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GRANITE AT MARBLEHEAD--
IGNEOUS OR METAMORPHIC?

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Introduction. The best exposure of granite invasion of basic rock in the Greater Boston region is to be seen along the shores of Marblehead, Massachusetts, just north of the boundary line with the town of Swampscott, in the section which is known locally as Clifton. Wave erosion has exposed a remarkably clean section of rock which reveals the extremely varied lithology and structure which occurs at the junction between a pink granite and a highly modified diabase. The area provides a test example of the possible origin of granite in such a geological setting.

Location. The area is immediately accessible to Route 129, just north of the boundary with Swampscott in Marblehead, as indicated by the enclosed sketch map of the area to be described.

General Description of Exposures

The rocks along the 500 feet of shoreline involved in this discussion have only recently been cleared of glacial till by wave action. This fact is indicated by the prevalent glacial striations, polish, and grooving to be seen on the flanks of the southern small peninsula shown on the map. The glacial deposits can be seen resting on preglacial terrace at the 26 foot level. This terrace, plus a forty foot one, is very noticeable along the entire Marblehead coast.

The four major rock types to be seen, from oldest to youngest are: recrystallized basalt, intermediate composition lighter colored rocks, granite, and later basaltic dikes. The recrystallized basalt can be seen as a roof above the intermediate and granitic types, and it is also seen as large inclusions within the intermediate and granite rocks. The intermediate type can be seen as inclusions and as irregular masses with no specific boundaries. The granite occurs as large granitoid masses, as aplite dike-like masses, and as pegmatite veins.

Faulting is omnipresent throughout the area. It is best observed in the offsets of granite dike-like masses as well as in the offset of the late basaltic dikes. The most convincing evidence for faulting in the Greater Boston Region is to be observed where basaltic dikes, one meter wide and 10 centimeters wide which are about 5 meters apart, are offset at least tem times in a distance of 60 meters. A well developed fault line scarp which shows fault breccia and slickensides appears as a 3 meter cliff on the southern edge of the northern peninsula. The large basaltic dike is offset along this fault line. In addition, wave erosion has preferentially carved a channel along this fault line which is much larger at sea level than it is 4 meters higher. When tide level is at the right height, and when waves move into this cave-like opening, the water converges and occasionally forms a spouting horn with water and spray rising as much as five meters above the narrow orifice at the inner end of the cave.

PETROLOGY

The Calfemag Suite. The setting in which the granite formed involved two major geological conditions. The first was the development of the Acadian Geosyncline with an unknown thickness of sedimentary rocks. The second was the superimposition of thousands of feet of basaltic flows and tuffs as a cover to the underlying sediments with their abundant connate sea water. The sedimentary rocks cannot be seen in the area under discussion, but they are readily observable in schistose form in the Andover, Massachusetts region.

Since the initial texture of the basalts in volcanic piles is vitreous, for the most part, we are assuming that the vitreous texture was characteristic of the rocks now exposed in the calfemag suite at Marblehead. None of this vitreous texture remains in the rocks at Marblehead, although it can be observed in rocks of the same volcanic pile in the Waltham section of Route 128. It is assumed here that the present granitoid texture of the calfemag rocks is the result of metamorphism and is not the primary texture of the rocks. Since the texture of marble and quartzite is essentially the same as that of the calfemag rocks here, and since the textures of marble and quartzite are quite clearly the result of metamorphic recrystallization, this assumption seems fairly safe. We suggest here that the recrystallization which changed the basalt glass into basalt and diorite was the result of the same over-all heating process which ultimately developed the granite or sinak rocks. This recrystallized rock appears on the southern edge of the third peninsula without any granite stringers or signs of granite invasion as a well defined roof over granite which contains extensive inclusions of the calfemag rock. The typical diabase texture of basalt is largely missing in the calfemag rocks, but it is present in minor amounts.

Modal Description of Calfemag Rocks. Although flows usually have a monotonous consistency in composition, there is notable variation in the modes of different specimens of the calfemag rocks. The following table is derived from point counts of 17 thin sections which have been reduced to averages of three somewhat different modes.

Modes (volume %) of Calfemag Rocks

Mineral	1	2	3
Quartz	1.54	0.00	0.00
Orthoclase	3.16	3.37	5.26
Orthoclase-perthite	0.00	0.00	0.00
Microcline-perthite	0.00	0.00	0.00
Plagioclase (an 47)	49.50	45.32	45.50
Amphibole	20.00	23.23	26.75
Pyroxene	10.00	4.55	7.75
Biotite	0.00	0.00	9.15
Chlorite	11.60	17.42	2.99
Magnetite	4.20	6.10	2.60
Total	100.00	100.00	100.00

The quantitative variations of the various modes is probably due to variations in metamorphism.

