copper Mine Road, 580 m north of Nichols Brook. The age of the collection is considered to be Upper Silurian or Lower Devonian.

Inasmuch as the Newbury Complex is everywhere in fault contact with surrounding formations and is not intruded by any of the plutonic units, this knowledge unfortunately provides no basis for dating other formations.

3.1.3 Devonian (?) rocks

3.1.3.1 Lynn Volcanic Complex: Flows, agglomerates, and ash falls of the Lynn Volcanic Complex (Clapp, 1910, 1921; Emerson, 1917; LaForge, 1932) are found on Marblehead Neck and outer islands in Salem Harbor. In this locality these rocks are usually dark purplish red to black felsites, originally glassy but now devitrified, dense, and always porphyritic to some degree. Petrographic examination and semi-quantitative spectrochemical analysis indicates that they are rhyolites. Closely spaced jointing into small rhombohedral blocks is characteristic. Layering is prominent but contorted with generally steep dips. Massive felsites to the south are succeeded northward by agglomerates and thinly flow-banded rocks; inclusions of massive felsites in the more northerly units suggests that their age also decreases northward. Clapp (1920) estimated the thickness to be of the order of 600 m.

The contact of these volcanic rocks with rocks of the Cape Ann Pluton is not exposed. Basalt porphyry and diabase dikes identical with those elsewhere shown to be cogenetic with the Cape Ann Pluton cut the volcanic sequence while sparsely porphyritic felsic dikes, identical in composition and appearance to the massive and banded volcanic rocks, cut Cape Ann Granite facies in the Gloucester and Rockport quadrangles. The Lynn Volcanic Complex is thus an extrusive facies of the Cape Ann Pluton intrusive rocks as believed by Clapp (1921) and Toulmin (1964).

Bell and others (1973) note the presence of remnants of unmetamorphosed latite porphyry lying on diorite of Byfield in exposures in excavations in the southwestern part of the Georgetown quadrangle. This deeply sapropelized latite is iron-and sodium-rich and has about the same composition as the intermediate facies of the Cape Ann Plutonic Series and, although it is more mafic than the felsites described above, rocks of the Complex outcropping immediately to the southeast of the area include mafic units. It is tentatively considered to be an extrusive phase of the Cape Ann Plutonic Series and may thus be included in the Lynn Volcanic Complex.

3.2 Intrusive Rocks

3.2.1 Possible Precambrian Rocks

Medium to coarse-grained comagmatic plutonic rocks ranging in composition from diorite to granite make up most of fault block III and all of area V, Figure 1 (area V is separated from area IV by an unconformity, not a fault). These rocks are a gradational sequence, dominantly granodioritic, in which the mafic facies grades into and is intruded by the salic facies. These rocks intrude only the mafic metavolcanic rocks of the Middlesex Volcanic Complex of probable Precambrian age and are themselves considered to be of probable Precambrian age although the evidence for this assignment is not conclusive.

The salic facies in the Salem quadrangle was termed Topsfield Granodiorite by Toulmin (1964) and given the informal name of granodiorite of Ox Pasture Brook locality by Bell and others (1973)

Dennen,(1975b).

The salic facies appears to be petrographically identical with the Dedham Granodiorite of Crosby (1880) and has been subjected to the same kind of hydrothermal alteration which produced distinctive colorations of red, green, and mottled combinations at different localities. The age, according to Barosh and others (1977), is also compatible with the presumed late Precambrian emplacement of these rocks and they assign the name Dedham Granite to the rocks outcropping in area V. Although these rocks may be probably correlated with the more extensive Dedham Granodiorite, the name Topsfield Granodiorite is retained herein in the absence of definitive field and laboratory study.

<u>3.2.1.1 Diorite of Rowley</u>:--constitutes the mafic member of this comagmatic suite. It outcrops in a roughly circular area about 3 km in diameter around the town of Rowley. The rock in the central part of the outcrop area is slightly altered hornblende diorite which is almost surrounded by an aureole of more salic rock that makes an intrusion breccia into the mafic metavolcanic rocks. Outlying small stocks and dikes of the diorite intrude the mafic metavolcanic rocks of the Middlesex Volcanic Complex.

Locally the diorite grades into a quartz diorite facies by an increase of quartz, potassium feldspar, and the albite component of the plagioclase. Dikes and stocks of the diorite are usually intensely saussuritized and chloritized.

<u>3.2.1.2 Topsfield Granodiorite</u>:--is the most widely distributed facies of this comagmatic suite. It forms about half of fault block III and all of the small area V, on Marblehead Neck (Figure 1). In the Salem quadrangle it is typically an unfoliated medium-grained to coarse-grained or porphyritic quartz diorite to

granodiorite. A slight foliation is occasionally seen in the Georgetown quadrangle to the northeast which becomes more marked in the Ipswich quadrangle.

In its original state, the rock was probably whitish or light grey speckled with variable quantities of black ferromagnesian minerals. Two episodes of pervasive hydrothermal alteration, however, have markedly changed its appearance. In different areas it may be mottled green, mottled orange-red and green, orange-red, dark red, or blue-grey depending upon the nature and intensity of the alteration process. During an early episode of alteration, ferromagnesian minerals were partly chloritized and feldspars partly saussuritized causing the rocks to become somewhat greenish. Feldspars later became salmon-red by impregnation with iron oxide and the deposition of small quantities of specular hematite in fractures. The later reddish alteration, which locally obliterated the earlier green alteration, is sometimes very conspicuous. The granodiorite exposed in the vicinity of Ox Pasture Brook in the northern part of the town of Rowley is moderately altered, mainly as a result of the early episode of hydrothermal alteration, but it is considered to be more nearly similar to the original appearance than any of this rock exposed elsewhere in the area. The granodiorite exposed at the type locality in the town of Topsfield is altered to a rather dark salmon-red color and has a very different appearance. Regardless of these color variations, this rock is characterized by ellipsoidal quartz grains or aggregates which are glassy when fresh but become milky blue on weathering.

The Topsfield Granodiorite encloses small lenses and dike-like masses of more siliceous aplite, intrudes the mafic metavolcanic rocks of the Middlesex Fells Volcanic Complex and lies unconformably beneath the rocks of the Lynn Volcanic Complex.

The salic facies was termed Topsfield Granodiorite by Toulmin (1964) and it seems reasonable to extend this term to include both the salic and mafic facies although Toulmin assigned the Topsfield a mid-Paleozoic age.

3.2.2 Silurian (?) or Devonian (?) Rocks

3.2.2.1 Diorite of Byfield: This diorite crops out abundantly in the low knobby hills of the western third of the Georgetown quadrangle (fault block I, Figure 1). According to Bell and others (1973), roof, border, and intrusion breccia zones of a large pluton constitute most of the unit exposed in this quadrangle and rock that probably is representative of the core of this pluton crops out in the vicinity of Byfield village in the southwestern part of the Newburyport West quadrangle. This diorite intrudes the Fish Brook Gneiss and Boxford Member of the Nashoba Formation and is intruded by small masses and veins of white to pink granodiorite considered to be comagmatic with it. The diorite is probably a facies of the Sharpners Pond Tonalite of Castle (1965).

The diorite of Byfield in the Georgetown and Salem quadrangles ranges from a hornblendic facies devoid of quartz to a biotitic facies containing about 15 percent quartz, 5 percent potassium feldspar, and no hornblende. The more mafic hornblendic facies is devoid of flow foliation and is thought to be representative of the core of the pluton while the biotitic facies forms the roof and border zones of the pluton. Within these outer zones there is considerable veining and diking of early biotitic facies by later facies, the older being more mafic and the younger more salic. Most outcrops show from two to eight cross-cutting facies.

The more biotite-rich facies commonly have conspicuous flow foliation parallel to vein or dike walls. Rock in the chilled parts of the roof and border zones is mostly fine-grained, dark-colored, and biotite-rich. Some of the dioritic rock in the roof and border zones has a pseudo-foliation inherited from partly assimilated metamorphic wall rock.

3.2.2.2 Pink Granodiorite: According to Bell and others (1973), this is a nonresistant rock that crops out very sparsely in areas having appreciable cover of glacial drift in the northern portion of the Georgetown quadrangle. It is seen in only a few outcrops and might not have been recognized as indicating a significant body, except that the outcrops represent southerly extensions of a large granodiorite mass that is more widely exposed just north of the quadrangle. The granodiorite is everywhere intruded into the diorite of Byfield, which is commonly intricately veined by the pinkish rock for some tens of feet adjacent to the larger masses of granodiorite. The recognition of these resistant-veined diorites and the local dominance of granodiorite erratics over other glacial detritus are the main basis for outlining the granodiorite bodies as they are shown on the map. The bodies might be much more extensive in the areas shown, but are not likely to be less. Where the granodiorite is even moderately sheared, the biotite has been obliterated, leaving an alaskitic-appearing rock that commonly forms a rubble that is heavily rust-stained.

3.2.2.3 Cape Ann Plutonic Series: Plutonic rocks of Cape Ann ranging from gabbro through granite to feldspathoidal syenite were described by Washington (1899) as belonging to the "petrographical province of Essex County, Massachusetts". Later workers divided these rocks into a number of named units, i.e., Nahant Gabbro (Clapp, 1910), (equivalent to Salem Gabbro-diorite, LaForge, 1932), Salem Gabbro-diorite (Clapp, 1910, 1921; Emerson, 1917; LaForge, 1932); Beverly Syenite (Clapp, 1910, 1921; Emerson, 1917), Cape Ann Granite (equivalent to Quincy Granite, Clapp, 1910; Emerson, 1917), Squam Granite (Clapp, 1910; related to Granite of Cape Ann, Emerson, 1917), Cherry Hill Granite and Wenham Monzonite (Toulmin, 1964).

Not only have distinct units been named, but they have been ascribed widely different ages because of their mutual intrusive relations. However, recent field and petrographic study (Bell and Dennen, 1972; Dennen, 1975a, 1975b, 1975c, 1975d), spectrochemical analysis of a number of the same minerals from the mafic and salic phases (Dennen, 1972), and studies of major and minor element chemistry (Survant, in progress; Norton, 1974, 1975, and Norton and others, 1975), make it apparent that Washington's assessment of these rocks as consanguineous, in his terms "a region of igneous rocks which possess in common certain characters, structural, mineralogical, or chemical, and in which the characters may vary continuously from one end to the other of the series of rocks represented" is correct and that separation into named stratigraphic units is unwarranted. The term "Cape Ann Plutonic Series" as proposed by Bell and Dennen (1972) is, therefore, used herein with those named units having long historical standing and showing clear cut intrusive relationships being retained as facies.

These rocks are characterized by a unique mineral assemblage, the same minerals occurring in different proportions in all facies. Feldspars, both potash feldspar and plagioclase, are typically greenish with a greasy luster and ferromagnesian minerals are fresh shiny black. Quartz is usually glassy.

The mafic facies contains abundant ferromagnesian minerals, principally ferrohornblende, with variable amounts of both a pinkish titaniferous pigeonite and a pale green augite. Biotite is a common minor product of alteration. Altered plagioclase of variable composition (usually about An_{30-40}) makes up about half of the rock. Small amounts of microcline microperthite and quartz are usually present.

The dominant minerals of the salic facies are microcline microperthite, ferrohornblende, and quartz. Small amounts of pyroxenes and plagioclase, about An_{30}, are often present. Toulmin (1964) made intensive petrographic and chemical studies of the principal minerals of the Cape Ann Pluton. The original composition of feldspars, now almost always either perthitic or rarely antiperthitic is shown in Figure 7, taken from his data. The progressive increase in the orthoclase component from syenitic to granitic facies probably represents progressive differentiation in this direction.

