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Bedrock geology of the Waldoboro East and Waldoboro West 7.5' topographic quadrangles, Maine

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Dear Bob,

Attached is my progress report to accompany the map I left with you last month. I would welcome your comments or those of anyone else who has time to look over what I've said.

Hopefully this has some progress on the certification exam question as I am anxious to get that done by late June or early July. (I know you've heard this before!).

Best regards,

Don

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BEDROCK GEOLOGY OF THE WALDOBORO EAST AND WALDOBORO WEST 7.5' TOPOGRAPHIC QUADRANGLES, MAINE

Introduction

The Waldoboro East and Waldoboro West 7.5' quadrangles together comprise the south half of the Waldoboro 15' topographic quadrangle. They cover an area approximately located between the coastal towns of Damariscotta and Thomaston. The Medomak River forms a roughly north-south boundary between the two 7.5' quadrangles.

Relief in the area is low...on the order of 250'. Despite this fact and the existence of numerous glacial deposits bedrock exposure is good, particularly along shoreline and in the higher elevations underlain by granite. Moraine near the town of Warren in the northeast portion of the area mapped precludes the examination of bedrock in that area.

Perhaps 70% of the area is underlain by Waldoboro granite. Although a compositionally variable body much of the granite is a light colored, buff weathering, biotite-muscovite granite. It is clearly intrusive into a sequence of metasedimentary and metavolcanic units (the Benner Hill sequence of Osberg and Guidotti, 1974) on the southeast. To the west and northwest the granite is in contact with a calc-silicate gneiss, the Bucksport formation. The nature of the contact between the granite and rocks of the Bucksport formation is unknown.

The rocks in the area mapped have been deformed three times. This conclusion is supported by structural observations made in the rusty weathering pelitic unit of the Benner Hill sequence. Elsewhere in the map area these events cannot be distinguished. This is caused either by the fact that the rocks generally are of such composition that they record tectonic events very poorly or may be due to the localized nature of one of the events.

Initially the rocks have been isoclinally folded about northeast trending axes with the development of strong axial plane foliation in the pelitic rocks. The Bucksport lithology was boundinaged during early folding with axial plane foliation poorly developed. Refolding of the rocks occurred along essentially north-south and gently plunging axes. Associated with the second fold event are mineral lineation, discontinuous axial plane foliation, or strong axial plane foliation. The nature of the lithology determines which of these is actually observed. Evidence for a third episode of folding is tenuous. If such an event occurred its result was the systematic rotation of earlier formed structures. For this the evidence is, at best, only suggestive.

Faulting has not affected the rocks in the Waldoboro quadrangles to any appreciable extent. Breccia, mylonite, and vein quartz in the area of Havener Cove document the existence of a significant northeast trending fault there. It has had post granite movement and may or may not be an extention of the large fault mapped by Osberg in the W. Rockport quadrangle (see Osberg and Guidotti, 1974, p. 49).

The rocks in the area mapped are at staurolite grade with sillimanite locally developed in the pelites in proximity to the granite. In rocks of the Benner Hill sequence pseudomorphs of muscovite after staurolite are common evidence that at least in the southeast portion of the map area the rocks have been affected by retrograde metamorphism. Little is known of the relationship between metamorphic and deformational events.

Description of Map Units

Waldoboro granite .... The mineralogical and textural variability of the Waldoboro granite suggests that it is a composite body of at least two separate intrusions. From the point of view of area mapped the most important unit of "the granite" is a buff weathering, medium grained biotite-muscovite

granite designated Wg on the map. In outcrop the granite appears massive but upon close examination is usually seen to possess a weak, discontinuous foliation defined by sub-parallel orientation of the micas. In thin section the undulatory extinction of quartz, mosaic texture, and subhedral or euhedral nature of the component crystals suggest mild cataclasis. In the south central portion of the Waldoboro West quadrangle the granite is of the same composition but has a strongly foliated appearance in outcrop. Wgf is used to designate that portion of the granite which shows this feature. Modal analysis of three thin sections presumably representative of these two units of the granite gave the following results:

	section 0-15	3-558	3.523	average of modes
plagioclase	19.4	24.3	20.9	21.5
microcline	41.7	35.6	28.5	35.3
biotite	4.1	5.3	2.0	3.8
muscovite	1.3	4.3	10.0	5.2
chlorite	1.2	0.3		
apalite	0.4	0.4		
opaque	0.4		0.1	
sphene			0.6	
quartz	31.6	29.9	36.9	32.8

