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ORIENTED INCLUSIONS IN GRANITE—FURTHER EVIDENCE FOR FLOORED MAGMA CHAMBERS

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ABSTRACT. Hundreds of extensive road-cuts rather uniformly distributed over the Cadillac Mountain pluton in southeastern Maine provide an unusual opportunity to investigate preferred inclusion orientation in great detail. Nearly 200 good to excellent readings show that a delicate but well-developed planar structure due to parallel inclusions is roughly horizontal over most of the granite pluton and inclines centripetally up to about 25° in the marginal zone.

It is concluded that this saucer-shaped structure-pattern is analagous to mineral layering in the Skaergaard intrusion. It developed as a sedimentational feature within the magma chamber that formed by cauldron subsidence. The floor upon which crystals and inclusions accumulated is represented presumably by the top of the subsided block.

Convection currents must have been active during the consolidation stage and appear to account for the size range, size distribution, shape, and state of alteration of the xenoliths and in part for their orientation. Centripetal dips in marginal areas are probably due to more rapid accumulation there.

The marked differences between the inclusions constituting the saucer-like structure-pattern and the more angular, diversely oriented xenoliths of the contact zone are petrogenitically significant in this and perhaps many other plutons. It suggests, furthermore, that piecemeal stoping played an an insignificant direct role in the formation of the body of granite.

INTRODUCTION

When we consider the voluminous literature dealing with layered stock-like plutons, constituting and associated with magmatic central complexes, it is surprising that geologists, and petrologists in particular, have not ventured further into the realm of speculation as to the initial conditions that led to layered bodies. In their classical study of the Skaergaard intrusion, Wager and Deer (1939) showed that the presumably conical form provided an effective floor upon which the crystal phases could accumulate. In more recent publications dealing with layered, steep-walled plutons, various authors have stressed the nature of petrological trends. Justly enough, emphasis has been placed on the detailed aspects of the layering, the mineral phases, and the conditions of consolidation within the magma. Explicit reference to the nature and particularly the shape of the lower portion of the magma chamber and pluton itself is practically nil. In a few papers (for example, Upton, 1960) the deep-seated relations are only vaguely mentioned or implied. Wager and others (1965), however, are more explicit.

The present writer feels there is ample evidence to justify developing a more definitive three-dimensional picture of certain types of magma chambers and that with such a model or group of models more rapid progress will be made in solving the many problems of magmatic central complexes. One purpose of this paper is to stimulate thought along this line.

The writer has recently (Chapman, 1966) pointed out certain evidence to indicate that magma chambers in many magmatic central complexes have floors. Further evidence for this conclusion is found in the granitic plutons along the coast of southeastern Maine (Chapman, 1968b).

This evidence is based largely on the preferred orientation of inclusions and is most strikingly revealed in the Cadillac Mountain pluton of Mount Desert Island.

The ground work for this investigation was laid in the 1920's when Mr. John D. Rockefellow, Jr. to whom the writer is greatly indebted, undertook a grand scale endeavor to construct an extensive network of horse-and-carriage roads over the hilly and mountainous, granitic terrain. Road construction was a major operation here, where the area was nearly stripped of its residual soil in Pleistocene time. It necessitated cutting into the granite slopes extensive terrace-like notches which may run almost without interruption for hundreds of yards. Moreover, the construction of many miles of auto road in other parts of the area added materially to the number of fresh openings in granite and provided an exceptional opportunity to sample and obtain highly reliable structural data on inclusions in 80 percent of the exposed area of the pluton.

Although this extensive engineering project was considered by many at the time to be purely folly and objected to strenuously, its scientific value should not be underrated. It has provided an unusual opportunity to establish clearly the existence of a somewhat obscure but well-developed internal structure, due to preferred orientation of inclusions, throughout what otherwise appears as a massive granitic pluton. Without such numerous and widespread fresh cuts this study would have been impossible.