Ferrohornblende is a ubiquitous mineral phase in all of the rock types of the series ranging from 10-30 volume percent in the mafic rocks and from 1.1-17 percent in the salic lithologies. It is found as well in associated pegmatites, some veins, and as coatings of early-formed joint surfaces. Other but less common ferromagnesian minerals reported as being present are all high-iron varieties and include biotite (annite and lepidolemane), aegiritic augite, fayalite, grunerite, cryophyllite, and hedenbergite. The amphiboles in the Cape Ann rocks were early recognized as high-iron Na-Ca varieties particularly in the salic

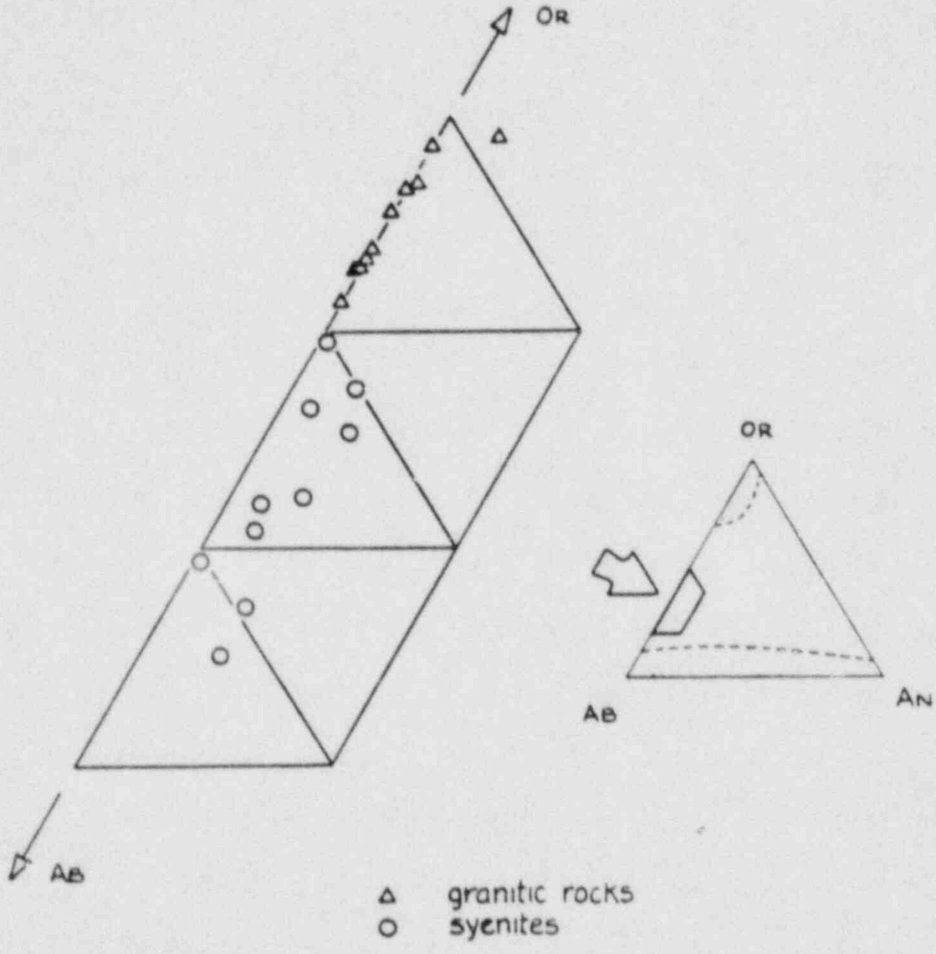

Figure 7. Ternary diagram showing the original composition of homogenized feldspar in salic rocks of the Cape Ann Plutonic Series between orthoclase (OR), anorthite (AN) and albite (AB), end members (from Toulmin, 1964).

lithologies, and have been described by many authors. Washington (1899) notes "the presence of the MgO-free 'glaucophane' molecule in the blue hornblendes of the region" and that "soda-hornblendes . . . are common". Warren and McKinstry (1924), in describing the Cape Ann granite, state, "The hornblende is clearly a soda-iron variety . . ." Its optical properties as given by Washington are: α bright yellowish green to light brownish-yellow; β dark greenish-brown; γ dark olive green. Absorption $\gamma = \beta > \alpha$; the extinction $\gamma \wedge C'$ about 30°; optic angle small; optically negative". Toulmin (1960) says the major ferromagnesian mineral (in the Cape Ann and Peabody granites) is a ferrohornblende containing about 10 to 35 percent of the arfvedsonite component.

Unpublished analyses by the author of many specimens from rocks of the Cape Ann Pluton shows the average amphibole to be close to hastingsite, (Figure 8), but to vary within the limits of approximately Na/ΣX 10 to 35, Fe/ΣY 60 to 85, and $Al^{IV}/\Sigma Z$ 5 to 25. No clear cut relations of hornblende chemistry with various measures of rock differentiation can be shown other than a general tendency of FeO*/MgO to increase from mafic to salic facies. Probably this is because only local heterogeneous equilibrium appears to have been established in this cumulate rock.

Rocks of the Cape Ann Plutonic Series are considered by Barker and others (1974) to be representative of an unusual gabbro-anorthosite-syenite-potassic granite suite. They propose a complex genetic model for such rocks "in which mantle-derived, convecting olivine basaltic magma first reacts with K_2O-poor lower crust of granulite facies to produce magma of quartz syenitic

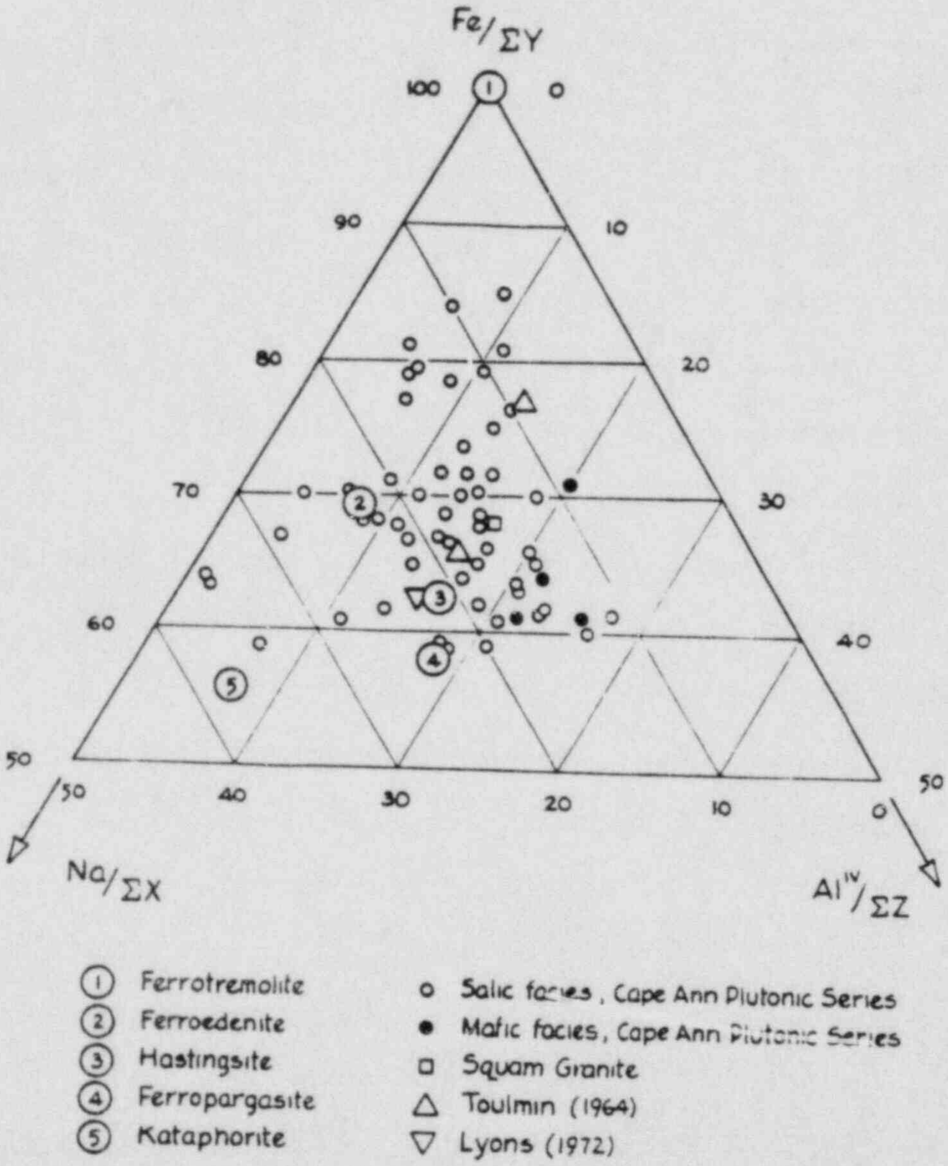

Figure 8. Ternary diagram showing the hornblende composition in the Cape Ann Plutonic Series between iron (FE/ΣY), aluminum (Al^{IV}/ΣZ) and sodium (Na/ΣX) end member.

composition. The syenitic liquid in turn reacts with granodioritic to granitic intermediate crust of amphibolite facies to produce the predominant fayalite-free biotite and biotite-hornblende granites of the batholith. The reactions of magma and roof involve both partial melting and the reconstruction and precipitation of refractory phases, as Bowen proposed. Intermediate liquids include MgO-depleted and Na_2O-enriched gabbro, which precipitated anorthosite, and alkali diorite. The heat source is the basaltic magma; the heat required for partial melting of the roof is supplied largely by heats of crystallization of the phases that settle out of the liquid - mostly olivine, clinopyroxene and plagioclase". The intrusive characteristics of this suite are intrusion as a ring- or ovoid-shaped mass. (evidence removed by erosion at Cape Ann?) into older cratonic rocks under anorogenic conditions in association with basaltic to intermediate consanguineous intrusives.

The emplacement of the Cape Ann Pluton as shown by field relations began with the intrusion of a mafic magma into a series of mafic volcanic rocks (?) and thin-bedded siliceous sedimentary rocks, probably siltstones in the main. Locally, rapid cooling resulted in a distinctive gabbro porphyry or anorthositic roof phase. This earlier intrusive pulse of mafic composition was closely followed by the emplacement of salic magma separated at depth from the common reservoir.

Settling of feldspar crystals from the salic magma onto the subjacent diorite, possibly in response to lowered pressure accompanying the extrusion of the Lynn Volcanic Complex (Toulmin, 1960) caused the early development of coarse-grained granitoid and trachytic feldspathoidal phases. Contemporaneous crystallization without crystal settling probably resulted in the formation of the fine -to medium-grained Squam Granite facies.

Crystallization of the salic magma continued with concomitant crystal settling as shown by the common cumulate texture in which the interstices between subhedral feldspar grains are filled by quartz and ferrohornblende. Differentiation by this process resulted in a large scale rough layering from quartz-poor basal to quartz-rich upper phases.

Following an intensive study of trace element distribution in many samples from the salic facies, Norton (1975) concluded that his data are ". . . consistent with a crystallization model involving continuous alkali-feldspar crystallization with late stage contemporaneous crystallization of a quartz-amphibole interstitial assemblage". Toulmin (1964) and Lyons (1972) consider the temperature to have been respectively 660°C and 650-750°C; Lyons (1972), and Buma and others (1970) suggest that oxygen fugacity was relatively low, based respectively on the presence of hastingsite as the dominant amphibole and the large Eu depletion.

Magnetic and gravity evidence (Joyner, 1963; Kane and others, 1972) indicates that the salic rocks of the Cape Ann Pluton are in the form of a rather thin sheet floored by a heavier and more magnetic body, probably Salem Gabbro-diorite. Mafic pendants and xenoliths in the body suggest it may be an unroofed sill. Many mafic dikes originating in the deeper unconsolidated basaltic portions of the pluton intruded the salic mush where they were chilled by the slightly cooler granite and then disrupted by its continued movement.

At some point in the consolidation history, most probably early in the emplacement of salic material, felsic stringers derived from the salic magma cut the dioritic rocks and provided the matrix for cognate breccias in the Gabbro-diorite.

The age of the Cape Ann Plutonic Series is in doubt, and neither geochronologic nor geologic studies have been able to refine the time of its emplacement closer than probably Siluro-Devonian. Norton (personal communication, 1976) has made a critical selection of the radiometric ages reported in the geochronologic literature for the northern Appalachians and has reinterpreted the data in the light of the nature of the event. Figure 9, showing only probable crystallization ages and not any believed due to resetting, is taken from his work. From the figure it may be seen that the mode for the ages of the salic rocks appears to be 410 m.y. (Taconic).

Geologically the rocks show no effects of regional metamorphism and are, therefore, either post-Acadian or representative of an anomalous region not affected by the pervasive metamorphism of that time.

Page (1968) assigns the Cape Ann Pluton to his "Late Devonian Plutonic Series" based on a number of features which it has in common with other New England intrusives of this age. Bell and others (1973) for geologic reasons conclude that "This plutonic series was emplaced prior to the regional faulting, possibly during a late stage of the Acadian orogeny or shortly thereafter. The maximum age for it seems to be Middle Devonian".