A large area of hornblende quartz diorite is exposed in the south central portion of the Waldoboro East quadrangle (Wgh). The rock is gray in color, has equigranular texture, and shows evidence of cataclasis. The feldspar in the rock is entirely plagioclase which occurs as large, zoned subhedral crystals. From a determination of extinction angles in sections perpendicular to x which show the traces of both the (001) and (010) cleavages the composition is oligoclase. Mafic minerals are biotite and hornblende with the latter occurring as larger ragged and fragmented crystals. The hornblende is strongly pleochroic and contains small bleb-like inclusions of quartz as well as tiny inclusions of an opaque mineral in apparent preferred orientation. A minor amount of pyroxene is also present as scattered, broken crystals

which are sometimes spatially associated with the amphibole.

While accessory apatite and sphene are to be expected, the latter mineral is present in unusually high concentration (see modes below). It occurs as ovoid grains which are scattered through the thin-sections of diorite examined to date. The sphene thus does not appear to be associated with any particular mineral of the assemblage present nor does it show preference for specific grain boundaries.

The mineral assemblage present in the hornblende quartz diorite suggests chemical reactions for which oxygen fugacities may be determinable. According to Wones (personal communication) the oxygen pressure may be an important indicator of the environment in which the melt was generated. Determination of magma source--oceanic versus deeper levels in the sialic crust--is of particular importance for plutons in this part of the Maine coast. The reactions which seem to be pertinent here have been briefly discussed by Carmichael et als., 1974. They are:

$$\underset{\text{magnetite}}{2/3\ Fe_3O_4} + \underset{\text{sphene}}{CaTiSiO_5} + \underset{\text{quartz}}{SiO_2} + \underset{\text{phlogopite}}{1/3\ KMg_3AlSi_3O_{10}(OH)_2} =$$

$$\underset{\text{Annite}}{1/3\ KFe_3AlSi_3O_{10}(OH)_2} + \underset{\text{ilmenite}}{FeTiO_3} + \underset{\text{diopside}}{CaMgSi_2O_6} \qquad (1)$$

and:

$$\underset{\text{sphene}}{6\ CaTiSiO_5} + \underset{\text{magnetite}}{4\ Fe_3O_4} + \underset{\text{quartz}}{18\ SiO_2} + \underset{\text{phlogopite}}{5\ KMg_3AlSi_3O_{10}(OH)_2} =$$

$$\underset{\text{annite}}{2\ KFe_3AlSi_3O_{10}(OH)_2} + \underset{\text{K-spar}}{3\ KAlSi_3O_8} + \underset{\text{ilmenite}}{6\ FeTiO_3} +$$

$$\underset{\text{tremolite}}{3\ Ca_2Mg_5Si_8O_{22}(OH)_2} + 2\ O_2 \qquad (2)$$

Since the quartz diorite contains no potassium feldspar it seems unlikely that the second reaction has occurred. However, an alternate reaction may be written involving the assemblage actually observed....

$$\underset{\text{sphene}}{6\ CaTiSiO_5} + \underset{\text{magnetite}}{7\ Fe_3O_4} + \underset{\text{quartz}}{18\ SiO_2} + \underset{\text{phlogopite}}{KMg_3AlSi_3O_{10}(OH)_2} + \underset{\text{water}}{3\ H_2O} +$$

$$\underset{\text{annite}}{KFe_3AlSi_3O_{10}(OH)_2} + \underset{\text{ilmenite}}{6\ FeTiO_3} + \underset{\text{ferro-tremolite}}{3\ Ca_2(Mg,Fe_4)Si_8O_{22}(OH)_2} + 7/2\ O_2 \quad (2a)$$