Microprobe chemical analyses were made of perthites, plagioclases, amphiboles, and pyroxenes in the three different rock types at Marblehead. These are not included in this paper but can be examined in the Masters Thesis File in the Boston University departmental offices for geology in Raman's thesis entitled "PETROGENY OF GRANITES AND ASSOCIATED ROCKS AT MARBLEHEAD, MASSACHUSETTS", (1973). On the basis of these analyses and with certain minor assumptions the average chemical compositions of the various rock types can be derived. Such an average chemical composition for the calfemag rocks at Marblehead follows.

Average Bulk Chemical Composition of Basic Rock Types

Mineral	wt%	wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	0.48	0.48	-	-	-	-	-	-	-
Orthoclase	3.00	1.94	0.55	-	-	-	0.51	-	-
Plagioclase	48.30	21.28	21.02	-	-	3.69	-	2.30	
Amphibole	23.40	1.47	4.72	6.45	5.30	4.04	0.57	0.74	0.11
Pyroxene	12.52	8.34	0.32	1.15	0.88	1.78	0.03	0.04	-
Chlorite	12.30	3.48	3.35	2.01	2.71	0.14	-	-	0.60
Totals	100.00	36.99	29.96	9.61	8.89	9.65	1.11	3.08	0.71

Modal Description of Intermediate Rocks. Rocks of the intermediate composition rock suite at Marblehead vary tremendously in texture and mineral composition. Some of the rock is a massive, rather homogeneous syenite. Much of the intermediate compositions are to be seen in the inclusions. The margins of many of the inclusions are surrounded by a hornblend rim which is much darker than the remainder of the inclusions. The inclusions vary from almost unchanged diorites or basalts to nothing but ghost-like areas of slightly differing compositions from the surrounding rocks. Many of the inclusions manifest a pervasion texture of potash spar megacrysts throughout the darker host rock; and there is a complete gradation from unaltered inclusions to that stage where the inclusion is no longer visible. Some of the inclusions are sharp and angular; others show gradational margins and are somewhat rounded. We have chosen three differing lithologies for the modal analyses which follow. They are indicative of the variations which can be observed, but they certainly do not embrace all of the possible modes in the intermediate rocks. The compositions of the amphiboles do not change very much from the ferrous hornblendes of the calfemag suite, but the plagioclases change abruptly from An47 to An23, requiring a tremendous introduction of sodium into the system. The grain size of the amphiboles decreases from the calfemag suite to the intermediate suite.

Modes (volume %) of Intermediate Rocks

Mineral	1	2	3
Quartz	3.73	11.90	8.10
Orthoclase	5.51	4.00	9.42
Orthoclase-perthite	10.72	8.40	26.00
Microcline-perthite	3.58	2.50	6.00
Plagioclase (an 23)	42.30	37.00	27.70
Amphibole	16.00	9.10	9.30
Pyroxene	7.40	4.10	5.30
Chlorite	7.00	3.37	4.90
Magnetite	2.72	0.11	1.28
Total	100.00	100.00	100.00

The marked increase in potash spar, the decrease in an content, the disappearance of magnetite, and the decrease in amphibole, pyroxene, and chlorite are particularly impressive as appears in the resulting chemical changes indicated by the average bulk chemical composition of the intermediate rocks.

Average Bulk Chemical Composition of Intermediate Rock Types

Mineral	wt%	Wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	6.57	6.57	-	-	-	-	-	-	-
Perthite	41.80	15.90	13.60	-	-	0.96	10.5	0.47	-
Plagioclase	27.82	12.18	10.30	-	-	1.18	-	4.33	-
Amphibole	11.45	0.68	2.05	2.85	3.48	1.79	0.25	0.30	0.05
Pyroxene	6.90	2.70	0.02	0.97	1.52	1.39	0.01	0.08	-
Chlorite	5.46	1.49	1.43	1.29	1.12	0.08	-	-	0.02
Totals	100.00	39.44	27.40	5.11	6.12	5.40	10.76	5.18	0.07

Modal Description of Sinak Rocks. The sinak rocks which were ultimately developed at Marblehead were true granites which were usually pink in color. Orthoclase perthites and microcline perthites were far more abundant than orthoclase. The amount of plagioclase is reduced to roughly one half or less of its abundance in the calfemag and intermediate type rocks. The femag minerals are reduced to about one eighth their abundance in the calfemag rocks. The three modal analyses which follow are derived from ten thin sections which were as judiciously chosen for the sake of variety as was possible.