GEOLOGIC SETTING

The Cadillac Mountain pluton is one of at least 14 granitic plutons along the eastern Maine coast. These roughly circular, stock-like bodies are 5 to 10 miles in diameter. They cut the mafic and felsic phases of the Bays-of-Maine igneous complex, of probable Early Devonian age (Chapman, 1968a and 1968b), as well as older stratified volcanic and sedimentary units. The Cadallic Mountain pluton forms the central and largely mountainous portion of Mount Desert Island (fig. 1). This body of hornblende granite appears to have been cut out in its northwestern part by a smaller intrusion of biotite granite. Surrounding the high granitic core of the island is a marginal lowland underlain by a variety of older and weaker rocks.

In contact with the granite, and surrounding it on all but the northwestern side, is a continuous fringe of brecciated country rock referred to as the shatter-zone. The breccia has developed largely from well-stratified silt-stones and tuffaceous beds of the Bar Harbor Series. Locally, fragments of disrupted mafic sills and dikes are abundant.

The fresh hornblende granite is pale pink to greenish gray, medium- to coarse-grained, and relatively equigranular. It is composed of about 60 percent microperthite, 30 percent quartz, and 5 percent hornblende in hypidiomorphic granular texture. Commonly more or less quartz is intergrown with microperthite, but much is interstitial to the feldspar. Accessories usually include apatite, magnetite, and zircon; locally biotite and sphene are present.

For convenience the pluton will be divided into three concentric and more or less distinct zones: (1) contact zone, (2) marginal zone, and