Reaction (2a) is not independent of the fugacity of water--at least not in the form written above. In addition, the reaction has the same difficulties pointed out by Carmichael et als. (1974, p. 111) with respect to reaction (2), i.e. "...since the calculation of the amphibole formula from the analyzed oxide components is not unambiguous..." the use of equations (2) and (2a) can lead to variable results. The time at which reaction occurred is also important. Petrographic and field evidence is required to determine whether reaction occurred pre or post emplacement and crystallization of the melt from which the hornblende quartz diorite formed. Textural relationships observed in the thin sections of this rock which have been examined thus far do not suggest any of the reactions above indicating, perhaps, that reaction occurred early in the history of the melt. Or, if late, the suggestive geometrical relationships may have been destroyed by cataclasis.

Modal analysis of the hornblende quartz diorite yielded the following results:

	section 3-506b	3-507	average of modes
plagioclase	34.3	46.2	40.2
biotite	24.3	26.2	25.3
apatite	0.9	1.2	1.0
opaque	0.9	1.4	1.2
amphibole	21.0	10.1	15.6
sphene	3.9	3.7	3.8
quartz	14.8	9.4	12.1
pyroxene		1.7	0.9

Along the east boundary of the Waldoboro granite another unit, characterized by large (< 3") potassium feldspar crystals in sub-parallel orientation, is recognized and has been designated as South Pond porphyry, Wgp. It is particularly well exposed in the higher elevations of Stahls Hill and generally in the area immediately south of South Pond. The rock has an unusual modal omposition (see below) and its contact with units of the Benner Hill sequence exposed to the east is gradational. The rock's composition has probably been considerably altered by reaction with the metasedimentary rocks to the east. However, recognizable inclusions are rare in this unit although angular blocks of gabbro are present within the South Pond porphyry in the northeast portion of the map area. The porphyry has mosaic texture with serrate grain boundaries. Undulatory extinction of quartz and bent twin lamellae in both microcline and plagioclase are common. The mafic mineral is biotite which shows metamict texture in proximity to small, included crystals of zircon. Small broken crystals of orthopyroxene form "trails" in thin section which are interstitial to feldspar and quartz. The most characteristic feature of the South Pond porphyry is the presence of potassium feldspar as both fragmented interstitial grains and as large prophyroblasts (phenocrysts ?). Modal analysis of a single stained thin section gave the following results:

	section 0-8
plagioclase	30.2
microcline	10.3
biotite	12.4
muscovite	0.2
apatite	0.1
opaque	0.1
pyroxene	1.8
quartz	45.0

gabbro (g) ... A small, roughly circular mass of gabbro outcrops near the south

boundary of the Waldoboro East quadrangle. It is medium to coarse grained consisting of plagioclase and pyroxene which is "dusted" with tiny opaque inclusions. The texture is ophitic. In one thin section (0-49) the pyroxene grains are rimmed presumably by pyroxene of different composition. The birefringence of the cores and rims are quite different and the rims are inclusion free.

While located near the axis of a syncline the gabbro does not appear to have been much affected by the folding of the Benner Hill sequence which it intrudes. The gabbro is older than the Waldoboro granite--at least the South Pond porphyry phase of the granite since it occurs as included blocks in the porphyry.

The intrusive rocks of the area mapped, that is, the granite and gabbro represent a suite of rocks not unlike those discribed by Chapman (1962) and referred to as the Bays-of-Maine igneous complex. Chapman considered the complex to extend southeast to Penobscot Bay. The 295 m.y. K-Ar date obtained on the Waldoboro granite presumably relates to prograde Permian metamorphism and as a result the age relationship of the igneous rocks in the map area and the Bays-of-Maine rocks is unknown.

