MECHANICS OF IGNEOUS INTRUSION IN NEW HAMPSHIRE.

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ABSTRACT. New Hampshire contains a vast amount of information on the mechanics of igneous intrusion. The post-tectonic Mississippian (?) White Mountain magma series is characterized by ring-dikes, stocks and a batholith. The ring-dikes, most of which range in composition from monzonite to quartz syenite, intruded arcuate and circular vertical fracture zones by piecemeal stoping and related mechanisms. Cauldron subsidence, although associated with some ring-dikes, is not essential for their intrusion. The stocks of the White Mountain magma series are chiefly biotite granite and were emplaced by underground cauldron subsidence.

The syntectonic Devonian New Hampshire magma series occurs as great sheets, lenses, and stocks, forcefully injected into the older formations. Some superficially plutonic rocks have formed by the atomic replacement of older formations. Still another type of igneous intrusion in New Hampshire, the “domes,” are of problematical origin.

INTRODUCTION.

It is quite appropriate that the author, in a testimonial to Prof. R. A. Daly, should choose as his subject the mechanics of igneous intrusion in New Hampshire. Daly’s first two papers dealt with igneous bodies in that state (18, 19). Moreover as a result of his studies at Mt. Ascutney, in the adjacent state of Vermont, he evolved his brilliant hypothesis of magmatic stoping (20). The author was most fortunate in having Professor Daly as his first teacher in geology; his thrilling and enthusiastic lectures lighted a flame that has never died. It was Professor Daly who suggested the North Conway quadrangle of New Hampshire to the author as a thesis area for the doctorate degree.

To numerous students and associates who have worked in New Hampshire during the last 15 years, I owe an immeasurable debt of gratitude, especially to C. A. Chapman, R. W. Chapman, Katharine Fowler-Billings, J. B. Hadley, F. C. Kruger, David Modell, George Moore, Lincoln R. Page, Alonzo Quinn, Althea P. Smith, and Charles R. Williams. Most of them were students of Professor Daly. Without their careful and patient work the present paper would be impossible.

I also extend my deepest thanks to Prof. J. W. Goldthwait

1 Numbers in parentheses refer to references at the end of this paper.
for his constant encouragement in all our studies in New Hampshire.

Geological investigations in New Hampshire during the last twenty years have revealed that the large intrusions of this state, called batholiths by some, but more appropriately described by the noncommittal term pluton, have been emplaced by various mechanisms. In fact, it seems probable that New Hampshire contains a greater variety of large intrusive forms than any area of equal size in the world. In some bodies, magmatic stoping has been important, but cauldron subsidence (ring-fracture stoping) has played a more important rôle than originally envisioned by Daly (20, 21, 22, 23). Some large bodies have been forcefully injected, pushing aside the adjacent wall rocks. The rôle of metasomatic replacement is still uncertain, but it has unquestionably occurred on a small scale; future studies will reveal its importance. Magmatic differentiation of the igneous rocks of New Hampshire has also been investigated during the last twenty years, culminating in one of the most complete studies of this subject made anywhere (16).

GEOLOGICAL SETTING.

The plutonic rocks of New Hampshire have intruded metasedimentary and metavolcanic rocks which, ranging in age from Ordovician (?) to lower Devonian, have an aggregate thickness of 16,000 feet (Fig. 1). These rocks have been highly deformed and regionally metamorphosed. The metamorphism is least intense in the western part of the state where the rocks consist of slate, sandstone, quartzite, limestone, dolomitic slate, albite-chlorite schist, and rhyolite. The metamorphism increases rapidly to the southeast and throughout the central part of the state the rocks, although the same age as those farther west, are sillimanite schist, andalusite schist, mica schist, quartzite, amphibolite, biotite gneiss, and lime-silicate granulite.

The Ordovician (?) rocks were mildly folded in the Taconic disturbance near the close of the Ordovician and all the strata were highly deformed in the Acadian disturbance during the middle Devonian. There is no evidence that the Appalachian revolution at the close of the Paleozoic greatly affected western and central New Hampshire.

Four magma series, each with its own distinctive petrography, were intruded during the Paleozoic. The Highland-
croft magma series is late Ordovician (?). The Oliverian magma series is approximately middle Devonian and has generally been believed to have been intruded just prior to the Acadian disturbance. The New Hampshire magma series is

Fig. 1. Geological map of central New Hampshire. Names in parentheses in index map indicate quadrangles the geology of which is not shown on the geological map. See legend on opposite page.
middle or late Devonian and was in part synchronous with the Acadian disturbance, although some members of this series are younger than the folding. The White Mountain magma series, distinctly younger than the Acadian disturbance, is probably Mississippian.