<u>3.2.2.3.1 Salem Gabbro-diorite Facies</u>: Hornblende diorite, in part the Salem Gabbro-diorite of Emerson (1917) and Toulmin (1964), with a variable but often well oriented fabric and sometimes intensely veined with pink felsic stringers, borders the salic rocks of the Cape Ann Pluton to the north and west and is found

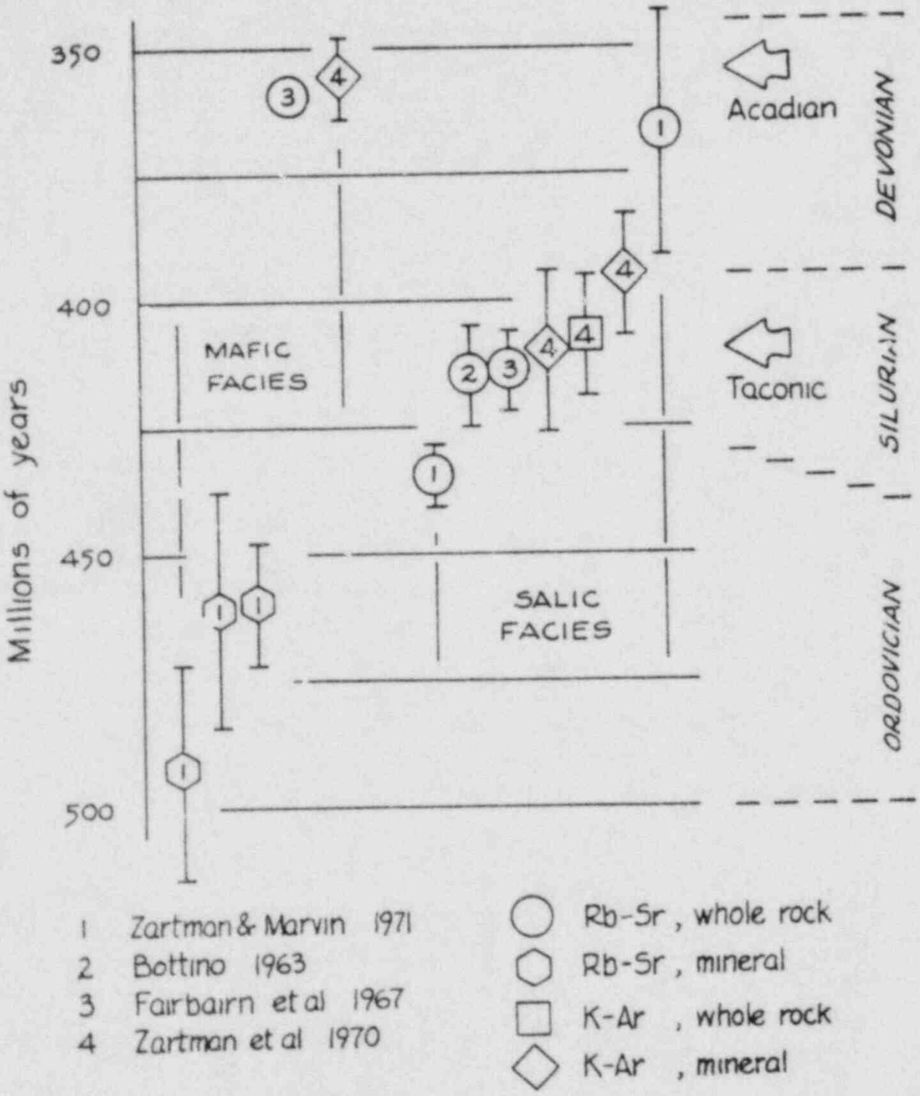

Figure 9. Diagram showing selected geochronologic ages for the Cape Ann Plutonic Series.

within the salic rocks in several large pendants and numerous xenoliths. Distinctive gabbro porphyry inclusions characterized by large (as much as 10 cm) white-weathering red-purple labradorite phenocrysts, locally concentrated into an anorthosite, are found in several areas in the pluton; along Route 128 for 1.3 km southwesterly from the Grapevine Road interchange, at the Gloucester terminus of Route 128 and for 1.1 km westerly, and for about 6 km along the northwest shore of Cape Ann, notably on Davis Neck, (Figure 10). Nahant Gabbro, a phase of the Salem Gabbro-diorite (Bell, 1948) composed of monoclinic pyroxene, labradorite, and minor amounts of olivine, biotite, pyrite and zircon is found on Great Misery Island in the Marblehead North quadrangle.

3.2.2.3.2 Squam Granite Facies: Fine-to medium-grained mafic granite, equivalent to the diorite of Shaler (1889), and the Squam Granite of Clapp (1910), forms an irregular ellipsoidal 1.3 x 4 km pluton trending N30°E from Little River to Ram Island, Gloucester, and is found widely scattered as inclusions throughout the other salic facies (see Figure 10). Field relations place it as post Salem Gabbro-diorite and pre-Cape Ann Granite facies

3.2.2.3.3 Cape Ann Granite Facies: Phaneritic salic rocks ranging in composition from quartzose alkali granites through alkali quartz syenites and syenites to feldspathoidal syenites are the principal rocks of Cape Ann, comprising all of fault block IV (Figure 1). They are generally unfoliated with an uneven hypidiomorphic to subporphyritic and occasionally cumulate texture and crystal sizes of 0.5 to 1 cm. Both texture and grain size are more variable in the syenite rocks of the border regions to the southwest where trachytic textures or very coarse grain sizes are found. Most of

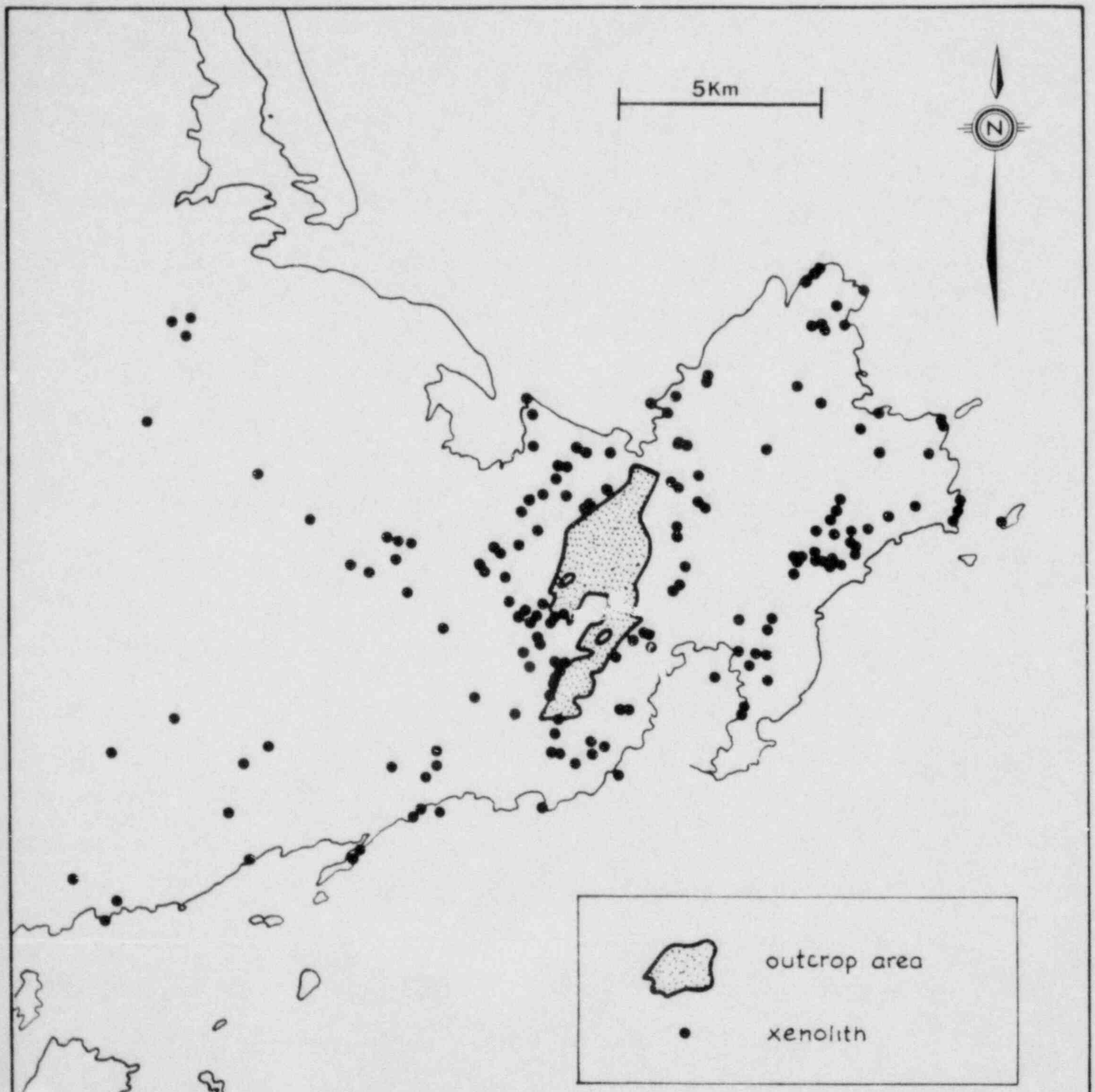

Figure 10a. Map of Cape Ann showing distribution of Squam Granite.

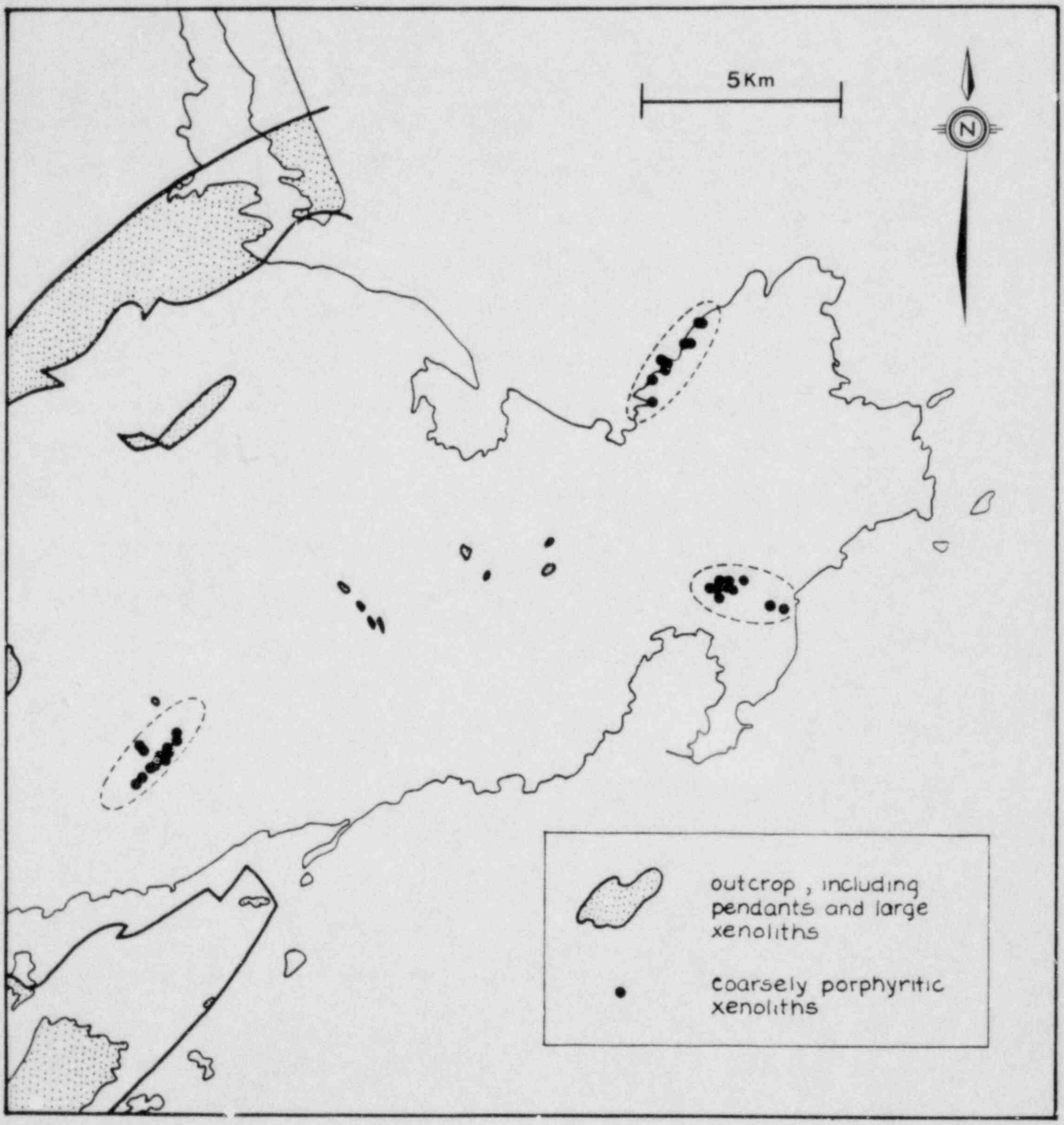

Figure 10b. Map of Cape Ann showing distribution of Salem Gabbro-diorite.

the syenite, however, is texturally equivalent to the granitic facies but usually contains small, irregular pegmatitic patches without well-defined boundaries and, in most places, is distinguished from the closely related quartz syenites and granites only by its negligible quartz content.