Benner Hill Sequence (Bfq, Bbq, Bbq-m, Bgss) ... Metasedimentary and metavolcanic rocks of the Benner Hill sequence are exposed in the southeastern portion of the Waldoboro East quadrangle. The oldest unit in the sequence, Bfq, is a thin bedded, light colored feldspathic quartzite which has a pinstriped appearance in outcrop due to the alternation of biotite and quartz rich laminae which are 1/4" or less in thickness. Differential weathering often results in a ribbed appearance on weathered surfaces with the quartz-feldspathic bands being more resistant to weathering than the micaceous bands. Some outcrops of this unit have a sandy texture and feldspar, in

addition to quartz, biotite, and muscovite, is doubtless an important constituent of the rock. However most outcrops (and all thin sections examined to date) indicate that very little feldspar is present. Map unit Bbq is a biotite quartzite which contains quartz-feldspar-mica grits which alone distinguish it from unit Bfq. In proximity to the granite contact this unit shows gradational change. The banding as defined by parallel orientation of the biotite becomes increasingly less distinct as one approaches the South Pond porphyry contact. Quartz-feldspar veinlets (?) transect the layering and quartz-feldspar augen are common. These textural features are taken as evidence of migmatization and where observed are designated Bbq-m. This unit is equivalent to "unit 2" of the Benner Hill sequence (Osberg and Guidotti, 1974) which, on the basis of deformed brachiopods found in the Thomaston quadrangle, has been assigned an Ordovician age (Boucot, et al., 1972).

The youngest unit in the sequence is a rusty weathering metapelite designated Bgss. This unit contains dark grey sandy weathering quartz-feldspar beds up to several feet in thickness alternating with narrow intervals containing coarse grained muscovite which may be pseudomorphous after sillimanite, garnet, and/or staurolites. In one thin section, 0-302, of a rock sample from the east boundary of the map area all three minerals are present. The sillimanite is anhedral with very irregular and "gradational" (with respect to muscovite) grain boundaries while the garnet and staurolite occur as large euhedral crystals. The sands and coarse muscovite bands are assumed to represent graded units from which numerous top determinations have been made.

Dark green, fine-grained, pitted lenses of amphibolite are present in the pelite. They probably represent boundinaged intercalated volcanic flows. The zone in which volcanics occur is narrow and near the axis of the syncline located on the map. To the southwest, west of the area in which the gabbro

outcrops the zone widens and extends into the Friendship quadrangle where pillowed flows were observed along the shoreline in the north central part of the quadrangle by A. Hussey in his reconnaissance study.

Megunticook sequence (Msgg) ... Due to glacial cover exposures of bedrock are poor or non-existent in the northeast portion of the map area. However a coarse grained sillimanite garnet gneiss outcrops in the vicinity of Warren Station. The rock in thin section contains a sillimanite-quartz-muscovite-biotite-garnet assemblage. Evidence of cataclasis is obvious in the "exploded" appearance of the sillimanite which contains abundant inclusions of muscovite. Garnet porphyroblasts also show evidence of crushing and granulation. The rock has a more or less massive texture particularly near the South Pond porphyry contact but the spindle shaped sillimanite crystals tend to define a lineation within the plane of the foliation as defined by subparallel orientation of biotite and muscovite. The garnet prophyroblasts appear to cut this foliation.

Bucksport Formation (B) ...

The Bucksport Formation is a distinctly layered calc-silicate gneiss exposed west of the Waldoboro granite and as small patches within it. It consists of dark biotite rich layers which have a suggestion of reddish brown color which may be done to a high magnesium composition of the biotite. These bands alternate with apple green bands which contain quartz and amphibole and/or pyroxene. In thin section the rock has a mosaic texture. The biotite and amphibole frequently show metamict texture due to included zircon. Minor plagioclase showing albite twinning and K feldspar are present. The rock contains no calcite but significant accessory sphene as scattered subhedral grains.

A narrow band less than 10' wide of rusty weathering tourmaline-

sillimanite-sericite schist outcrops in the south-central part of the Waldoboro West quadrangle. Because aluminous intervals are elsewhere non-existent in the Bucksport this interval is split out as a separate unit and designated Bp. In thin section the sillimanite occurs as fragmented crystals lying in an earlier foliation which has been cut by a later-developed foliation.

Btss is another unit--also tentatively assigned to the Bucksport--which outcrops on the east side of the Medowak River. It is a sulfidic rusty weathering tourmaline-sericite schist. Outcrops of this unit along the shoreline tend to be very broken and the rock very friable, presumably the result of destruction of the fabric of the rock by sulfuric acid generated by the oxidation of iron sulfides.