**STOPING AND RELATED MECHANISMS.**

**General statement.** Stoping and related mechanisms are exemplified by the White Mountain magma series, which is characterized by ring-dikes, stocks, and a batholith. This series occurs in the following places in New Hampshire and adjacent parts of Vermont: Mount Monadnock, Vermont (44); Percy area (A4; 12); Pliny Range (B4; 14); Cherry

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*Places referred to in the text may be located on Fig. 1 by means of the coördinate system on the margins of the map. The letter and number before the semi-colon locates the area; the number after the semi-colon refers to the references at the end of this paper.*
Mountain (B3 and B4; 13); Franconia quadrangle (C3; 42); Crawford Notch quadrangle (C4); North Conway quadrangle (C5; 4); Plymouth quadrangle (D3; 33); Mt. Chocorua quadrangle (D4; 41); Ossipee Mountains (D4, D5, E4, E5; 31); Belknap Mountains (E4; 32); Pawtuckaway Mountains (40); and Mt. Ascutney, Vermont (20).

The rocks of the White Mountain magma series are mildly alkalic and such minerals as nepheline, sodalite, riebeckite, and hastingsite are found in some of the rocks. Much of the magma of the White Mountain magma series was erupted on the surfaces to form the Moat volcanics. Tuffs, breccias, and lavas, composed chiefly of rhyolite, andesite, and basalt, but also including some trachyte, are typical. Rhyolite is by far the most common, trachyte is rare.

The intrusive rocks range in composition from gabbro to granite, and a great variety of intermediate types are developed. Chapman and Williams (16), in a careful, detailed study, have shown that the mafic rocks are the oldest and the felsic are the youngest. They have also determined the areal extent of the plutonic rocks and calculated the percentage of each compared to the whole magma series. The order of intrusion, from oldest to youngest, and the percentage of each as exposed at the surface, are: gabbro, norite, diorite, and quartz diorite (0.5 per cent); monzodiorite and monzonite (1.5 per cent); syenite, including some nepheline-sodalite syenite (9 per cent); quartz syenite (10 per cent); granite and granite porphyry (79 per cent). Although the rocks in general became more siliceous as differentiation progressed, this is not true in detail. Especially important is the fact that the Albany quartz syenite is younger than the granite porphyry. This is significant in considering the tectonic evolution of the area.

Chapman and Williams have also shown that fractional crystallization controlled the evolution of the series, but that abyssal assimilation played an important rôle.

The Moat volcanics, in large part contemporaneous with the granite porphyry, are older than the Albany type of quartz syenite, but their age relative to the more mafic plutonic rocks is uncertain.

Ring-dikes. Studies during the last 15 years have revealed numerous ring-dikes associated with the White Mountain magma series. A ring-dike complex is a structural unit containing one or more ring-dikes. Ten such complexes are known
in New Hampshire: the Percy area, in the southern part of the Percy quadrangle (A4); the Pliny Range, in the northern part of the Mt. Washington quadrangle (B4); the eastern part of the Franconia quadrangle (C3); Mt. Pequawket and Moat Mountain, in the central and southwestern parts of the North Conway quadrangle (C5); Mt. Tripyramid, in the northwest corner of the Mt. Chocorua quadrangle (D4); Red Hill, in the southwest corner of the Mt. Chocorua quadrangle and northwest corner of the Winnipesaukee quadrangle (E4); Ossipee Mountains at the junction of the Mt. Chocorua, Winnipesaukee, Ossipee Lake (D5), and Wolfeboro (E5) quadrangles; Belknap Mountains in the southern part of the Winnipesaukee quadrangle; and Pawtuckaway Mountains, 30 miles south of the Belknap Mountains.

Altogether, 36 ring-dikes have been described in New Hampshire. Actually, the number cannot be stated precisely because it is difficult to decide in some instances whether an arcuate body should be considered to be a single ring-dike, composed of a number of several intrusions, or whether it should be considered to be several discrete ring-dikes. There are five ring-dikes at Mt. Tripyramid, four each in the Pliny region and the Franconia quadrangle, and six in the Belknap Mountains, although the six separate intrusions could be considered to belong to two composite ring-dikes. Ring-dikes have also been described from adjacent areas in Quebec and Maine.