Modes (volume %) of Sinak Rocks

Mineral	1	2	3
Quartz	21.2	18.10	17.40
Orthoclase	5.56	10.30	8.04
Orthoclase-perthite	27.00	20.23	20.60
Microcline-perthite	18.00	26.50	23.71
Plagioclase (an 21)	24.00	16.50	18.22
Amphibole	5.21	7.35	3.16
Pyroxene	0.13	0.00	0.00
Biotite	0.00	0.00	0.00
Chlorite	0.00	0.00	6.05
Magnetite	0.00	0.00	2.82
Total	100.00	100.00	100.00

The overall decrease in calcium, iron, and magnesium is particularly impressive when the average composition of the sinak rocks is considered. The concomitant increase in silicon and potassium is equally noteworthy, and both facts will be of considerable importance when we discuss the implications for magmatic versus metamorphic origin of the granite.

Average Bulk Chemical Composition of Sinak Rock Types

Mineral	wt%	wt% of various oxides							
		SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O
Quartz	17.80	17.80	-	-	-	-	-	-	-
Perthite	53.42	23.28	15.77	-	-	1.14	12.69	0.54	-
Plagioclase	16.43	7.80	5.70	-	-	0.55	-	2.34	-
Amphibole	9.35	1.63	2.85	2.30	1.16	1.26	0.02	0.09	0.04
Chlorite	3.00	1.00	1.03	0.88	0.07	-	-	-	0.02
Totals	100.00	51.51	25.35	3.18	1.23	2.95	12.71	2.97	0.06

Summary of Chemical Changes. The chemical changes in the environment are really monumental. Let us assume that the specific gravity of the calfemag rocks is 2.9; that of the intermediate rocks is 2.8; that of the sinak rocks is 2.65. One cubic meter of the calfemag rocks would then weigh 2,900 kg; one cubic meter of intermediate rocks would weigh 2,800 kg; and one cubic meter of sinak rock would weigh 2,650 kg. The following table shows the composition in one cubic meter of the various oxides, exclusive of water.

Oxide Weights in 1 m^3 of Various Rock Types

Oxide	m^3 calfemag 2,900 kg Wt. in kg	m^3 intermediate 2,800 kg Wt. in kg	m^3 sinak 2,650 kg Wt. in kg	Net change in kg
SiO_2	1,073	1,104	1,365	+672
Al_2O_3	869	767	672	-197
FeO	279	143	84	-195
MgO	258	171	33	-225
CaO	280	151	78	-202
K_2O	32	301	337	+305
Na_2O	89	145	79	- 10

The only anomalously behaving oxide is soda. Its decrease in the final stage rocks, the granites, is to be explained in terms of the unstable position of plagioclase in the developing environment.

Probably the most important problem regarding the emplacement of the granite is the destination of the subtracted materials. Since the emplacement of the granite was not accompanied by any marked volume changes, as evidenced by the unfractured roof of calfemag rock above the granite, the calfemag materials which were in the country rock must have migrated somewhere, whether the granite is igneous or metasomatic in origin. If the calfemag constituents had moved outward from the granite body, the roof should be greatly enriched in those elements. There is no evidence for this enrichment. The only conclusion which one can draw is that the calfemag constituents were moving down as the sinak constituents moved upward. It is easy enough to bring sinak components into the region in watery solution; but the mechanism whereby the calfemag constituents move down toward the heat source is less obvious. The calfemag constituents are less soluble in the environment which was developing, as evidenced by the amphibole halo around the inclusions, but how the amphibole constituents completely disappear is a major problem. In all probability, the ions migrate until they are precipitated as less soluble constituents or minerals deeper in the column and nearer the heat source.

Origin of the Rocks at Marblehead

If the granite problem cannot be solved at Marblehead, it is probable that there is little chance of any solution being found. The usual view of these rocks, as suggested by LaForge, is that granite magma in a large batholithic chamber was invading an already emplaced batholithic mass of the Salem gabbro-diorite. The inclusions are xenoliths in the Daly sense of piece meal stoping. The tongues and veins of granitic composition are apophyses. Yet, there seems to be cogent evidence at Marblehead that the granite could be of metsomatic origin. Let us, therefore, submit the field evidence which must be explained, regardless of which approach is used.

1. The emplacement of the granite is apparently a volume for volume process.

2. No matter what the origin of the granite, calfemag constituents and alumina must be removed from the region.

3. If the calfemag inclusions are to be digested, a tremendous amount of super heat is required to carry on the process, if the granite came in as a magma.