Coarse-grained syenites that have crystal sizes of several centimeters, sometimes containing nepheline and sodalite, (the pulsakite and umptekite phases of the Beverly Syenite of Washington (1898, 1899) and Clapp (1921)) occur in dikes and masses along the Beverly-Manchester shore and the adjacent harbor islands close to the contact of the salic rocks with the diorite. The composition of this coarse-grained syenitic facies, except for the occasional presence of feldspathoids and lack of quartz, is the same as that of the granitic facies.

Medium-grained trachytic syenite makes up Bakers Island, where it is a cognate igneous breccia that has 10-20 cm ovoidal clasts mineralogically and texturally very similar to the matrix but slightly darker in color. Trachytic syenite is also found as a textural variant in the coarse-grained facies and as dikes intruding the coarse-grained phase.

The quartz-bearing salic rocks range from alkali quartz syenites to alkali granites in which quartz and ferromagnesian minerals are interstitial to blocky feldspar grains. Small blotches and stringers of aplite and pegmatite are common, but well-developed salic dikes are rare.

The amount of quartz in subunits of the Cape Ann Granite is consistent over areas often mappable in square kilometers and varies rather smoothly from one lithotype to another. Arbitrary divisions of 5, 15 and 25 percent quartz as determined by measurement on the outcrop have been used for mapping purposes. On the basis of their different quartz content, the various salic rocks are arranged in irregular northeast-trending bands. Neither the stratigraphic succession nor dips are known, but field relations suggest the superposition of quartz-rich on quartz-poor types.

The pronounced similarities in texture and mineralogical makeup between quartzose and syenitic rocks of the Cape Ann Pluton coupled with their strong chemical similarities (Survant, in preparation; Norton, 1974, 1975; Survant and others, 1975) suggest that the Beverly Syenite of earlier authors should be considered to be a variant of the Cape Ann Granite facies and not a distinct stratigraphic unit.

Weathering causes sequential color changes in these rocks from dark green to green-grey or grey, then to brown, tan, and finally to white on exposed surfaces; under vegetation, the weathered surface is black-brown and grus is common.

Xenoliths, usually small and well-digested but occasionally preserving their pre-incorporation character, are scattered throughout the pluton. These xenoliths include cognate blocks of the Squam Granite, diorite and other mafic rocks which are fine-grained and commonly porphyritic, and siliceous sedimentary rocks. Many of these latter were originally finely laminated (0.1 to 5 mm.) and have been transformed by thermal metamorphism into thin-banded quartz-biotite rocks which also contain feldspars and hornblende. Muscovite, pyroxene, and garnet were seen in a few of these metasediment xenoliths, and sillimanite in one. Grain orientation due to recrystallization in a stress field is absent.

Contacts between facies of the Cape Ann Plutonic series and of the pluton with its wall rocks are not well exposed and are often faulted. The zone of contact between intruding syenitic facies rocks and the Salem Gabbro-diorite facies is exposed only on Salem Neck where the relations are complex and exact location of the contact is a matter of choice. Toulmin (1964) mapped a transitional contact zone between the Beverly Syenite and Salem Gabbro-diorite on Salem Neck and Winter Island which is here included with Gabbro-diorite. In this area are found dioritic xenoliths including a breccia with ovoidal mafic clasts in a syenite matrix, syenitic apophyses and dikes, and hybrids of the two rocks. The same rock types and textural variability are found on Great Haste and Misery Islands. In contrast to this complex area, the poorly exposed contact area between salic and mafic facies west of Longham Reservoir in the Marblehead North quadrangle is not marked by extensive rock variability. The principal effect is the development of a porphyroidal texture in the granitic rocks by enlargement of feldspar grains.

Granophyric apophyses from the Cape Ann Granite cut the Gabbro-diorite facies in the Salem quadrangle and mafic meta-volcanic rocks along the Ipswich River, and Cape Ann Granite differentiates form the matrix of the intrusion breccia out-cropping on Meeting Green in the town of Ipswich.

<u>3.2.2.3.4 Dike Rocks of the Cape Ann Pluton</u>: The Cape Ann Plutonic Series and associated volcanics are cut by a diverse suite of dikes whose types and inter-relationships suggest a close genetic association to the irruptive and eruptive rocks. The location of those having widths greater than 3 meters is shown on the map. Some dikes are petrographically similar to

the massive phases, some are broken by movement of an unconsolidated host, and mutual intrusive relations are noted. The distinct classes of dikes found on Cape Ann, divided on the basis of their nature, source, and host are shown in Figure 11.

The aplites and pegmatites derived from the Cape Ann Granite facies are mineralogically simple rocks comprised of dominant microcline microperthite, quartz, and ferrohornblende which sometimes include graphic granite, biotite, zircon, amazonite, or fayalite. They are white to grey within the salic rocks and salmon pink in the Salem Gabbro-diorite facies.

The syenitic dikes are mineralogically and texturally similar to the massive syenites and are comprised of dominant microcline microperthite together with ferrohornblende, plagioclase(An_{30}), sometimes nepheline or sodalite, augite, biotite and opaques.

Mafic dikes are texturally variable, generally fine-to medium-grained rocks composed of highly altered plagioclase, usually andesine, hornblende, augite or pigeonite, and biotite. Olivine is rare. Accessories include apatite, sphene, magnetite and pyrite. Phenocrysts are typically andesine. These dikes are typical lamprophyres which are " . . . intrusive into granite or syenite at such a stage of magmatic history that they are easily deformed and intruded by the late residual magma of the granite" (Grout, 1932), and most are either diabase or camptonite.

Rhyolite dikes have phenocrysts of much altered subhedral to euhedral potash feldspar, sodic plagioclase or euhedral beta quartz-forms in a very fine-grained devitrified glass matrix. Minor minerals include potash feldspar, anorthoclase, and hornblende. Accessories are opaques, biotite, zircon, and sphene.

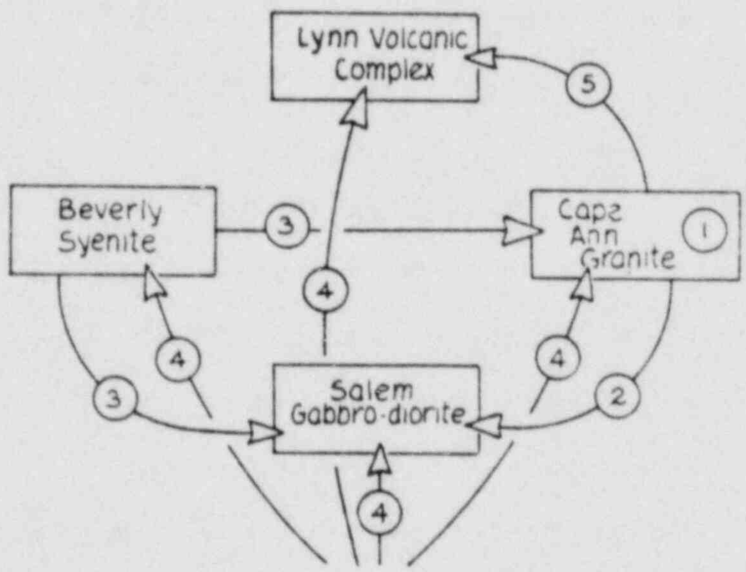

Figure 11. Diagram showing the type, source and host of various distinct classes of dikes found on Cape Ann.

A critical feature often observed in the mafic dikes cutting the Cape Ann Granite is that they have been pulled apart into a series of more or less cleanly broken blocks which are now aligned in a matrix of unfoliated granite. This feature was noted by Toulmin (1964) and ascribed to the formation of a vitrophyric matrix in the cooling granite which could fracture to admit the dike material and behave as a viscous liquid under longer term stress. Close inspection reveals that the dike borders show normal chilling whereas the ruptured ends are not chilled and that the intrusive granite in both tiny dikelets and general matrix is uniformly grained, unfoliated, and shows no evidence of flow. Several separated dikes in the same area and having different strikes may all show separation essentially normal to their strike direction as if each was placed in tension, and suggests the entire system to have been expanding.

These phenomena require that the dike be emplaced in the consolidating granite mass at a time when it was mechanically capable of both easy fracture and flow. The dilatancy principle of Mead (1925) suggests that rupture of the granite could readily occur in response to a sudden stress at any time after the crystals in the cooling magma were in contact, or alternatively, space could be provided at this time simply by closer grain packing. Temperatures of the nascent granite at this stage would be well below that of injected mafic dike material which would, consequently, show chilled borders. Since the granite magma was incompletely solidified and probably undergoing slow, large-scale irruptive movement, fragile rigid masses such as dikes would be torn apart in the expanding system while granitic material filled in between the separated blocks. This in-filling without crystal orientation was probably accomplished by resorption and reformation of the mineral constituents of the granite; at this time they must have been in delicate equilibrium with the rest magma and the increased heat accompanying dike intrusion would have temporarily reversed the crystallization process.

Intrusion of mafic dikes during the irruption of granitic magma requires a nearby source at the critical time. An examination of the dike chemistry (Norton, personal communication) indicates them to be primitive representatives of the Cape Ann Plutonic Series and thus to have had their source in undifferentiated magma at depth.

The location and attitude of the dikes of outer Cape Ann (Gloucester and Rockport quadrangles) were exhaustively studied by R.S. Tarr and reported by Shaler (1889). He concluded that " . . . 5 to 10 percent of the superficial area is occupied by such material. In other words, the horizontal extension of the granites has been increased by somewhat between one-tenth and one-twentieth of the superficial area." Tarr's estimate of horizontal extension assumes a dike density everywhere equivalent to that found locally along the shore. This does not appear to be the case, however, as shown by Figure 12 in which the cumulative width of dikes observed within one-half mile squares is plotted and a strong tendency for the dikes to cluster may be seen. In order to reach values of 5 percent, the cumulative width of dikes in each square would have to reach 132 feet (40.2 meters), a value seldom if ever attained.

Tarr's data for mafic dikes was combined with observations made in adjacent areas to re-estimate the amount and principal