Complete ring-dikes that encompass 360 degrees are rare, but the ring-dike of the Ossipee Mountains and some of those on Mt. Tripyramid are of this type. Most ring-dikes are arcuate in plan and those in New Hampshire encompass, on the average, 170 degrees of the total possible 360 degrees. The average radius of ring-dikes in New Hampshire, measured from the outer margin of the ring-dike to its center of curvature, is three miles. A ring-dike composed of Albany quartz syenite in the Franconia quadrangle (C3) has a radius of 9.2 miles and is one of the largest known anywhere in the world. The smallest ring-dike in New Hampshire, with a radius of only 0.8 mile, is on Mt. Tripyramid (northwest corner of D4). The average width of ring-dikes in New Hampshire is 1900 feet. The arcuate body of amphibole granite in the southern part of the Franconia quadrangle (C3) is 14,000 feet wide, but this may not be a true ring-dike.
In order to define completely the shape of a ring-dike it is essential to know the attitude of the contacts. Unfortunately, critical data bearing on this subject are scanty in all parts of the world. In New Hampshire sixteen observations have been made, either on cliffs or in valleys as much as 600 feet deep. On the average the contacts dip 86 degrees outward, but generally they are essentially vertical. In the Percy area (A4)

![Diagram showing relation between abundance of ring-dikes and stocks compared to their composition.](image)

Fig. 2. Frequency diagram, showing relation between abundance of ring-dikes and stocks compared to their composition.

one contact dips 78 degrees inward. At one place in the Belknap Mountains (southern part of E4) the dip of a contact is 33 degrees outward, but this is exceptional for the state as a whole.

The ring-dikes of New Hampshire are of intermediate composition, as shown by Fig. 2, in which the rock type is plotted on the abscissa, the number of ring-dikes on the ordinate. There are no gabbro or diorite ring-dikes. Six ring-dikes are composed of monzodiorite, monzonite, and quartz monzonite. Ten are syenite, including one nepheline syenite, ten are
quartz syenite, and six are granite porphyry or amphibole granite. Only four are composed of biotite granite (Conway granite), which is the youngest and by far the most abundant rock in the White Mountain magma series; moreover, these four are small and rather insignificant. The importance of this observation is considered later.

Moat volcanics in a subsided central block are present in ring-dike complexes in the five following areas in New Hampshire: northeastern corner of the Franconia quadrangle (C3); Moat Mountain, southwestern part of C5; Mt. Pequawket, central part of C5; Ossipee Mountains (D4, D5, E4, E5), and Belknap Mountains, southern part of E4. Volcanic rocks are absent in the ring-dike complexes in the Percy area, the Pliny Range, Mt. Tripyramid, and the Pawtuckaway Mountains. Two points deserve special emphasis. First, these extrusive rocks are found only inside a ring-dike, never outside of it (Fig. 3). Second, the ring-dike within which the Moat volcanics have subsided is always composed of the same rock, a porphyritic quartz syenite (Albany quartz syenite). The significance of this is considered later.

The Moat volcanics are at least 10,000 feet thick (4, p. 92) and rest with pronounced angular unconformity on the older metamorphic rocks of the Littleton formation and the plutonic rocks of the New Hampshire magma series (42, p. 1025). It is almost always impossible to determine the attitude of the Moat volcanics, because many of the pyroclastic rocks and lavas are devoid of bedding and flow structure. Available data indicate, however, that near the ring-dikes the volcanics are essentially vertical, but towards the center of the complex the dips become progressively less (Fig. 3).

Unfortunately, precise data concerning the amount of subsidence are difficult to obtain in New Hampshire. The key horizon used for such studies is the base of the Moat volcanics. It is apparent from Fig. 3 that the center of the subsided block has settled 10,000 feet relative to the margins of the block near the ring-dike (Fig. 3). Moreover, the edge of the subsided block just inside the ring-dike has apparently settled at least 5000 feet relative to the rocks some distance outside of the ring-dike (4, p. 130). Therefore, the center of the subsided block has dropped at least 15,000 feet relative to the rocks some distance outside of the ring-dike. It is apparent that the intrusion of some ring-dikes is associated with the subsidence of a
central block. It does not follow, however, that all ring-dikes are associated with central subsidence.