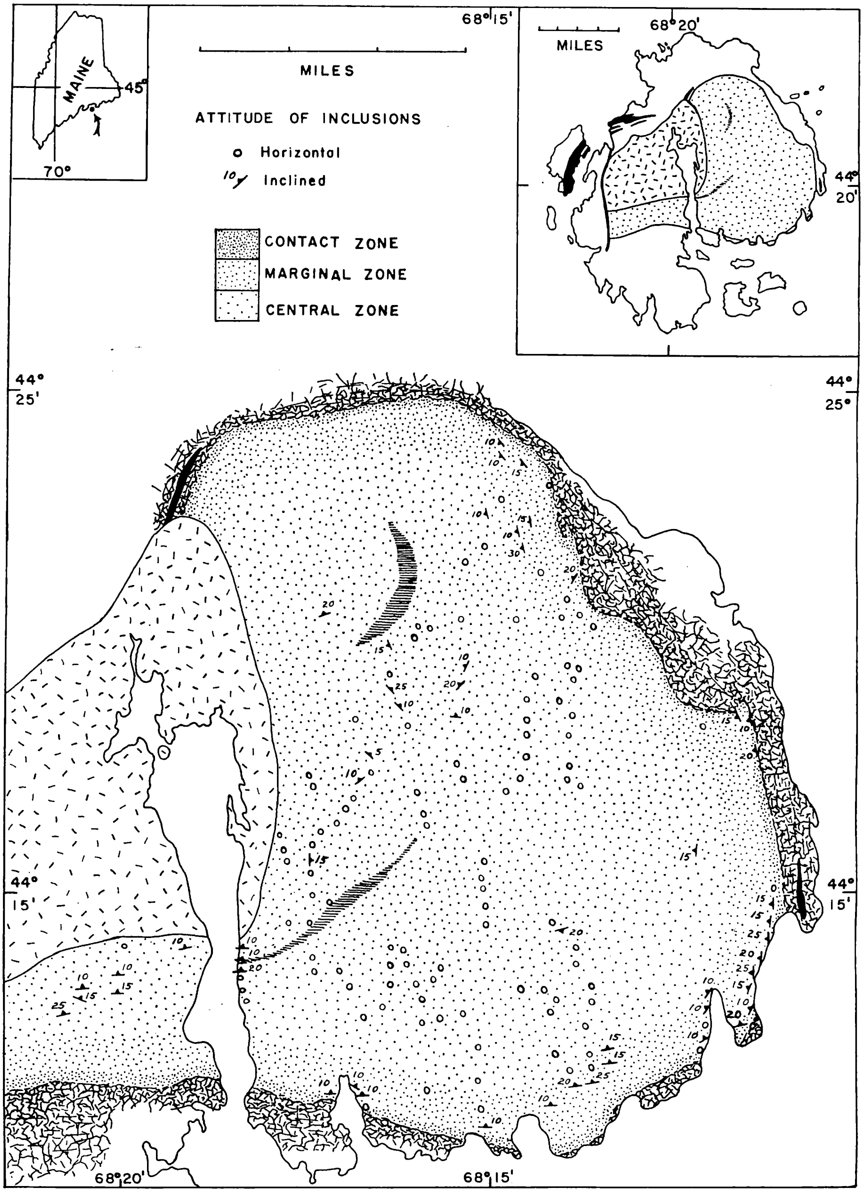

Fig. 1. Location of Mount Desert Island and the orientation of inclusions in the Cadillac Mountain pluton. Biotite granite—dashes; ring-dike granite—black; recrystallized granite—ruled; hornblende granite (Cadillac Mountain pluton)—stipple; country rock—blank; shatter-zone in country rock—mosaic.

(3) central zone. The contact zone, generally a few hundred yards wide, is composed of the finest-grained granite. It is nearly free of inclusions along its inner edge, but toward its outer edge it becomes crowded with xenolithic material and gradually passes into the shatter-zone at the contact with the country rock. In spite of its somewhat-gradational character, the contact of the pluton may be fairly sharply defined. In crossing the shatter-zone, one passes from thoroughly jumbled breccia through severely shattered country rock to mildly ruptured material and finally to the undisturbed beds of the Bar Harbor Series.

In from the contact zone is the marginal zone of generally coarser-grained granite. Its outer boundary, as will be shown later, is rather sharply defined at a distance approximately 200 to 300 yards from the shatter-zone. The inner boundary, however, is highly gradational and is placed very roughly at twice that distance. The central zone constitutes the largest portion of the pluton and is composed of relatively uniform, medium- to coarse-grained granite.

The probable origin of the granite has already been considered (Chapman 1953, 1962a, 1962b, 1968b). The following lines of evidence indicate that the rock formed by crystallization of a granitic magma. (1) A thermal metamorphic aureole of hornfelsic rock surrounds the pluton. (2) There is a marked reduction in grain size of the granite against its contact. (3) The pluton abruptly cross-cuts structural features of the country rock. (4) Apophyses of fine-grained granite fill dilated fractures in the country rock. (5) Angular inclusions of country rock in the granite exhibit sharp contacts and diverse orientation, and many appear re-broken, dilated, and veined by granite. (6) The feldspar is highly perthitic and appears inverted from a high-temperature form.

The magma is considered (Chapman 1953, 1956, 1962a, 1962b, 1968b) to have been emplaced in a large chamber roughly 10 miles in diameter by ring-fracturing and cauldron subsidence. Very briefly the evidence is as follows: (1) subcircular outline of pluton, (2) smoothly curved sharp boundary, (3) paucity of granitic apophyses, (4) presence of ring-dikes and possible cone sheets, (5) shatter-zone along contact of pluton, (6) ring-dikes passing into shatter-zones, (7) web vein pattern and web breccia pattern in adjacent country rock, (8) external centripetal dip pattern, and (9) chilled contacts indicating rapid ascent of magma.

NATURE OF THE INCLUSIONS

Inclusions in the contact zone decrease not only in abundance but also in size away from the shatter-zone. Near the shatter-zone they are commonly 3 or 4 feet across; but if present near the marginal zone, they seldom exceed a few inches. Angular to subangular blocks in which bedding is still apparent are very common, and their disposition with respect to bedding planes and external form is such as to present a thoroughly jumbled appearance.