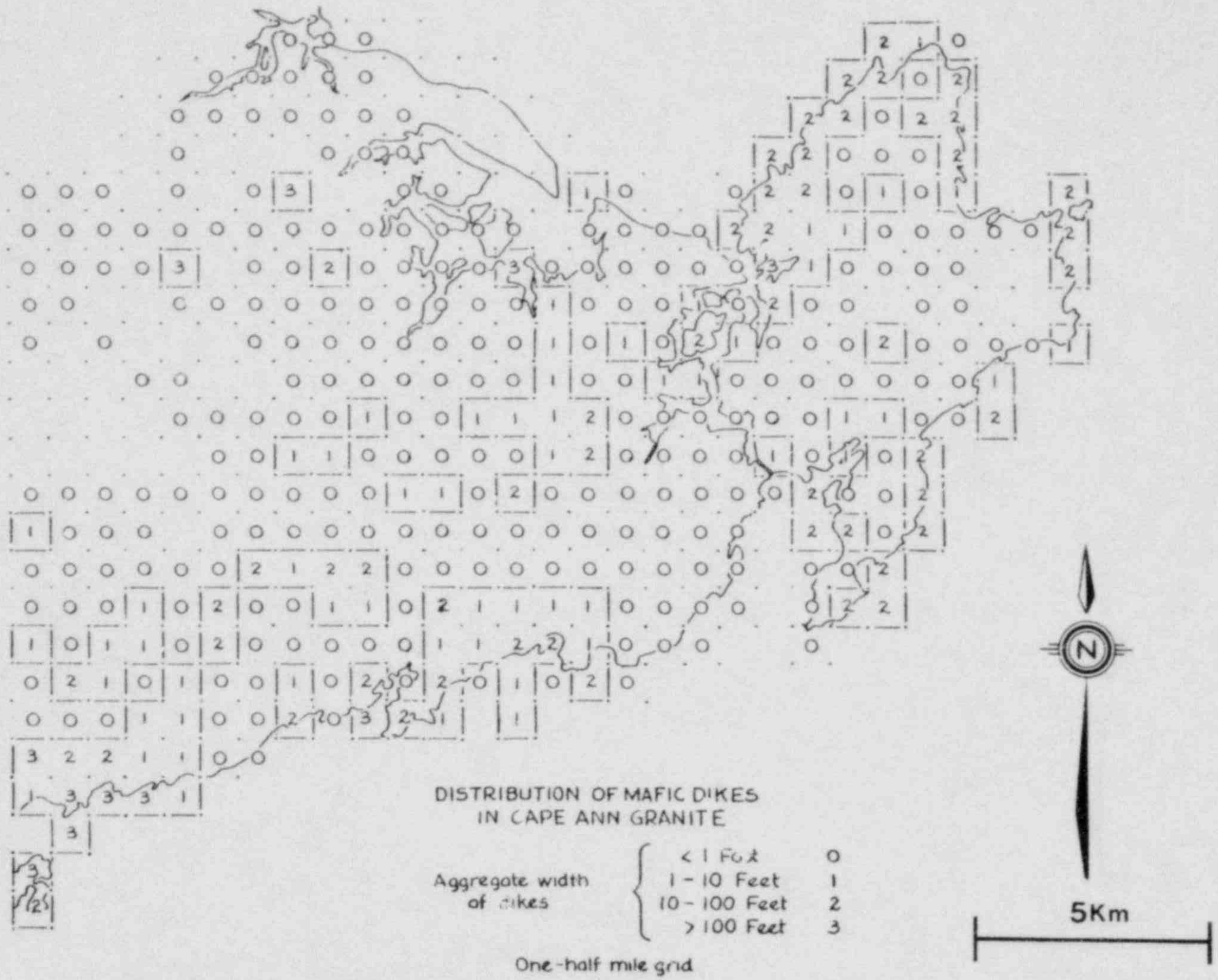

Figure 12. Map of the Cape Ann area showing the distribution of mafic dikes in Cape Ann granite as the aggregate thickness per one-half mile squares.

direction of extension of the granite rocks. Width of 477 dikes (Figure 13) are distributed in an approximately lognormal fashion with a median width of 2.1 feet (0.64 meters). Strike and dip data indicate the typical dike to strike N 22.5° W and dip 75° E. The Cape Ann Granite is exposed for a distance of about 29 kilometers normal to the most common strike of the dikes, i.e., along a line of N 76.5° E through the center of the body. The extension of the body is thus approximately

$$\frac{477 \times 0.64}{29 \times 1000} \approx \frac{305}{29000} \approx 1 \text{ percent}$$

A number of massive, banded, and porphyritic rhyolite dikes are exposed along the shores of Cape Ann, especially in the Gloucester and Rockport quadrangles. Many have the typical black, purplish-red or dark red colors and massive, banded, and porphyritic textures of the Lynn Volcanic Complex which underlies Salem Neck and the outer islands of Salem Harbor. The similarity of these rhyolitic dike rocks to the flows, tuffs, and agglomerates of the Lynn Volcanic Complex make it reasonable to assume that these dikes represent feeders to the extrusive complex and, further, may have their source in the Cape Ann Granite.

Mafic dikes identical with those which cut Cape Ann Granite, etc., also cut the Lynn Volcanic Complex, although they are not separated in this host. If these mafic dikes are indeed the same as elsewhere, then the Lynn Volcanic Complex must have been extruded simultaneously with the intrusion of the granitic rocks.

4.0 METAMORPHISM AND ALTERATION

Metamorphic effects in the Cape Ann area are sharply delimited by major faults. Effects in fault block II (Figure 1) occupied by rocks of the Newbury Complex are very slight and

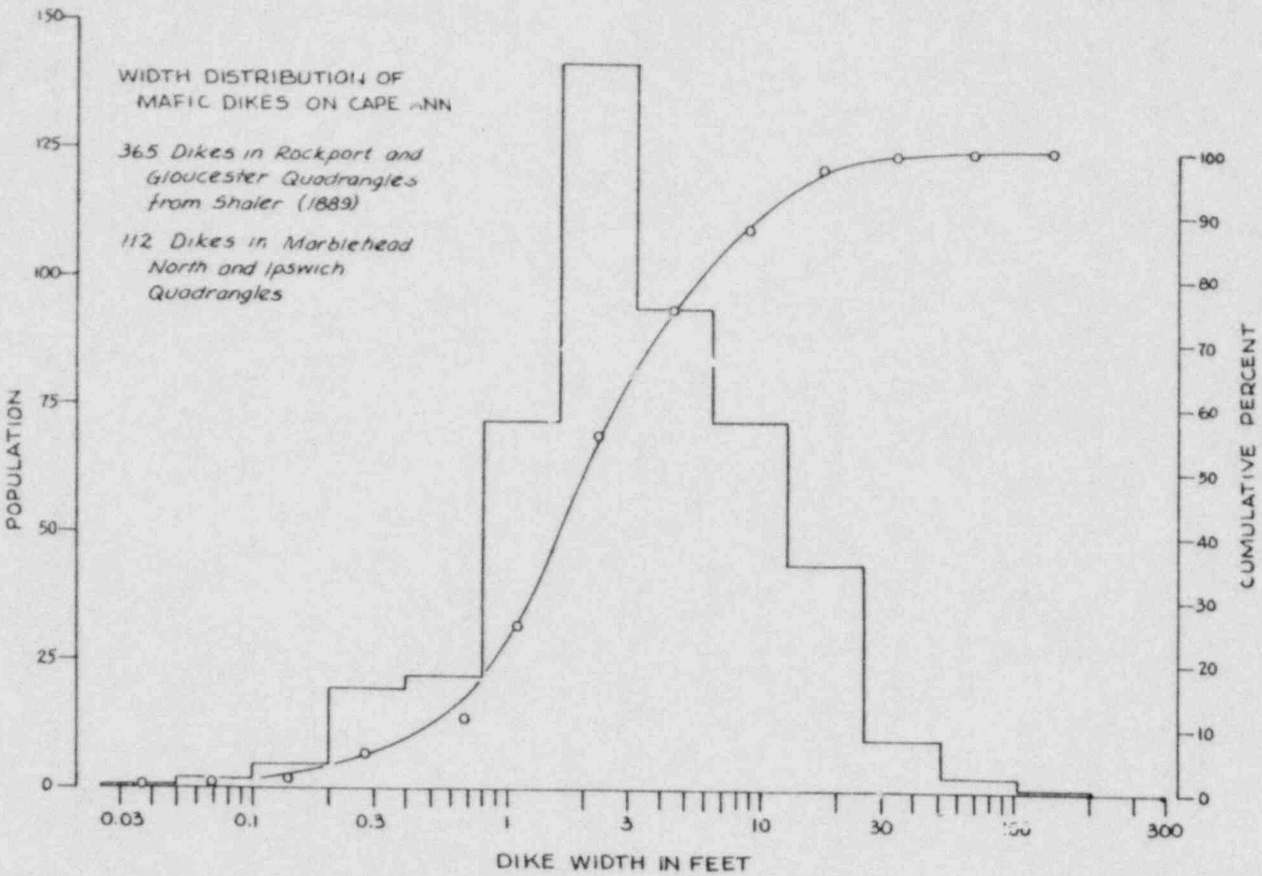

Figure 13. Diagram showing the width distribution of mafic dikes on Cape Ann.

probably essentially deuteric. In the extensive area occupied by rocks of the Cape Ann Plutonic Series (fault block IV), effects are restricted to thermal metamorphism of inclusions to metasediments of garnet grade and the development of porphyritic texture in the granite adjacent to inclusions. Post-consolidation hydrothermal activity has locally effected a color change in the feldspars of rocks of the Cape Ann Pluton from their normal grey-green to pink and chloritized the ferromagnesian minerals.

In contrast to this modest metamorphism of the younger rocks, the older rocks in fault blocks I and III have been regionally metamorphosed to amphibolite facies. Retrograde changes which obliterated their distinctive earlier fabrics have been pervasive in some of these rocks, but only locally apparent in others. A single episode of regional metamorphism, probably Acadian, followed by two episodes of hydrothermal activity, which may be related to the emplacement of younger irruptives and to regional faulting, adequately explains the observed effects.

The mafic metavolcanic rocks were raised to amphibolite facies either by thermal metamorphism during the intrusion of the Topsfield Granodiorite or by regional metamorphism in Taconic time. These metamorphic effects have been largely obliterated or obscured by later hydrothermal alteration.

The Topsfield Granodiorite preserves the effects of regional metamorphism only in its locally marked foliation and presence of large ellipsoidal quartz grains or grain aggregates. The pervasive minor cataclasis of quartz and feldspar may be the result of metamorphism, but more probably was imposed by the regional faulting. Hydrothermal alteration has caused local differences in superficial appearance by different degrees of bleaching, chloritization of ferromagnesian minerals, saussuritization of feldspars or impregnation of feldspars with iron oxide resulting in grey, pink and green, or red rock.

The Fish Brook Gneiss and Boxford Formation were regionally metamorphosed to amphibolite facies and only locally show retrograde effects due to later hydrothermal episodes.

5.0 ECONOMIC GEOLOGY

The Cape Ann Granite has been extensively quarried in the past for riprap, dimension and decorative stone. The principal quarries are located in Gloucester and Rockport where the granite is texturally uniform and contains 15-25% quartz. Granite of identical nature and quality is sporadically distributed throughout the salic portion of the Cape Ann Pluton. Other crystalline rocks of the area have served as sources of crushed rock and rough fill. The principal quarries are described by Dale (1908, 1911).

Sand and gravel are produced from numerous localities in the Cape Ann area. Most deposits are small or of poor quality, but some good sand is available.

Hydrothermally altered gouge zones of some minor faults are slightly mineralized with copper, lead, and zinc but the probability that significant deposits of these metals exist seems small. Minor sulfides are found within the mafic metavolcanic rocks at Bull Brook Reservoir and were encountered in drill holes along Paradise Road and near Six Goose Creek in the Ipswich quadrangle. A very early mining venture, reported by Dow (1940) as the first attempt to mine copper in the English colonies in North America, was unsuccessfully undertaken in 1648 on land belonging to Governor John Endecott in the northwestern portion of the Salem quadrangle.

6.0 ENVIRONMENTAL GEOLOGY

The Cape Ann area is characterized by a varied seacoast with numerous harbors, rocky headlands, beaches and tidal marshes of great scenic attraction. The major cities, Beverly and Gloucester, are located on excellent harbors of moderate size and most of the towns are similarly located but on smaller embayments reflecting the historical maritime development of the area. Major ports both to the south (Boston) and north (Portland) make further development of these harbors, other than for recreational use, unlikely.

The country inland is rocky and wooded with numerous small knobby rock hills and drumlins separated by narrow to broad and often marsh-filled valleys. The countryside appears well-suited to its present use for residential and recreational areas, specialty farms, and light industry.

Water supply for the area is principally from reservoir storage of surface run-off and groundwater supplies in glacial outwash deposits. The quality is good, but present demand equals or exceeds supplies and increased catchment and storage areas are needed. Groundwater storage may be anticipated locally within joint systems in the granite bedrock and especially along the numerous fault lineaments crossing the area.

Excavation may be anticipated to be difficult in the extensive outcrop areas of Cape Ann. The irregular bedrock topography mantled by glacial debris presents serious problems for the planner. In general, bedrock is more deeply covered in the northwestern portion of the area, for example in much of the towns of Hamilton and Ipswich, and excavation should be more straightforward. The ease of excavation is to some extent reciprocal to the quality of foundation; bedrock excavation will provide the most solid footings, foundations in glacial deposits will be satisfactory if no clays are present, and foundations in coastal and inland marshes should be avoided.

Cape Ann lies within the most active seismic area of Massachusetts, which is, in turn, included among the higher-risk areas in the eastern and central U.S. Records show, however, that although many small tremors occur, earthquakes which inflict significant damage have not been documented in the past 175 years. In this area, more than 64 tremors per 10^4 km^2 have been recorded since 1800, but only one had an intensity greater than III on the Modified Mercalli scale, i.e., was felt quite noticeably indoors especially on upper floors with vibration like a truck passing, but not recognized by many people as an earthquake (Hadley and Devine, 1972). This earthquake activity is probably related either to minor adjustments on the extensive, but essentially dead, fault system in eastern Massachusetts or to small continuing adjustments at depth to accommodate mass or thermal instabilities inherited from pre-Triassic plate collisions and separations. The probability of structural damage from an earthquake in this area is not considered great although damage from even minor earthquakes could occur in an area of natural or man-made fill.