The origin of ring-dikes has been discussed by Anderson (1), Richey (38), and Billings (9). There is general agreement that the intrusion of ring-dikes is preceded by the formation of one or more steeply dipping annular fractures. In some areas, such as Glen Coe (17), and Mull (2), it is possible to prove that the fracture was a fault. Stratigraphic evidence that the fracture was a fault is lacking in New Hampshire, but Modell has shown that in the Belknap Mountains a ring-dike was intruded along a zone of mylonite (32, p. 1918-1922).

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Fig. 3. Structure section through the Ossipee Mountains. After Kingsley.

The original interpretation by E. M. Anderson is discussed briefly in the Mull Memoir (2, p. 11-12) and elaborated in a later paper (1). Anderson assumed that a magma reservoir, the top of which was four to five miles beneath the surface of the earth, existed just prior to the intrusion of the ring-dikes. He supposed that the specific gravity of the magma was equal to that of the surrounding rock. Whenever there was an increase in pressure in this reservoir, the magma pushed outward, expanding the surrounding rocks and subjecting them to tension. The tension fractures, which formed perpendicular to the contact of the magma reservoir, dipped inward toward a common center (Fig. 4A). Magma intruded into such fractures would form cone sheets.

If the pressure in the magma reservoir decreases, the surrounding rocks are subjected to tension. Tension fractures, if they formed, would be parallel to the contacts of the reservoir as shown by the broken lines in Fig. 4B. The outward inclination of such fractures is too low, according to Anderson,
to be the ruptures occupied by ring-dikes. He believes these intrusions follow the steeper of the two possible shear directions, the solid lines of Fig. 4B. The block bounded by such a fracture or fracture system will be a paraboloid convex upward. A potential cavity between the country rock and the subsiding central block is occupied by magma rising from the underlying reservoir (Fig. 5A). Subsequently, erosion from such an intrusion produces an intrusive body that is circular or arcuate in plan and has steep outward dips.

In his mathematical analysis, Anderson of necessity assumed that the rocks surrounding the magma reservoir were homogeneous. Actually, of course, they would lack homogeneity, and existing directions of weakness would influence the attitude of the fractures and the shape of the block so isolated. It is obvious that the block shown in Fig. 5A is an ideal shape that would probably never be attained in nature.

It became apparent in New Hampshire during the early 1930's that the hypothesis outlined above was not entirely satisfactory. In New Hampshire the contacts of the ring-dikes are essentially vertical. It is obvious that no cavity forms at the margins of a subsiding cylindrical block bounded by vertical walls. It is also difficult to understand on Ander-
son's hypothesis why a block stops once it is isolated and starts to subside.

Vertical ring-dikes are explicable if we assume that intrusion was controlled by an annular vertical fracture zone the width

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Fig. 5. Origin of ring-dikes. Broken line is present erosion surface.
of which was comparable to the width of the ring-dike (Fig. 5B). Such a fracture zone, being a place of weakness, would be very susceptible to piecemeal stope. Sometimes the stope might proceed in the manner originally envisioned by Daly, whereby small blocks settle in the magma to be assimilated at depth. On the other hand, if the fractures reached the surface, many blocks might be carried upward by the rising magma. The abundance of small xenoliths in the Albany quartz syenite, which forms some of the most conspicuous ring-dikes in New Hampshire, indicates the validity of this hypothesis. The piecemeal stope hypothesis also explains why the contacts of some ring-dikes are so irregular.

In discussing Fig. 5B, it has been tacitly assumed that the vertical fracture zone encompasses 360 degrees. It is possible, however, that the fractures extend around only part of the subsided area, as suggested by Fig. 5C. Magma, stope along such a fracture zone, would form a ring-dike that encompassed only part of a circle. Moreover, the net slip along the fracture zone might be small. Huffington (28) has recently described in the northern Quitman Mountains, trans-Pecos Texas, a ring-dike along which the net slip has been slight.

Scotch geologists have offered evidence that an arcuate block may be bounded by two steep, essentially concentric, ring-fractures that intersect in such a way as to form an arcuate block. If such a block, cut off above by a horizontal fracture, were to subside, the resulting potential cavity (Fig. 5D) would be arcuate in plan. The major concentric fractures might encompass 360 degrees or only part of a circle.

In some instances, if the rocks in a circular or arcuate fracture zone are blown out by violent explosions, the space might be occupied by vent agglomerates. Later, rising magma might take the place of the agglomerate, either by piecemeal stoping or by forceful injection (Fig. 5E).