4. The amphibole rims around the inclusions must be explained.

5. Sinak eyes or sunbursts in the calfemag rocks some distance away from obvious sinak rock need explanation.

6. All degrees of pervasion textures and potash feldspar development in inclusions can be seen.

The explanation for the volume for volume emplacement is easily handled by both approaches to the origin of granite. If the granite came in as magma, the amount the magma rose by piece meal stoping would be equivalent to the volume of material which would settle into the magma and fill the potential void which was produced by the rising of the magma. If the granite were emplaced by metasomatism, the amount of material dissolved from the roof would be exactly equal to the amount of calfemag material which would crystallize in depth. Sinak and calfemag constituents simply exchange positions in equilibrium with the temperature gradient.

Calfemag constituents could be removed readily if the granite were emplaced as a magma simply through the sinking of calfemag crystals in the sinak magma. Certainly, the basic condition of equilibrium for the earth is to have sinak rocks above calfemag rocks. Bowen's Reaction Series suggests that calfemag constitutents dissolve last or crystallize first, and gravitational settling is very possible. The fact that many of the inclusions are in all stages of change into granite just below the calfemag roof, suggests, however, that very little gravitational settling of the inclusions was taking place. Amphibole crystals surround the inclusions; and they probably should have migrated away. We have already indicated that ionic diffusion in a thermal gradient might well produce crystallization of calfemag constituents in depth, with sinak constituents simultaneously moving away from the heat source; but this is problematical at best.

Daly (personal communication) said long ago that his biggest problem with piece meal stoping was the tremendous heat requirement to keep the process going. Of course, if he had visualized an adequate source for the magma generation in the first place, radioactivity, he would not have been so troubled by the superheat requirement. The heat for magma invasion and metasomatism can easily be supplied by radioactivity. In fact, since there can be no other source for the heat, ultimately, there must be enough radioactivity to supply the needed heat.

The pervasion textures and sinak <u>eyes</u> both require sinak diffusion into the inclusions. Since it is possible, as borne out by the existence of these phenomena, the source of the solutions for the diffusion is the major problem. If the solutions are emanations from the granite, the granite should simultaneously be enriched in calfemag minerals. This is not the case. The authors suggest that the sinak solutions are products of solution of sinak sedimentary rocks lying in the geosyncline below the volcanic pile. The volcanic pile acted as a thermal and solution blanket until heating in the underlying sediments produced an unstable region beneath the pile, and solutions began to move up. Evidences for such permeation of sinak solutions into the overlying volcanics can be seen along Route 128 from Reading to Waltham. It can also be seen along 193 from Woburn to Andover and Tewksbury. Certainly, if solutions from granite magma can permeate inclusions, sinak solutions which are formed in depth in a geosyncline could do the same. The fact that nearly 1,000 kg of sinak substitution and 900 kg of calfemag subtraction has taken place in the Marblehead region for every cubic meter strongly suggests the metasomatic origin. The fact that many granitic dike like bodies apparently required no space for their emplacement also suggests the metasomatic origin. No chill border can be observed between granite and country rock; in fact, the granite masses are usually coarsest near the contacts. This again suggests a metasomatic origin. The basis process, therefore, we believe, is one of differential solution, ionic migration in solution, and crystallization in equilibrium with a thermal gradient downward.

Outstanding Spots in the Region to be Visited.

Consult the Map.

Description of Localities at Marblehead-Clifton

1. Best place to start trip. Pervasion textures in calfemag inclusions. Sharp and transitional boundaries. Amphibole rims around some of the inclusions. Pegmatite veins, often zoned. Extensive faulting and rehealing by quartz and epidote. Glacial striae, grooves, and polish. Striae trend S 21 E.

2. More glacial striations. Rock is recrystallized basalt. Faulted pegmatite veins. Sinak eyes in recrystallized basalt.

3. Glacial striae disappearing under till. Faulted 34mm wide aplite "dike".

4. One of many major faults trending N 65 W and vertical. Permeation texture in basalt.

5. Step faulted aplite dike. Pegmatite veins with reaction margins. Sinak eyes. Glaciated old terrace disappearing beneath cover of glacial till. Many deeply weathered pebbles and boulders in the till.

6. Beautiful example of pebble beach with nearly spherical pebbles resulting from the direct inflow and outflow of waves and currents. Northern end of beach is more sheltered and often shows sand instead of pebbles. If the swell is rolling, note the roar of pebbles undergoing autocomminution in the undertow.

7. Ten foot high fault line scarp. Slickensides and breccia can be observed here and there along fault line. Fault zone is geomorphically incompetent. Rock on wall of fault line scarp is largely unaltered "batholith" roof.