In the marginal zone inclusions are strikingly different. They are tabular or lenticular with high length-breadth ratios, and dimensional

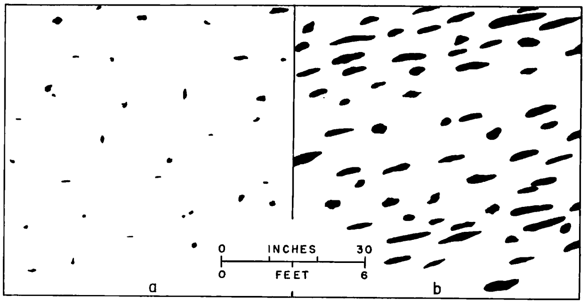

Fig. 2. Schematic representation of inclusions in the Cadillac Mountain pluton. a—central zone; b—marginal zone. Note! Distances between inclusion centers are indicated by the feet scale; dimensions of inclusions are indicated by the inches scale.

parallelism is highly perfect. Inclusion size and abundance here have suddenly increased, and length commonly exceeds 1 or 2 feet. Well-rounded forms are the rule, and all inclusions have been thoroughly recrystallized and homogenized (see fig. 2).

Passing from the marginal zone to the central zone, the size and frequency of inclusions gradually diminish. Throughout the central zone inclusions generally range up to 2 or 3 inches across, and only a few occur per square yard of outcrop surface. Their mass per cubic yard, therefore, is extremely low compared with that of the marginal zone. The degree of rounding and alteration, however, resembles that of the marginal zone.

Petrographically the inclusions of the marginal and central zones are similar. Most commonly they are light to medium gray, fine grained, and composed largely of plagioclase and hornblende with more or less quartz and alkali feldspar. The lighter colored inclusions are richer in quartz and alkali feldspar and were derived presumably from stratified rocks of the Bar Harbor Series and felsitic volcanic material. The darker inclusions are predominantly plagioclase and hornblende and appear to represent fragments of mafic volcanic material and intrusive doleritic rock. Inclusions are strongly recrystallized with allotriomorphic to hypidiomorphic granular texture, commonly exhibiting interlocking grains. Occasionally a few scattered porphyroblasts of alkali feldspar, like the crystals of the enclosing granite, are seen.

Preferred orientation of inclusions is best developed and most striking in the marginal zone where inclusions are large, abundant, and highly tabular or lenticular. But even here the planar structure is often not obvious, except on steep, lichen-free surfaces, because of its subhorizontal attitude. In the central zone preferred orientation is much less conspicuous and commonly difficult to detect. In fact without the numerous fresh road-cuts, it would be difficult to demonstrate that a systematic structural pattern even exists. On natural outcrop surfaces the small inclusions are usually concealed by weathered material, surface strains, and lichen.

Careful inspection of fresh surfaces reveals that, although there is a strong tendency for inclusions to lie with their longer dimensions nearly horizontal, very locally vertical inclusions may predominate. Elsewhere inclusions representing both preferred orientations may be interspersed in certain parts of the outcrop. Rarely, however, do the vertical inclusions show a common strike. Furthermore, inclusions inclined at various intermediate angles are common, widespread, and generally interspersed with vertical and/or nearly horizontal ones. These, however, show wide variation in strike. It is quite clear then that one and only one planar inclusion structure exists. This structure, except very locally, is horizontal or less commonly low-dipping.

The persistence of this subhorizontal planar structure may be readily substantiated by observation of inclusion parallelism in the closely spaced rectangular blocks of granite aligned to form a rather continuous guard along the outside edge of the many miles of roadway over the granitic terrain. These fresh-looking blocks, roughly 1 to 3 feet on a side, provide a very high specific surface and, therefore, a better opportunity to observe the three-dimensional relation than the natural outcrop surface or even many roadcuts. Numerous blocks, furthermore, retain approximately half the bounding surface of a great many 2-inch drill holes, prepared in the formation of the road-cuts. Commonly such holes intersect inclusions and provide an excellent opportunity to determine their three-dimensional form.