The Scotch geologists have suggested that the magma may in some cases make room for itself by pushing apart the walls of a ring-fracture (2, p. 169). There is no evidence in New Hampshire supporting or contradicting this suggestion.

Modell (32, p. 1925-1926) and Billings (8, p. 286-288) have discussed the formation of incomplete ring-dikes, encompassing less than 360 degrees, by Anderson's mechanism.

All hypotheses concerning the formation of ring-dikes are
similar in assuming that intrusion is preceded by the formation of one or more ring-fractures, but we have not yet considered critically the forces involved in the development of these fractures.

We have already pointed out that Anderson assumes that the ring-fracture forms when the magma in reservoir is under reduced pressure. Richey (38, p. 134) has pointed out, however, that it is difficult to conceive of magmatic pressure falling to such an extent that the roof rocks are subjected to tension. On the other hand, the mechanism recently described by Howell Williams (43) to explain such calderas as Crater Lake, Oregon, involves a reduction of the magmatic pressure in the reservoir due to the eruption of large quantities of lava.

The contacts of most ring-dikes in New Hampshire are vertical. This is inconsistent with the outward dip deduced by Anderson in his analysis. We should therefore consider the thesis that the ring-fracture is produced by upward pushing magma. Granitic and intermediate magmas have a lower specific gravity than the older crystalline rocks into which the ring-dikes of New Hampshire were intruded. Consequently, the magma would be trying to rise, as Nettleton (34) has shown in his analysis of the fluid mechanics of salt domes. Cone sheets result if the overlying roof rocks fail by the formation of shear fractures. On the other hand, circular vertical fractures, analogous to extension fractures, may form (8, p. 103). None of these extension fractures will necessarily encompass 360 degrees and many of them may occupy only a small part of the whole circle. Several ruptures may lie close together to form a fracture zone. The central block does not necessarily subside relative to the country rock outside the ring-dike and the roof might even be domed up (Fig. 5F). Piecemeal stopping into such a fracture zone would form a ring-dike.

Once, however, the magma has established an easy passage to the surface of the earth, the mechanical conditions are vastly different. The magma no longer exerts pressure on its roof, but rises along channelways toward the surface of the earth. The heavier roof rocks sag into the lighter magma below (Fig. 5C). If a continuous ring-fracture has formed, a cylindrical block subsides into the reservoir (Fig. 5B).

Applying the principles discussed above to the ring-dikes of New Hampshire, it is apparent that the five ring-dikes of Albany quartz syenite, which enclose a subsided block of Moat
volcanics, are of the type illustrated by Fig. 5B. It is probable that all the ring-dikes of Albany quartz syenite originally encompassed 360 degrees, but that parts of them have since been cut out by younger intrusives.

The other ring-dikes present a different problem. There are no central volcanics within these ring-dikes, and it is impossible to say whether or not the central block has subsided. At the present stage of our knowledge any one of the various mechanisms illustrated by Fig. 5, C, D, E, and F may have operated.

Stocks. Stocks, as defined by Daly, are common in New Hampshire. Some of these stocks are composed of rocks belonging to the White Mountain magma series, others are composed of rocks belonging to some of the older magma series. In the present section, we are concerned only with those stocks belonging to the White Mountain magma series. As shown by Fig. 2, stocks of mafic and intermediate composition are rare, and most of the stocks are composed of biotite granite (Conway granite). The stocks are generally more or less circular in plan and reach a maximum diameter of six miles. In some localities, such as the Percy area, (southern part of A4) the stock is elongated and has a scalloped border, apparently due to the coalescence of several circular stocks. In the Franconia quadrangle (C3) the contacts of stocks of Conway granite are essentially vertical (42, p. 1038). More commonly, the contacts dip outward at angles of 30 to 60 degrees. At Mt. Ascutney, recent road cuts show that the contacts of the stock of Conway granite dips 60 degrees outward (15, p. 199).