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PETROGRAPHIC DESCRIPTIONS OF ROCK UNITS

Bedrock Geology of the Cape Ann Area, Massachusetts

Stratified or Layered Rocks

a

Middlesex Fells Volcanic Complex

Dark to light greenish-grey, chloritized and epidotized mafic metavolcanic rocks. Protoliths of the sequence were amygdaloidal and massive mafic and minor felsic flows, pillow lavas, mafic pyroclastic deposits, and ash-fall tuffs. These rocks were metamorphosed to amphibolite facies and subsequently hydrothermally down-graded to yield a massive rock with closely spaced blocky joints. Bedding, foliation, and textural features have been generally obliterated and much of the rock has a seemingly massive, fine-grained, featureless appearance. Locally, however, relict fabrics which include ophitic, agglomerate, amygdaloidal, and porphyritic fabrics are preserved in less altered rocks. Former mineralogy and textures generally are recognizable in thin section.

The metamorphosed phase, prior to alteration, consisted mainly of hornblende and plagioclase and minor quantities of magnetite and pyrite. An example of this rock is the fresh amphibolite which supports the navigational spindle at the entrance to Island Sound in the Ipswich quadrangle. The altered rock, in its present state, consists mainly of chlorite, usually pseudomorphic after hornblende and biotite, saussuritized plagioclase, and epidote. Remnants of hornblende and biotite occur locally. Secondary or introduced calcite and hematite are common minor constituents. In the southern part of the outcrop area, joint surfaces are commonly coated with hematite.

oligoclase gneiss whose maximum biotite content is about 20 percent. Calc-silicate beds are whitish or pale green and tend to be devoid of foliate features. These beds are composed of 30-65 percent oligoclase, 25-60 percent epidote and clinozoisite, 0-20 percent quartz and accessory opaque minerals and sphene. Much of the Boxford Member is pyritiferous, causing the rock to become strongly iron-stained on weathering.

d, e, f, h, j, k, m, u

Newbury Complex

Extrusive and intrusive igneous rocks with intercalated sedimentary horizons:

u) undifferentiated.

m) Alaskite Member. Massive, fine-grained, even textured, holocrystalline, micrographic alaskite, light-colored in hues of red to brown, commonly weathering to buff or dark colors; devoid of internal structures other than joints; composed almost wholly of quartz and feldspars; microcline, microcline-microperthite, and an incipient form of microperthite are abundant; twinned oligoclase generally is present in quantities of less than two percent; opaque minerals less than one percent; micas are uncommon accessory constituents.

k) Limestone-Shale Member. Medium to dark-grey aphanitic limestone and limy shale; weathers olive grey; thin-bedded or thinly laminated; locally contains abundant ostracodes.

j) Red Mudstone Member. Greyish red to dull dark red, soft and friable mudstone. Much of it contains very fine-grained detrital mica, bedding features generally are obscure, but some parts of the unit are very thinly and rather conspicuously bedded.

h) Siliceous Siltstone Unit. Dusky yellowish-green or dark greenish-grey to very dusky purple dense flinty rock in thin beds apparent only on weathered exposures. Includes minor thin interlayered whitish, pinkish, greenish chert-like bands and lenses, and thin beds or zones including calcite and calc-silicate minerals.

f) Andesite Member. Greyish-red or greyish green to dark grey, mostly porphyritic andesite, mainly as massive layers of breccia and tuff breccia but sometimes flow banded, agglomeratic or amygdaloidal intercalated with andesite flows and minor units of water-laid conglomerate, sandstone, and mudstone composed of andesitic detritus, tuffaceous shale, and a rare thin layer of fossiliferous calcareous mudstone also containing much andesitic detritus; propylization is pervasive. In porphyritic flow-banded rocks the phenocrysts are altered subhedral plagioclase (An_{30-40}) and rare quartz, and the groundmass is very fine-grained devitrified material charged with hematitic dust and granular blobs. Agglomerate clasts include lithic volcanic fragments, plagioclase, and rare quartz grains; interstitial pleonaste and sparry calcite are sometimes present.

e) Rhyolite Unit. Dense white, flesh-colored, greyish-red to dusky red-purple minutely laminated (flow-banded) rhyolite vitrophyre now wholly devitrified. Sporadically porphyritic with zones of conspicuously spherulitic rhyolite common near the mid-section. Common xenomorphic intergrowths of quartz and potash feldspar. Sparse plagioclase, minor muscovite and iron oxides.

b

Fish Brook Gneiss

Fine-to medium-grained, generally equigranular, biotite-quartz-feldspar gneiss with weak metamorphic foliation defined by alignment of biotite flakes. The unweathered, unaltered rock is pale grey finely streaked or intermittently pin-striped with biotite. Biotite content ranges from 2 to 10 percent, quartz from 20 to 50 percent, plagioclase of composition AN_{25-30} from 40 to 65 percent, and potassium feldspars are generally less than 5 percent. Hornblende is an uncommon minor constituent. Finely granular pyrite is dispersed throughout the gneiss. Zircon is an accessory constituent in some layers. On weathering the rock becomes pale yellowish-brown from oxidation of a minute quantity of pyrite. Hydrothermally altered rock is somewhat greenish because of alteration of biotite to chlorite and development of minor epidote or is reddish-brown because of impregnation by iron oxides. This altered rock usually shows a bleaching of the biotite and partial replacement of mineral grains by calcite.

c

Boxford Member, Nashoba Formation

Fine-grained interbedded amphibolite, mafic gneiss, and calc-silicate rock. Mafic beds are moderately to strongly foliated and are usually dark grey or black in color but locally may be dark greenish grey because of chloritization of hornblende and biotite. Amphibolite beds are composed of 40-85 percent hornblende, 10-50 percent oligoclase, 0-10 percent quartz, and 3 percent or less of opaque minerals, mostly pyrite but some secondary iron oxide. Hornblende typically exceeds plagioclase in amount, and many beds contain no quartz. Amphibolite grades to biotite-hornblende-

d) Basaltic Member. Fine-grained, greenish-grey basalt as flows 30 meters or more thick with scoriaceous, non-resistant flow borders. Thoroughly propylitized. Tuffaceous and fossil soil zones up to a meter thick between flows are non-resistant and crop out only sporadically in swales.

n,o

Lynn Volcanic Complex

o) Dark purplish-red to black, massive, flow-banded, and agglomeratic porphyritic rhyolite. Contains sparse sericitized phenocrysts of subhedral to euhedral plagioglase approximately An_{30}, 1 to 4 mm in diameter in a very fine-grained bladed and felted devitrified matrix with some microlites and scattered lenticular and spheroidal aggregates of fine-grained quartz. Ferromagnesian minerals, principally biotite, make up less than 5 percent of the rocks. Opaque constituents make up less than 2 percent of the rocks and consist of tiny blebs and strings, rarely magnetite crystals. Chemical composition (range and median of 5 samples) $Si0_2$ 67.8 - 76.0 (73.2) percent, Al_20_3 12.0 - 16.5 (13.7) percent, total iron as Fe_20_3 1.26 - 5.61 (2.61) percent, Mg0 1.38 - 2.47 (1.73) percent, Ca0 0.16 - 1.89 (0.42) percent, Na_20 1.50 - 4.17 (3.28) percent, k_20 0.94 - 4.40 (2.04) percent

n) The latite porphyry in the Georgetown quadrangle (Bell and others, 1973) is a holocrystalline rock consisting of pale grey phenocrysts, maximum dimension about 6 mm., and smaller books of reddish-brown biotite in a very fine-grained pale brown, reddish or lavender groundmass. Rock has well-developed flow structure. Some of the phenocrysts seem to have been white, some glassy, but all are now clouded by alteration products. About half of the phenocrysts are twinned oligoclase, some as zoned crystals, and half are sanidine, some as Carlsbad twins. The groundmass is composed of minute feldspar microlites clouded by a clay-like alteration product and by dusty iron oxide and interstitial iron oxide granules. The rock is 85-90 percent feldspar, 2-7 biotite, 2-3 percent iron oxide, 0.5-2 percent quartz, and accessory zircon(?). Chemical analysis of a sample from an outcrop 732 m N67^{o} W from the junction of Haverhill Street with Rowley Road, Topsfield is reported by Bell and others (1973), (Analyst: S.D. Botts). SiO_2 60.4 percent, TiO_2 .89 percent, Al_2O_3 17.9 percent, Fe_2O_3 3.7 percent, FeO .84 percent, MgO .60 percent, CaO 2.2 percent, Na_2O 6.1 percent, K_2O 4.4 percent, P_2O_5 .31 percent.

Intrusive Rocks

1

Diorite of Rowley

Medium-grained, equigranular, non-foliated mottled pale green and black diorite. The principal minerals are plagioclase with an average composition of An_{35}, usually as subhedral grains but ranging from anhedral to euhedral shapes, 60 to 75 percent, and somewhat poikilitic and partly chloritized hornblende, 15 to 25 percent. Anhedral grains of untwinned potassium feldspar and quartz are each present at less than 5 percent. Opaque granules of mostly magnetite but some pyrite concentrated in or near the hornblende and sparse apatite and zircon are accessories.

The feldspars are moderately to intensely saussuritized causing them to be greenish. Quartz shows intense strain shadows and is clouded by randomly distributed dust-like particles; it is greyish or smoky on freshly broken surfaces and becomes bluish after exposure.

Chemical analysis of a sample from an outcrop 595 m S40° E from the junction of Weathersfield Road and Bennett Street, Rowley, is reported by Bell and others (1973). (Analysts: P. Elmore, J. Glenn, J. Kelsey, H. Smith). SiO_2 53.5 percent, TiO_2 1.4 percent, Al_2O_3 18.6 percent, Fe_2O_3 3.1 percent. FeO 6.4 percent, MgO 4.2 percent, CaO 7.9 percent, Na_2O 2.4 percent, K_2O .52 percent, P_2O_5 .25 percent.

2

Topsfield Granodiorite

Medium- to coarse-grained, generally non-foliated, equigranular, granitic-textured granodiorite which locally grades to subporphyritic phases and to a foliated fabric. The color is highly variable and depends on the locally predominant process of alteration; in the northern part of the area it is light grey or whitish spotted by variable amounts of pinkish feldspars and tinted or streaked by greenish alteration products; in the southern part it is mottled green or salmon red.

This granodiorite is typically composed of about 30 percent each of plagioclase, microcline, and quartz and 10 percent or less of hornblende plus biotite. Modal variations occur among these principal minerals, mainly in the relative proportions of the feldspars and the amount of hornblende, and may reach 45 percent plagioclase, 5 percent microcline, 30 percent quartz, and 20 percent hornblende.

The feldspar grains are mostly subhedral to euhedral and more or less altered, plagioclase to saussurite and microcline to sericite with microcline generally being fresher. Many plagioclase crystals are zoned with compositions ranging from a core of An_{30} to a rim of An_{15}. Potassium feldspars are mostly untwinned, but some grains show partial microcline twinning.

In most parts of this granodiorite the quartz is found as prominent ellipsoidal grains or grain aggregates 3 to 15 mm in greatest dimension. In thin section, quartz is seen to contain inclusions of microcline or to have microcline selvages on the grains in an aggregate. It shows intense strain shadows and is mostly clouded by randomly distributed dust-like particles. The quartz is glassy and greyish or smokey on freshly broken surfaces and becomes blue when exposed.

Ferromagnesian constituents tend to occur as small, fine-grained clots and wisps. Hornblende is less altered than biotite and exceeds it in quantity; both are more or less altered to chlorite. A few percent of muscovite as dispered shreddy grains is always present. Magnetite and less commonly pyrite occur as tiny granules within and near the ferromagnesian minerals. Apatite and zircon are very minor accessory constituents.

3

Diorite of Byfield

Mostly medium- to fine-grained diorite and quartz-diorite but grades locally into minor granodiorite and granite facies. The most mafic facies is medium-grained, equigranular, speckled black and white diorite. It is composed of 40-60 percent plagioclase, about An_{35} , 40-55 percent hornblende, commonly poikilitic, having plagioclase inclusions, 1-3 percent magnetite, and accessory biotite, quartz, sphene, and apatite. This rock grades to a biotite facies composed of 5-15 percent quartz, 40-60 percent plagioclase (An_{25} to An_{35}), 0-10 percent potassium feldspar, 5-25 percent biotite, 0.5-2 percent magnetite, and accessory sphene, apatite, and zircon. Border facies are biotitic, fine-grained, and commonly altered; ferromagnesian minerals have been chloritized, and feldspars show extremely fine-grained micaceous alteration. All of these rocks are speckled black and white or are dark grey except chloritized parts which may be dark greenish grey.