Not only do the blocks exhibit planar orientation of inclusions but surprisingly enough, this directional structure maintains remarkable continuity from block to block. It inclines steeply and strikes parallel to the line of blocks, swinging right or left with each curve in the road. Obviously the continuity of structure is due to a preferred orientation of the blocks themselves, as may be readily confirmed by comparing the attitudes of drill holes. In the ledges, drill-hole axes are steep; in the blocks, axes are horizontal and trend perpendicular to the line of blocks (across the length of the road). Most blocks, therefore, have been taken from the road-cuts and rotated roughly 90° from their original position.

It may appear incredible, but the arrangement of blocks, which led to parallel inclusions along the barricades, was controlled by a planar structure within the granite. Well-developed and closely spaced sheeting fractures controlled the formation of the blocks and provided them with large faces parallel to the sheeting surfaces. It was the large face that the road-builders set vertical and parallel to the length of the road in order to provide maximum screening in the rock barrier. It is doubtful if inclusion structure was even seen by the road-builders. Its continuity in the line of blocks is due to its close parallelism with the sheeting structure of the granite.

In determining the attitude of inclusion parallelism in the outcrop, the greatest reliability was placed on the more tabular and thinner lenticular inclusions. In the marginal zone such inclusions are plentiful.

In the central zone the most consistent results were obtained with inclusions between three quarters and one and a half inches long that in cross-section showed a length-breadth ratio of 5.0 or greater. Furthermore, only data obtained from relatively fresh cuts can be considered of first-class quality. Of the 194 structural measurements recorded to represent over 80 percent of the pluton in this study, all but 7 were obtained from artificial cuts.

In summary, a careful study shows nearly horizontal inclusions to be by far the predominating type throughout the central zone. At most stations in this zone the planar structure recorded was horizontal, but locally dips as high as 20° were obtained for this structure. In the marginal zone the structure is much more commonly inclined, and dips between 15 or 25° were recorded at numerous stations. The highest value obtained here was 35°. The dip direction in the marginal zone is radial, toward the center of the pluton. For all practical purposes, then, the inclusion structure-pattern over the granite pluton appears to be roughly saucer-shaped.

CAUSE OF INCLUSION ORIENTATION

Accepting that the inclusions represent xenoliths incorporated in a granitic melt, four theories are considered to account for their preferred orientation: (1) orientation due to differential flow in the magma; (2) orientation due to incorporation of slabby fragments of horizontal, well-bedded rocks; (3) orientation due to slabby fragments settling through a viscous melt; and (4) orientation due to slabby inclusions coming to rest upon a roughly horizontal floor or crystal layer.

The first hypothesis will not explain satisfactorily the numerous vertical inclusions commonly dispersed among the horizontal ones. If we assume, for example, horizontal laminar flow at any locality, we might expect the greatest number of inclusions to attain a horizontal attitude, and the frequency of dip values at progressively higher angles should diminish. The actual distribution of dip values, however, is commonly strongly bimodal (horizontal and vertical).

To assume that slabby inclusions could be introduced into a melt initially with horizontal attitudes, inherited from fractured horizontal beds of country rock, is reasonable and appears to have occurred locally on a small scale near the contact of the pluton. To assume that such ideal conditions could prevail over the exposed 46 square miles of the pluton seems very unlikely. The common association of vertical and horizontal inclusions seems quite inconsistent with this hypothesis also.

If the slabby inclusions had settled through a granitic melt, it seems that they should have assumed a common orientation in conformity with hydrodynamic principles. It is believed that the conditions of settling in a viscous granitic melt would favor a vertical orientation for the inclusions rather than a horizontal one. At any rate it is difficult to explain the common association of vertical and horizontal inclusions on the basis of settling alone.