Unfortunately, there are comparatively few data available to indicate whether these stocks are concordant or discordant, because many of them have been intruded into areas already occupied by relatively massive or weakly foliated older plutonic rocks. For most of the stocks there is no direct evidence. The most conclusive data come from Mt. Ascutney, where C. A. Chapman and R. W. Chapman confirmed Daly's observations that the stock cuts discordantly across the steeply-dipping, north-striking older strata. Moreover, they made the new important observation that the lineation and fold axes in the older rocks are essentially horizontal both near and far away from the stock. That is, the attitude of the linear features has not been modified by the intrusion; the stock cuts discordantly across the lineation and fold axes.
It is also apparent in the Percy area (A4) that the irregular stock of Conway granite cuts discordantly across the older ring-dikes.

Daly evolved the hypothesis of piecemeal stoping to explain the emplacement of such stocks (Fig. 6A). In 1909, Clough, Maufe, and Bailey (17) presented a hypothesis that has since been called underground cauldron subsidence. In its simplest form (Fig. 6B), this involves the sinking of a cylindrical block bounded by vertical sides and cut off at the top by a horizontal fracture. As this block subsides and magma fills the potential cavity between the subsiding block and the overlying roof, a disc-like or cylindrical intrusive body forms. When erosion eventually exposes such a body, it would be more or less circular in plan and have vertical contacts. Anderson’s hypothesis (Fig. 6C) is not unlike this, except that the walls of the
block, and consequently the contacts of the resulting intrusion, dip steeply outward. A third variant of underground cauldron subsidence might be proposed. If the pressure in the magma reservoir were to drop, tension fractures in the roof would form parallel to the upper contact of the reservoir according to Anderson (1). The magma would rise and fill the potential cavity left by the subsidence of blocks bounded by these and minor fractures (Fig. 6D). If the tension fractures are numerous, and the blocks small, the mechanism would be very similar to, if not identical with, Daly's piecemeal stoping.

The rarity of xenoliths in the stocks of Conway granite suggests that a process involving the subsidence of large blocks rather than the sinking of small blocks has been important. Moreover, the relatively smooth, rounded contacts of many of the stocks favors the idea that large blocks have subsided. The evidence that some of the ring-dikes have been associated with the subsidence of a large cylindrical block also favors this hypothesis.

It is clear, therefore, that the stocks of the White Mountain series have been emplaced by some stoping mechanism. However, it is apparent that the stoping has been accomplished chiefly by the sinking of large blocks approximately the size of the present stocks.

**Batholith.** The White Mountain batholith occupies the eastern half of the Franconia quadrangle (C3), the northern part of the Mt. Chocorua quadrangle (D4), the western part of the North Conway quadrangle (C5) and much of the Crawford Notch quadrangle (C4). Unfortunately, the geology of the Crawford Notch quadrangle has not yet been studied in the modern survey of New Hampshire. It is apparent, however, from those areas already studied that the White Mountain batholith is a complex of many coalescing ring-dikes and stocks. The batholith has been emplaced, therefore, by the same mechanisms as the ring-dikes and stocks.

**Tectonic History of the White Mountain Magma Series.** The tectonic history of the White Mountain magma series is controlled by the magmatic differentiation of the main underlying reservoir. The remarkable uniformity of the White Mountain magma series throughout New Hampshire implies that a single reservoir underlay much of the state. The petrographic peculiarities found in the smaller complexes, such as Red Hill
and Mt. Tripyramid, imply that these rocks evolved in small cupolas rising from the main reservoir (7, p. 91).

Magmatic differentiation in the main reservoir proceeded progressively from gabbro through diorite, monzodiorite, monzonite, syenite, quartz syenite, granite porphyry, quartz syenite of the Albany type, amphibole granite, and biotite granite (16, 1935).

The gabbro of the White Mountain magma series, found at Mt. Tripyramid, Mt. Ascutney, the Belknap Mountains, and the Pawtuckaway Mountains, was probably forcefully injected, pushing aside the older rocks. At both Mt. Ascutney and the Pawtuckaway Mountains, the inward dip of the banding of the gabbro suggests that these intrusions occupy funnels that narrow downward. Balk (3, p. 92-95) has discussed this characteristic of gabbro massifs elsewhere. Moreover, it is interesting to note that the average specific gravity of the crystalline rocks older than the White Mountain magma series would be of the order of 2.55, whereas the specific gravity of gabbro magma would be of the order of 2.70 (24, p. 276). Thus, during the gabbro stage, stoping of any kind would be impossible.