Bell and others (1973) gives the chemical analysis of a sample from a roadcut on the west side of Middleton Road 366 m south of its junction with Fuller Road - River Road, Boxford. (Analyst: S.D. Botts). SiO_2 55.5 percent, TiO_2 1.2 percent, Al_2O_3 18.9 percent, Fe_2O_3 1.8 percent, FeO 5.1 percent, MgO 2.7 percent, CaO 8.1 percent, Na_2O 4.0 percent, K_2O .64 percent, P_2O_5 .37 percent.

4
Pink Granodiorite

Shride (1967) describes this rock as "pinkish-grey to greyish-orange-pink, rusty weathering, medium- to coarse-grained seriate-textured rock, characterized by greyish-orange pink translucent perthitic microcline of very irregular outline, clear grey quartz, and minute (1 mm) ragged flakes of bright biotite. Quartz and milky white oligoclase each compose about one-third of the rock, microcline somewhat less, and biotite about 5 percent. The characteristic inequigranular texture varies with size of microcline grains; as these progressively increase in size the texture becomes, first, subtly porphyritic, then obviously porphyritic with phenocrysts as much as 20 mm in length. Phases most nearly equigranular are dominant and are mostly quartz monzonite; the distinctly porphyritic phases are granodiorite."

5

Salem Gabbro-Diorite Facies, Cape Ann Plutonic Series

Medium- to medium coarse-grained texturally variable mottled black and greenish-white ferrohornblende-diorite containing vari ble amounts of biotite, augite, pigeonite, and quartz. The rock consists of 55-65 percent plagioclase as twinned andesine (zoned crystals An_{20} to An_{35}) and untwinned albite or oligoclase, 5 percent potash feldspar, 1-5 percent quartz, 0-25 percent pale-green augite, 0-10 percent pinkish titaniferous pigeonite, 10-30 percent green pleochroic iron-rich hornblende, 0-10 percent reddish-brown biotite, and 1-5 percent opaques as scattered granules and exsolved blades in pyroxenes. Accessory apatite, zircon, and sphene are also present as grains and as rims on opaque granules. Chlorite, iron oxides, and calcite are present as alteration products. Mafic minerals are always somewhat poikilitic and commonly occur in zonally arranged aggregates that represent a reaction series from augite to biotite with magnetite granules dispersed throughout the aggregate. Biotite occurs as irregularly shaped and scattered flakes. The feldspars are pale grey-green and have a greasy luster. The fabric is irregular and uneven. The rock is often brecciated and cut by salmon-pink felsic stringers.

A labradorite porphyry roof phase of the Salem Gabbro-diorite is found only as xenoliths and xenocrysts within the Cape Ann Granite facies (See Figure 10). White-weathering purple-red phenocrysts in a gabbroic matrix are characteristic. The phenocrysts are tabular and range from 1 to over 10 cm in long dimension. In a few instances, segregations of the phenocrysts result in small patches of anorthosite.

6

Squam Granite Facies, Cape Ann
Plutonic Series

Fine- to fine medium-grained, medium-grey granite which weathers brown with a highly siliceous appearance. Texturally and mineralogically variable rock; texture ranges from hypidiomorphic or allotriomorphic granular to subophitic and subporphyritic. Plagioclase as anhedral to subhedral zoned and unzoned equant or bladed grains variable in amount and composition, ranging from less than 5 to more than 40 percent of the rock and from about An_{30} to An_{55}. In subporphyritic varieties phenocrysts are more sodic than groundmass plagioclase (An_{30} vs An_{40}). The potash feldsapr may be orthoclase, microcline, or microcline microperthite either alone or in combination and range from a minor to the dominant constituent. Grains range from anhedral to subhedral, equant to bladed and fresh to highly sericitized. Zoning is fairly common. Anorthoclase is often present as an accessory mineral. Quartz is in slightly strain-shadowed equant or interstitial glassy grains and makes up 15 to 30 percent of the rock. Ferromagnesian minerals comprise from less than 5 to more than 50 percent of the rock. Poikilitic ferrohornblende and red-brown biotite are the principal dark constituents and are present in roughly equal quantities. Pyroxene (pigeonite) is rare and typically occurs as unreacted cores. Accessories include apatite, zircon, opaque minerals, sphene, allanite, and monazite.

7

Syenite Facies, Cape Ann Plutonic Series

This facies includes, but is not restricted to, the Beverly Syenite. It is comprised of predominantly unfoliated medium-grained granitoid rocks whose composition, except for lack of quartz and occasional presence of nepheline or sodalite, is identical with other facies of the Cape Ann Granite. Generally texturally variable and often shows small pegmatitic patches, rarely flow-banded. Textural extremes, essentially restricted to the Beverly-Manchester shore and islands of Salem Harbor, include very coarse-grained (2-5 cm) granitoid and ophitic phases, pegmatites, and medium-grained trachytic rocks (Bakers Island) which sometimes contain nepheline and sodalite.

8, 9, 10

Cape Ann Granite Facies, Cape Ann Pluton Series

Predominantly unfoliated fine medium to coarse-grained (0.3 to 1.5 cm) leucocratic alkali granite to alkali syenite. Ranges and medians of the principal minerals are potash feldspar 58-85 (63) percent, plagioclase (An_{6-12}) 0-22.5 (2.8) percent, quartz 0-41 (24) percent, ferrohornblende 0.1-17 (4.5) percent, biotite 0-3.2 (0.8) percent, and opaques 0.2-7.5 (1.0) percent. Augite occasionally present. Accessory minerals include sphene, zircon, apatite, fluorite, allanite, magnetite, and ilmenite. Feldspars in unaltered rock are pale green-grey, have a greasy luster, and weather to a faintly pinkish tan or white. Potash feldspar is the dominant mineral, usually microcline microperthite but sometimes homogeneous microcline; albite or oligoclase is present in minor quantities. Quartz is glassy, shows weak strain shadows, and contains dust-size inclusions. Feldspar and quartz occur as large single grains and grain clusters partly to completely surrounded by finer-grained interstitial quartz and feldspar. Ferromagnesian minerals are variable in amount and occur as ragged clots, wisps, single subhedral crystals, and zonally arranged reaction aggregates. Augite is colorless to pale green as cores partly or completely surrounded by pale green amphibole, darker-green soda-iron amphibole, and reddish-brown biotite with magnetite granules scattered throughout the reaction aggregate. Isolated crystals and clots of soda-iron amphibole, biotite, or both are common. The rock fabric is principally uneven granitoid, but varies to subporphyritic, and is locally cumulate. Joint surfaces of all facies have distinctive brown, iron-rich facings or, rarely, are plated with hornblende.

The Cape Ann Granite facies may be divided into lithotypes based on its modal quartz content as measured on outcrops; the following divisions being used herein:

7) 0-5 percent quartz (includes previously distinguished Beverly Syenite plus other syenitic rocks).

8) 5-15 percent quartz (approximately equivalent to nordmarkite as used by Warren and McKinstry, 1924).

9) 15-25 percent quartz.

10) More than 25 percent quarts.

Dike Rocks of the Cape Ann Pluton

Numerous salic and mafic dikes intrude the various facies of the Cape Ann Pluton. They include a wide variety of lithologies comagmatic with the Cape Ann Plutonic series and its extrusive equivalents as well as possibly younger dike rocks:

1) Syenite and feldspathoidal syenite including trachytic, massive, and pegmatitic types. Potash feldspar dominant, 0-10 percent nepheline and sodalite, 5-15 percent ferromagnesian minerals. Occasionally well-crystallized magnetite. Feldspathoidal types often have a bluish-grey appearance.

2) Fine- to medium-grained mafic rocks with granular, diabasic and porphyritic textures. Texturally and mineralogically variable. Plagioclase altered, commonly labradorite. Hornblende is the dominant mafic mineral, also pinkish pigeonite, pale green augite, and biotite; rare olivine. Accessory apatite, sphene, magnetite, and pyrite. Often separated and cut by unfoliated granite. Chilled margins typical but fractured ends of separated blocks are not chilled.

3) Rhyolite, black, red, or tan with sparse to abundant potash feldspar and beta-quartz phenocrysts. Sometimes banded or agglomeratic.

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APPENDIX

JOINT STUDY

Measurement of attitude, surface character, micro-movement, etc., was made on about 4000 joints in the eastern portion of the Cape Ann area. No pre-selection was practised, rather all available surfaces were measured. The observed features of each joint were encoded according to the scheme below and transferred to punch cards.

JOINT TYPE

10 Master. Joints which dominate the pattern of jointing over an extended outcrop.

20 Principal. Prominent joints which provide extensive exposed surface or dictate the form of an outcrop.

30 Minor. Less prominent joints with no special attributes.

40 Butt. Joints terminating at another joint.

50 Offset. Joints showing small offset where crossing another joint.

60 Wavy. Joints with wavy surfaces having wave lengths in excess of 1 meter.

70

80

90 Sheeting. Jointing parallel or subparallel to the surface and dipping less than 30°.

JOINT SURFACE

10 Smooth.

20 Stepped. Joint follows a zone of closely spaced en-echelon fractures which it transects at a small angle. The stepping from fracture to fracture leaves small ($\pm$ 1 cm) subparallel scarps across the joint surface.

30 Shear feathered. Feather-like patterns are present on the joint surface.

40 Slickensided.

50 Mineralized. Post-jointing mineralization; nearly always hornblende on Cape Ann.

60 Wavy. Surface rippled with small waves with 1-10 cm wavelengths.

DDH RELIEF Attitude of principal open cracks generated by blasting.

STRIKE AND DIP OF PLUNGING LINEAR FEATURE

RELATIVE MOTION

10 North side east.

20 North side west.

01 North side up.

02 North side down.

All strikes to north quadrant using 360°

A program to plot pole-to-plane data to the lower hemisphere of an equal-area net taken from Warner (1969)[1] and modified for use with an IBM 370-65 computer was utilized to assemble attitude data for joints within six fault-bounded blocks and narrow ($\pm$ 1 km) zones of the bounding faults as shown in Figure 2.

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1. Warner, J., 1969. Fortran IV program for construction of PI diagrams with the Univac 1108 computer: Computer Contributions 33, State Geolcgical Survey, The University of Kansas, Lawrence. 37p.

Joints within fault-bounded blocks were further separated into a group of consolidation (early) and a set of tectonically induced (later) joints using the following field criteria:

CONSOLIDATION

Surface mineralized

Butt, offset, or wavy

Dip less than 70°

Limited strike length

TECTONIC

Master and principal joints

Dips greater than 70°

Surface stepped, shear feathered, or slickensided

The computer program generated plots of pole concentrations over 1 percent areas which were hand contoured. Simplified contours of the principal pole-to-plane concentrations for fault-bounded blocks and fault zones are shown in Figures A-1 and A-2 respectively. Examination of Figure A-1 shows an overlapping of the patterns of joint poles ascribed to consolidation (solid contours) and to tectonism (dashed contours) based on field criteria. In such instances the joints were reassigned as having a tectonic (later) origin. Information from these plots as corrected for overlap was then combined with the known stress directions during consolidation derived from observations of the attitude of separated dikes (Figure 3 and Section 3.2.2.3.4) to determine the horizontal projections of the strain ellipsoids during the late stages of magma consolidation (Figure 4a).

The horizontal projection of the strain ellipsoids of the joint sets related to post-consolidation and possibly pre-faulting tectonism (Figure 4b) was determined from the distribution of pole-to-plane concentrations shown by the dashed contours of Figure A-1.

Joints in the fault zones are dominated by the faulting event(s) and have pole concentrations as shown in Figure A-2. The orientations of the horizontal projection of the strain ellipsoid for these joints is given in Figure 4c.

When dip as well as strike information is taken from the pole-to-plane diagrams, it is possible to define and orient the various sets of surfaces of maximum shear in three dimensions. These conjugate surfaces intersect in the line of least principal stress whose intersection with the lower hemisphere of an equal-area net may, in turn, be found. The sequential positions of this pole in each of the fault-bounded blocks and fault zones is shown in Figure 6. Differential rotation of the stress field in each block and fault zone is clearly shown.