Finding the other theories untenable, it is concluded that the parallelism of inclusions represents a sedimentational feature formed by accumulation of crystals and xenoliths on the floor of a magma chamber. This theory not only explains the high frequency of horizontal inclusions but accounts for the vertical preferred orientation, which is usually subordinate but so commonly accompanies the horizontal one. Presumably most xenoliths settled with their shortest dimension horizontally, but upon reaching the cumulate layer at the base of the melt, they rotated 90° to assume the most stable equilibrium position. Many inclusions, however, must have retained their vertical attitude as they became wedged or partially buried in the upper part of the cumulate layer. The vertical inclusions, therefore, are considered to represent relics of the orientation pattern of the settling inclusions.

Many inclusions probably wedged in a vertical attitude only temporarily and later topped to a more nearly horizontal position after having been disturbed by slight movement of the melt or the fall of other solid bodies. Except rarely, inclusions with high length-breadth ratios are parallel to the preferred direction (horizontal or low-dipping). Thick lenticular and ellipsoidal inclusions apparently rotated much less frequently to the horizontal orientation but stopped at an intermediate position of unstable equilibrium. It should now be clear why in the course of field study the most successful results were obtained with inclusions exhibiting length-breadth ratios of 5.0 or greater.

ORIGIN OF THE SAUCER-SHAPED STRUCTURE-PATTERN

To explain the saucer-shaped pattern of oriented inclusions, a mechanism similar to that postulated by Wager and Deer (1939) for the Skaergaard intrusion is proposed. By ring-fracturing and cauldron subsidence a roughly cylindrical magma chamber was created in the Mount Desert Island area. The floor of this chamber was represented by the top of the subsided block upon which crystal cumulates were deposited. Interred with these pyrogenetic crystals were the numerous inclusions that had been widely distributed throughout the melt. More rapid accumulation in the marginal portion of the chamber is indicated by the centripetal dips of the planar structure formed by inclusions in the marginal zone. Dips of 15 to 25° are common here, but values higher than 35° were not observed. As one passes through the marginal zone up to the contact zone of the pluton, inclusions generally become larger, more abundant, and more perfectly oriented.

These relations suggest that convection currents in the melt played an important role. The larger inclusions collected nearer the margin of the pluton whereas the successively smaller ones were swept farther and farther inward toward the central zone before they could come to rest. Great numbers of inclusions collected in the marginal zone, at the base of the steep chamber wall, as the descending currents were deflected to a more gently inclined course and across the chamber floor. The action of relatively strong currents in the marginal zone may be registered in the much higher proportion of well-oriented inclusions. Unstably perched xenoliths should have quickly assumed and maintained the most stable orientation, parallel to the centripetally sloping surface of the cumulate material.

Two other observations point to active convection within the chamber. First, the differences between inclusions of the contact zone and inclusions of the marginal and central zones are striking. In the marginal and central zones, where parallel orientation occurs, inclusions are not only smaller but well-rounded, thoroughly altered, and recrystallized. The degree of rounding and metamorphism appears very constant throughout these zones. The abrupt change in these two respects, as one crosses onto the contact zone, brings out clearly a marked difference in the history of the two types of inclusions. Obviously the inclusions of the contact zone, once incorporated in the granitic melt, were quickly frozen in. The xenolithic material of the marginal and central zones, however, was carried in the magma for a much longer period of time. This could have been accomplished by convective stirring of the melt to permit reaction, dissolution, and recrystallization. Even the larger inclusions of the marginal zone were not locally derived from the nearby country rock because they are as thoroughly affected as any in the pluton. Convective stirring could have kept them in suspension for a long time.