When the magma had evolved to monzodiorite, however, it would have a lower specific gravity than the overlying rocks, and stoping would be possible. The magma would now be pressing upward on the roof, and steep fractures of the type shown in Fig. 5F, would develop. Piecemeal stoping or the collapse of large, arcuate blocks (Fig. 5D) would result in the formation of ring-dikes. Similar conditions existed while the magma in the main reservoir was progressively differentiating to monzonite and syenite. There is no evidence of cauldron subsidence during these stages of the evolution of the White Mountain magma series.

When the upper part of the differentiating magma reservoir had attained the composition of the Albany quartz syenite, ring-fractures encompassing 360 degrees penetrated to the surface of the earth. Great cylindrical blocks subsided many thousands of feet, dropping the Moat volcanics to a level below the present erosion surface. Surface cauldron subsidence was the rule during this stage.

By the time the reservoir had reached the composition of biotite granite (Conway granite) a new tectonic stage was initiated. Stocks, rather than ring-dikes, formed. Mechanisms similar to those illustrated by Fig. 6B, C, and D, were appar-
ently operating. At this stage the conditions postulated by Anderson may have existed. The difference between the specific gravity of the magma and that of the country rock was at a maximum. Moreover, with numerous passageways now open to the surface of the earth, excessive extrusion of effervescing magma may have caused such a depletion of the reservoir that the roof was under tension (43, p. 101-107).

It is quite plausible that in other areas of ring-dikes the tectonic history would be very different from that in New Hampshire. At Ardnamurchan (39) and Mull (2), for example, the stage illustrated by Fig. 6C might have been initiated very early because the country rock was chiefly basalt and would have a higher specific gravity than molten gabbro.

FORCEFUL INJECTION.

Large igneous bodies may make room for themselves by pushing aside the older rocks. Many plutons belonging to the New Hampshire magma series, notably the Kinsman quartz monzonite (Meredith granite) and Bethlehem gneiss, have been emplaced by forceful injection.

French Pond Pluton. The French Pond pluton near North Haverhill (C1 and C2) is one of the most striking examples of forceful injection (Fig. 7). In this part of New Hampshire the schistosity and bedding of the country rock, essentially parallel to each other, strike northeast and dip steeply. On both the north and south sides of the pluton, however, the essentially vertical bedding and foliation strike northwest and west. It is apparent from Fig. 7 that the foliation and schistosity wrap around the intrusion, indicating forceful injection.

Mt. Clough Pluton. The Mt. Clough pluton, composed of Bethlehem gneiss, is undoubtedly the longest intrusion in New Hampshire. The main body extends southward for 90 miles from the northern part of the Franconia quadrangle (C3) to the south end of the Lovewell Mountain quadrangle, which is beyond the limits of Fig. 1. The width ranges from half a mile to 7 miles. In the Moosilauke quadrangle (C2) the contacts are essentially vertical and the pluton is a vertical sheet (Fig. 10). Further south, however, the contacts dip to the east and along the eastern border of the Mascoma quadrangle (E1) and the western border of the Cardigan quadrangle (E2), the upper and lower contacts dip 30 degrees east. Here the pluton is a huge sheet inclined to the east (Fig. 8).
Fig. 7. French Pond pluton, Moosilauke and Woodsville quadrangles, New Hampshire. Oo=Orfordville formation; Oos=Sunday Mtn. member of Orfordville formation; Oal=Abee formation; Oam=Ammonoosuc volcanics; Sc=Clough formation; Sf=Fitch formation; Dl=Littleton forma-
The Bethlehem gneiss, of which the Mt. Clough pluton is composed, is primarily quartz monzonite and granodiorite. Primary foliation is generally well developed and in places a secondary lineation is conspicuous.

The Mt. Clough pluton is essentially concordant. A glance at the geologic map (Fig. 1) shows that the western margin of the main pluton is in contact with the upper part of the Ordovician (?) Ammonoosuc volcanics, but locally patches of the Silurian Clough and Fitch formations are preserved. The roof is composed of schists of the Littleton formation.