8. Pegmatite vein, well zoned with quartz core and vug containing quartz crystals.

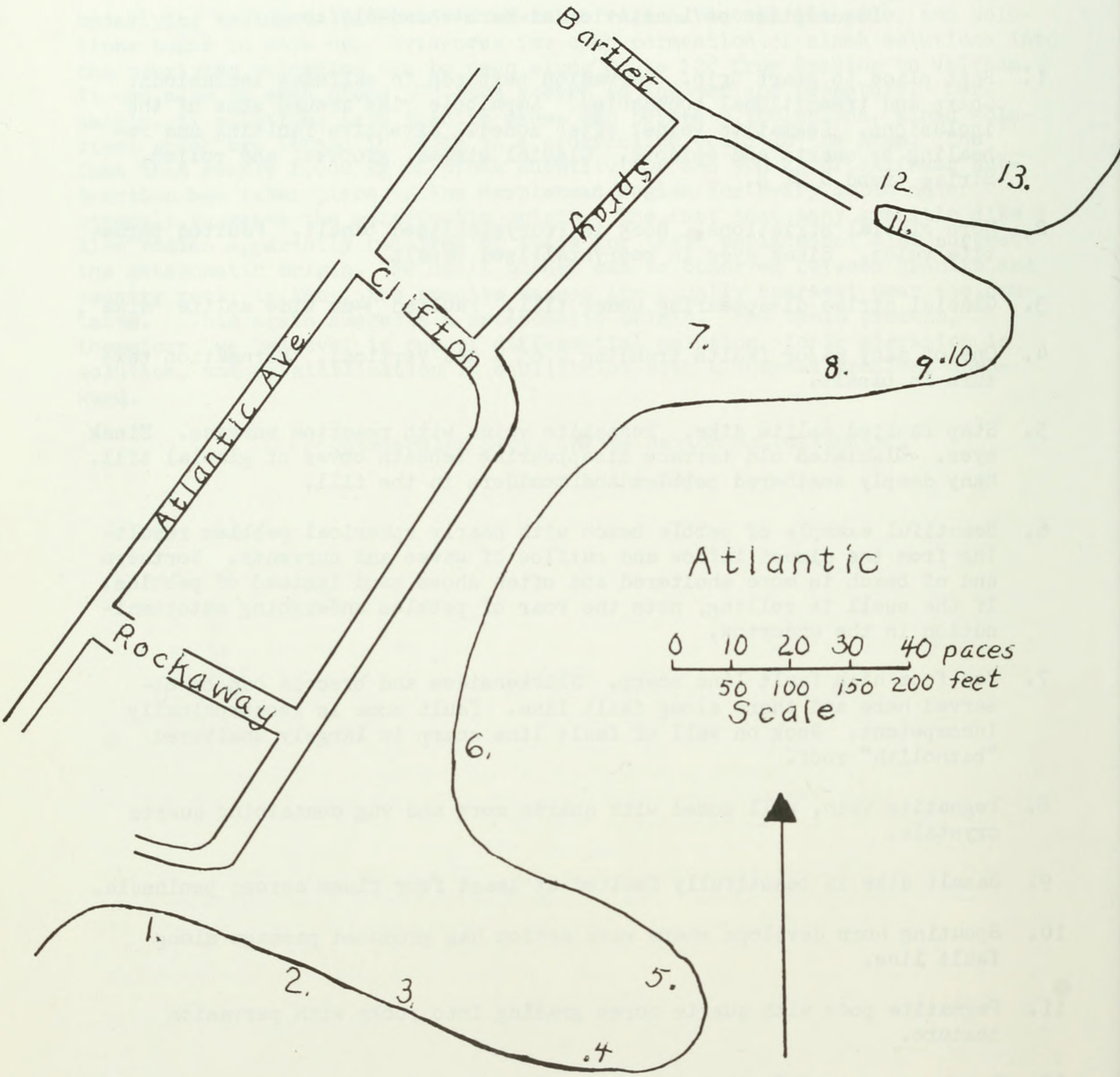
9. Basalt dike is beautifully faulted at least four times across peninsula.

10. Spouting horn develops where wave action has produced passage along fault line.

11. Pegmatite pods with quartz cores grading into rocks with pervasion texture.

12. Best exposure of "batholith" roof. Note transition downward.

13. Basaltic dike of locality 9 continues with repeated faulting. 10 cm dike five meters inshore from larger dike parallels the large dike and is affected by the same faults. Here is the best region to study the relationships between inclusions and granite. Pervasion textures in all degrees of development can be seen. Amphibole rims on inclusions. Sharp and imperceptible contacts are both visible. Ghost inclusions are common. Sinak eyes occur in dark rock and in inclusions of dark rock. Small cliff here permits the study of the "batholith" in three dimensions.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MARBLEHEAD