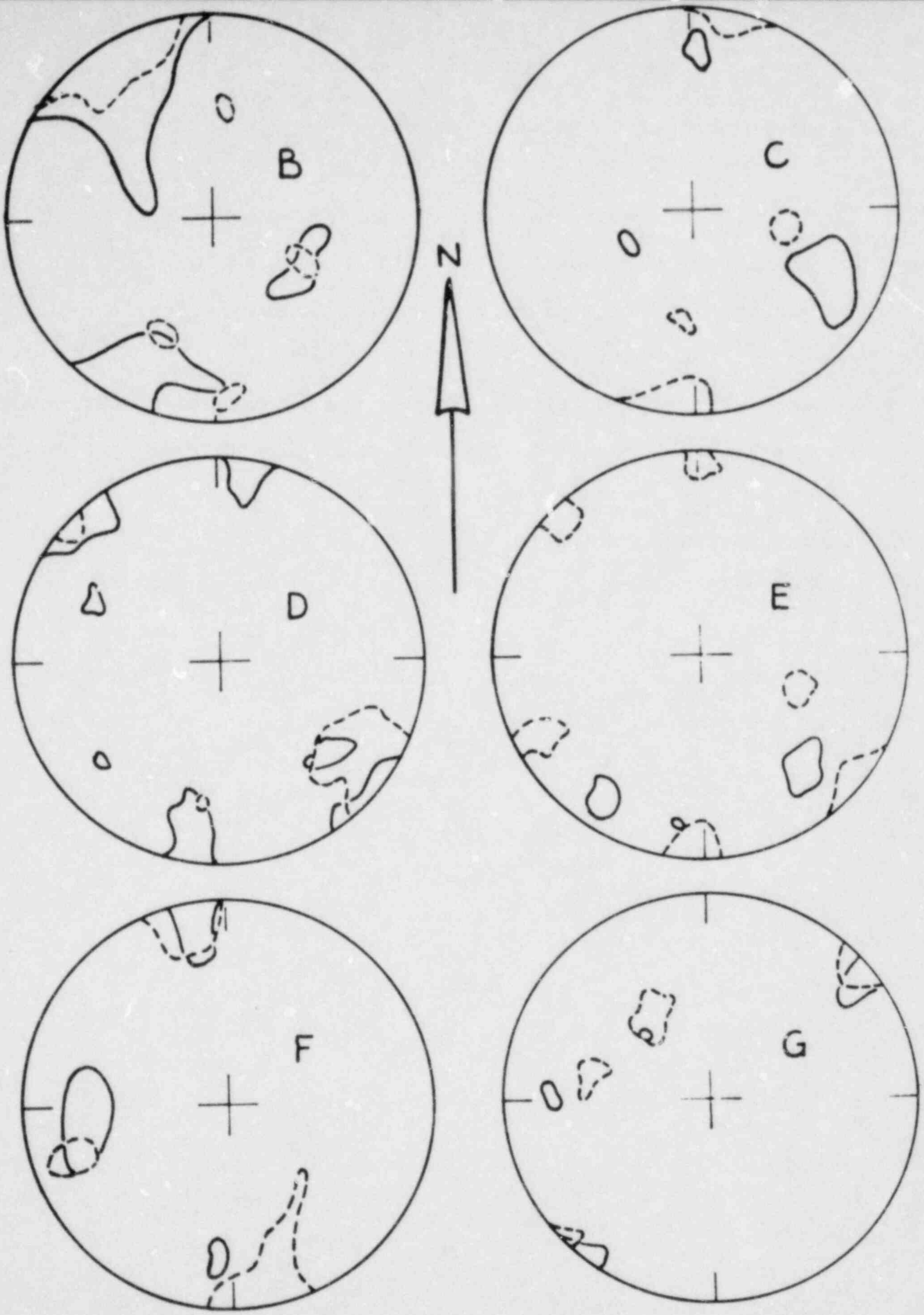
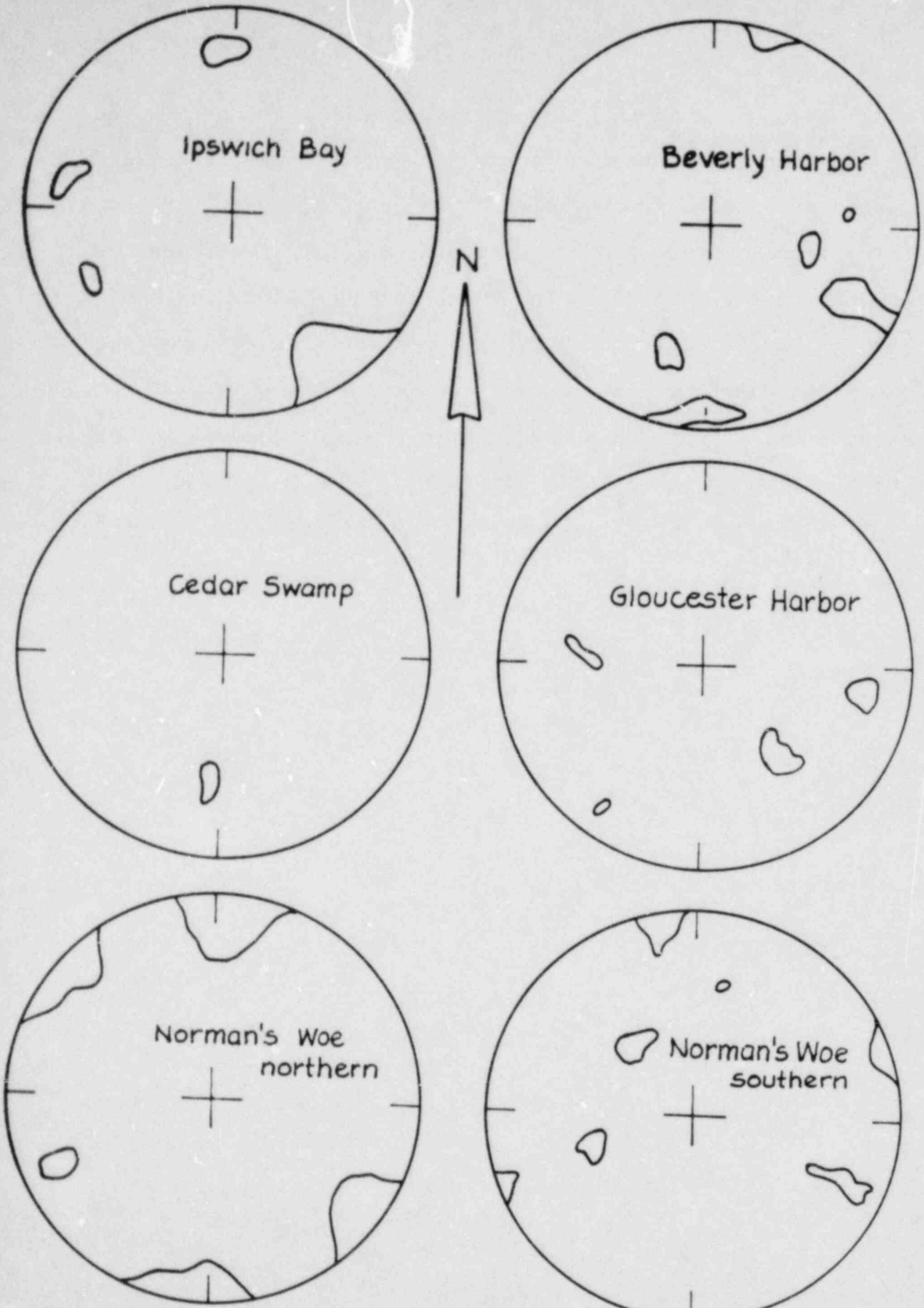


Figure A-1. Diagrams showing contoured polar projections to the lower hemisphere of an equal-area net of consolidation and tectonic joint data. Joints ascribed to consolidation shown as solid contours, joints ascribed to tectonism as dashed contours (Figs. 4a and 4b). Letters refer to fault bounded blocks shown on Figura 2.



igure A-2. Diagrams showing contoured polar projections to the lower hemisphere of an equal-area net of fault-related joint data from Cape Ann (Fig. 4c).

Many joints in the Cape Ann Granite show stepped surfaces because the large observed surface follows a zone of closely-spaced en-echelon fractures which it cuts at a very small angle. The apparent movement of such joints, believed tectonically induced, was recorded and the apparent movement directions show strong clustering around N 33° E for north side east movement and N 84° W for both north side east and north side west motion (Figure A-3). This data suggests an average regional principal horizontal compression of N 64° E.

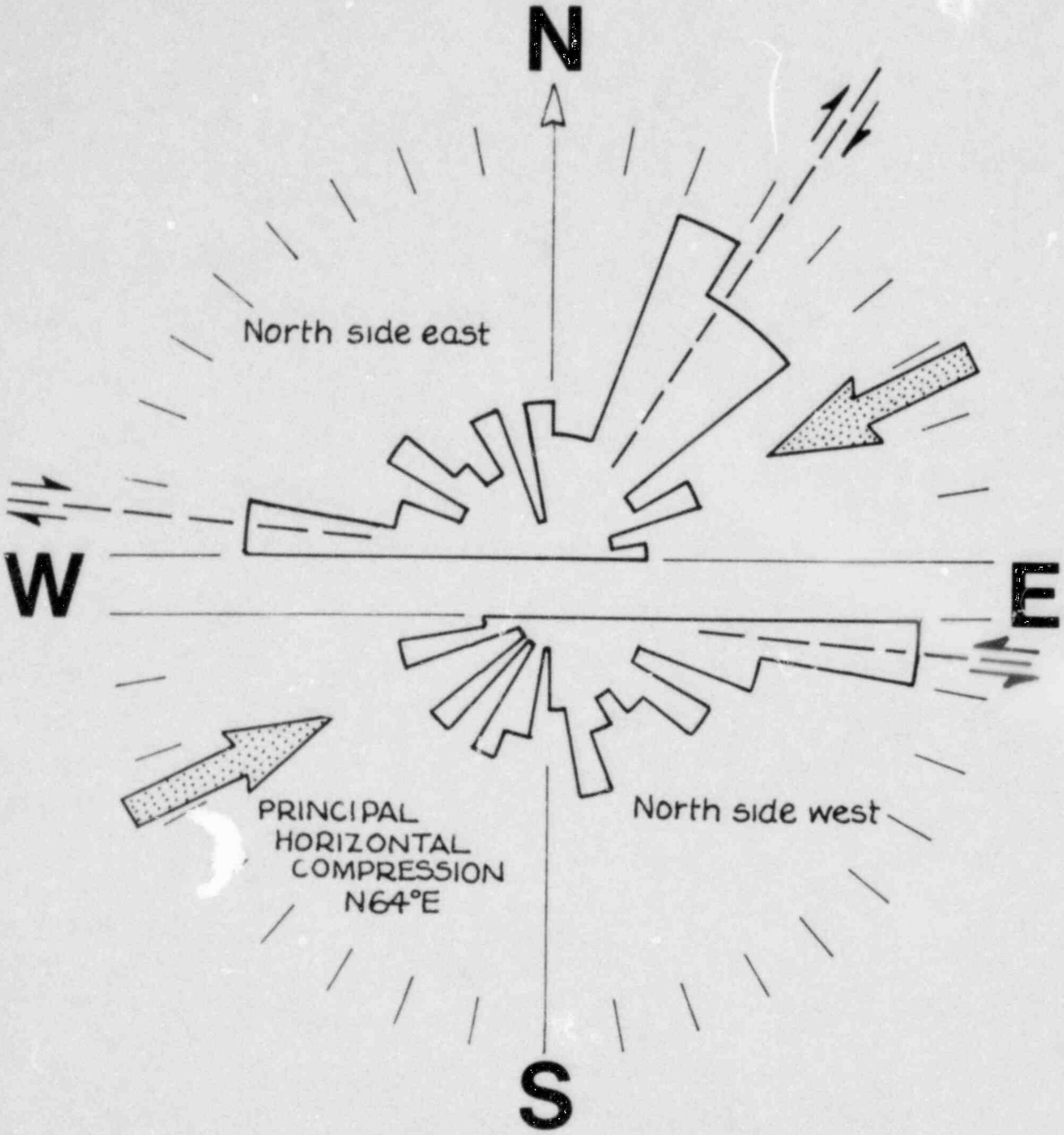


Figure A-3. Diagram showing the orientation and direction of apparent movement on stepped joints and derived direction of principal horizontal compression on Cape Ann.

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16. ABSTRACT *(200 words or less)*

Cape Ann on the Massachusetts eastern shore is dominated by igneous rocks. Intruded into an igneous and metamorphic complex all cut by numerous faults.

Geophysical investigations include total intensity aeromagnetic and gravity and magnetic studies.

This report addresses structural features, stratigraphy, economic and environmental geology at the bedrock geology of the Cape Ann Area.

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