Age Relationships of Metasedimentary Units

One of the important questions concerning the distribution of lithologic units in the area mapped is that of the relationship between the Bucksport Formation outcropping west of, and within, the Waldoboro granite and the units which outcrop east of the granite. The Bucksport type lithology outcrops along U.S. route #1 just south of North Pond and rocks which appear to be transitional between the Bucksport and the garnet-staurolite-mica schist of the Benner Hill sequence occur just east of Waterman Brook in the geographic center of the Waldoboro East quadrangle. Units exposed east and west of the granite do not appear in closer proximity than this. It is therefore highly speculative but interesting to consider the Bucksport as the time-equivalent of a portion at least of the Benner Hill sequence. The granite would then have been emplaced along a zone where the sedimentary facies changed.

Another equally speculative but interesting suggestion is that the garnet-sillimanite gneiss of the megunticook sequence is equivalent to the Appleton Formation (Cheney, 1967). From preliminary work done by Norton in

the Union quadrangle the Appleton may be represented by the Clary Hill migmatite near the Waldoboro granite. The pluton may have been emplaced along a fault contact between these two units (?).

Structure

Folding ... The identification of three foliations in the pelite of the Benner Hill sequence suggests that the rocks in the map area have been subjected to three separable episodes of folding. However, elsewhere in the two quadrangles evidence of three deformational events is clearly absent. This means either that a third event did not affect these rocks or, alternatively, that they have not recorded a third period of folding in clearly observable ways.

In general--and irrespective of rock type--any individual outcrop will document two periods of folding. In the calc-silicate rocks, drag folded boudins on the limbs of second generation folds and rotated and tectonically transported irregular blocks of granite and pegmatite on the limbs of "F-2" folds provide the evidence of this. Less commonly a folded foliation is observed in this lithology. In the Waldoboro granite, particularly where it is strongly foliated (see map), there are also two foliations. The earlier one consists of streaks of biotite which resemble a flow structure (schlieren) related to the mechanics of emplacement. However at the granite--Bucksport contact (see sketch #1) the mafic streaking is seen to transect the two units and hence must be an early post emplacement tectonic structure. This early foliation is folded by a second deformational event which resulted in the development of a weak, discontinuous axial plane cleavage defined by the rotational reorientation of muscovite. (This weak, discontinuous F-2 cleavage is observed in much of the granite but is prominent in an area designated on the map as Wgf.) In the pelitic rocks the axial plane F-2 foliation is much better developed allowing the attitudes of minor F-2 fold structures to be

before F-2 folding and its development may be related to the thermal aureole of the Waldoboro granite. (In any event its preservation in the rocks appears to be controlled by its proximity to the granite contact.) At present there seems to be no easy way to decide between two alternatives to explain the observed assemblages .... 1.) incomplete retrograding of sillimanite during the formation of garnet and staurolite by prograde reactions (see Albee, 1968) or, 2.) destruction of sillimanite during the retrograde formation of garnet and staurolite.

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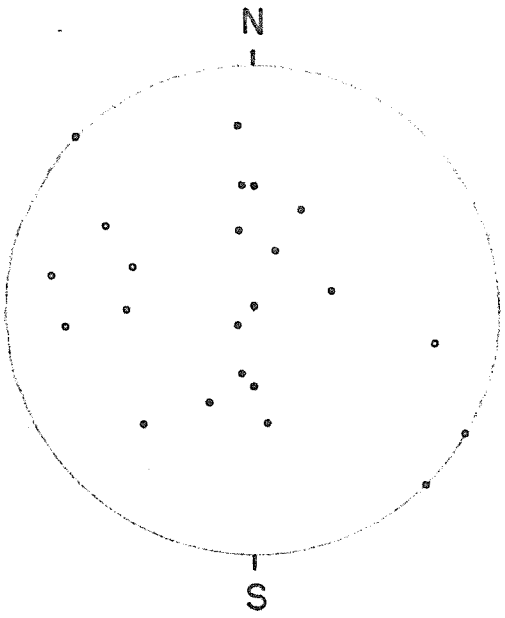

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