A second and perhaps equally significant fact is the small range in the size of xenoliths within the central and marginal zones. In the central zone the length of inclusions rarely exceeds 6 inches, and at most localities it does not exceed half that amount. In the marginal zone, where inclusions are generally larger, the length of xenoliths rarely exceeds 24 inches. Here, however, inclusions have on the average the highest observed length-breadth ratios. It would appear, from this rather narrow size-range, that the magma was capable of effectively sorting incorporated material. Such sorting could have been accomplished by convection currents in the magma chamber. There is a limit to the size of the fragment which may be maintained in a given current. Fragments in excess of this limit would soon settle to the chamber floor. This may explain the apparent absence of large inclusions in the marginal and central zones. Undoubtedly many large and perhaps huge xenoliths were incorporated in the melt, but they must have settled out early. Active stirring by convection must have continued over an extended period of time and at least during the interval required to accumulate the exposed portion of the granite. The absence of large and huge inclusions and the very low, total xenolithic content of the granite indicate that piecemeal stoping played an insignificant role during the same interval.

If we take into account the inclusion shape, an interesting relationship emerges. In general the size of an inclusion maintained in suspension will vary directly with its specific surface. For a given mass the viscous drag effect will be greater on those inclusions possessing the most inequant form. This helps to explain why the larger inclusions of the marginal zone have such high length-breadth ratios.

CONCLUSIONS

The question arises as to how representative the internal structure of the unusually well-exposed Cadillac Mountain pluton may be and how much internal structure in other plutons has escaped detection due to inadequate exposures. Evidence is accumulating, at least over the New England area (Chapman, 1968b), to indicate that structural phenomena like those registered in this pluton are truly widespread.

Inclusions with dimensional parallelism were noted in the outer zones of the Tunk Lake pluton (Karner, 1968) about 30 miles northeast of Mount Desert Island. These inclusions resemble those of the Cadillac Mountain pluton. This intrusion is remarkably similar structurally and petrographically to the Cadillac Mountain pluton. In the northwestern, northeastern, and eastern portions of the marginal zone of the Tunk Lake pluton, inclusions trend parallel to the contact on horizontal outcrop surfaces. In the northeastern and eastern portion the inclusions dip inward toward the center of the pluton at 30 to 40°. Karner interpreted this parallelism as a possible flow structure, which formed in the magma as it flowed past an inward dipping contact of the pluton.

In view of the present study, however, it seems likely to me that the Tunk Lake pluton also possesses a saucer-shaped structure-pattern formed by accumulation of inequant xenoliths on an aggrading floor of a magma chamber. The concentric pattern of rock types, furthermore, may be largely an expression of this saucer-shaped rock layering within the pluton. Corroborating my opinion is the zircon study of the pluton by Helgeson and Karner (1965). Here zircon crystals decrease in size and abundance from the border toward the core.

Other neighboring granitic plutons of the Maine coastal belt are being investigated by the writer and his students (Chapman, 1968b). The inclusion structure-pattern of the North Sullivan pluton (Donald Allen, personal commun.), about 15 miles north of Mount Desert Island, is somewhat more complicated than that of the Cadillac Mountain pluton, but it appears to me that the consolidation history of all these intrusions has been much the same. In the Great Wass pluton (James Ward, personal commun.), about 35 miles east-northeast of Mount Desert Island, planar parallelism of inclusions is not so conspicuous as is the planar parallelism of feldspar, but the patterns of both structures appear similar.

Mineral parallelism and mineral layering in the Maine coastal plutons are poorly developed compared with those features in the granitic and syenitic bodies of southwestern Greenland (Upton, 1960, 1962, 1964; Pulvertaft, 1961; Harry and Pulvertaft, 1963; and Emeleus, 1964). This difference may be due largely to the lower content of mafic minerals and more equant feldspars crystals of the Maine plutons. Internal structures appear much more strikingly developed in the Maine coastal plutons than in similar plutons found elsewhere in New England. This apparent difference is believed due to the much better exposures in the coastal area.

It might be concluded from this study that in those intrusions where mafic content is low and feldspar crystals are nearly equant, inclusion parallelism may serve as a partial substitute for mineral layering and parallelism, thereby enabling us to learn much concerning the consolidation patterns and differentiation trends.

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