The main body of Bethlehem gneiss lies southeast of the domes containing the Oliverian magma series but, as the map shows, in the southern part of the Mascoma quadrangle (E1) a lobe of Bethlehem gneiss extends four miles to the northwest between two of the domes (Fig. 8). Structurally, the western part of this lobe occupies a synclinal basin west of the domes (Fig. 8, section CD). If erosion were to lower the region about 1500 feet, an isolated basin of Bethlehem gneiss would lie west of the domes. This observation gives a clue to the structural relations of two bodies of Bethlehem gneiss, each about 12 miles long and 2 miles wide, which lie west of the domes in the Mt. Cube (D1) and Moosilauke (C2) quadrangles. One of these bodies appears in the northern half of Fig. 8. Both bodies lie at essentially the same stratigraphic horizon as the main Mt. Clough pluton east of the domes. It is apparent that these two bodies are merely a western extension of the Mt. Clough pluton (Fig. 9B). The connecting link has been destroyed by erosion. The Bethlehem gneiss, injected as an essentially horizontal concordant pluton (Fig. 9A), was later domed up into its present anticlinal form. This subject is discussed more fully below.

Although the Mt. Clough pluton is essentially concordant, its base rises somewhat toward the west (Fig. 9). Moreover, the Silurian quartzites, which are thin or absent on the east side of the domes, form large massifs on the west side of the domes. This indicates that the quartzites have been pushed and dragged westward by the Mt. Clough pluton to accumulate as large
bodies of quartzite with complex structure, notably Black Mountain in the southwestern part of the Moosilauke quadrangle (C2), and Mt. Cube in the east-central part of the Mt. Cube quadrangle (D1).

Fig. 8. Map and structure sections of Mascoma and Cardigan quadrangles, and parts of Hanover and Mt. Cube quadrangles. After C. A. Chapman, K. Fowler-Billings, L. Kingsley, E. P. Kaiser and J. B. Hadley. Oo=Orfordville formation; Oop=Post Pond volcanic member of Orfordville formation; Oam=Ammonoosuc volcanics; Sc=Clough formation; Di=Littleton formation. Oliverian magma series: sm=Smarts Mtn. group; m=Mascoma group; cr=Croydon group; lg=Lebanon granite; lb=border gneiss of Lebanon granite. New Hampshire magma series; bg=Bethlehem gneiss; k=Kinsman quartz monzonite; co=Concord granite.
The Mt. Clough pluton is a synchronous, forcefully injected igneous body. It is younger than some of the deformation of the region because it is younger than one of the large thrust faults (5, p. 537). Moreover, in the Bellows Falls quadrangle,

![Diagram of Mt. Clough pluton](image)

Fig. 9. Mt. Clough pluton. A. After pluton was injected, but before doming. B. After doming; broken line is present erosion surface. Oam—Ammonoosuc volcanics; Sc—Clough formation, including some Fitch formation; Dl—Littleton formation; ol—Oliverian magma series; bg—Bethlehem gneiss.

Dr. F. C. Kruger has shown me inclusions of folded schist derived from the Devonian Littleton formation. The orientation of the schistosity of each inclusion is different from that of nearby inclusions. Therefore, prior to the intrusion of the Bethlehem gneiss, the orogeny had been sufficiently intense to produce a schistosity. On the other hand, the Mt. Clough
pluton has not only been domed up since its intrusion, but a secondary lineation has been imprinted on the rocks of which it is composed.

*Kinsman, Stinson, and Cardigan Plutons*. A series of plutons composed of Kinsman quartz monzonite lie east of the Mt. Clough pluton.

The most northerly of these plutons, which may be called the Kinsman pluton, occupies the western part of the Franconia quadrangle (C3) and adjacent areas in the Moosilauke (C2), Rumney (D2), and Plymouth (D3) quadrangles. This body is oval in plan, the longer axis trending north-northeast. The pluton is 25 miles long and 6 miles wide at a maximum. The contacts are concordant with the bedding and schistosity of the surrounding schists of the Devonian Littleton formation. The northwest and southeast contacts of the pluton are essentially vertical. The Kinsman pluton is a gigantic lens, essentially vertical in the surrounding schists.

The Cardigan pluton (25) in the Cardigan quadrangle (E2) is likewise a large concordant lens, but the contacts, and the lens itself, dip about 30 degrees to the east (Fig. 8). The Stinson pluton, between the Kinsman and Cardigan plutons, is irregular (25 and 33).

The concordant character of these great lenses of Kinsman quartz monzonite indicate that they have been forcefully injected, pushing aside the adjacent schist in their ascent. A local, secondary lineation shows that some deformation followed their intrusion.

**Metasomatic Replacement.**

Some granitic rocks in New Hampshire are the result of metasomatic addition of material to older sediments. This subject has been studied most completely in the southern part of the Mt. Washington quadrangle (B4; 6). Gneisses, which lie just above the Ordovician (?) Ammonoosuc volcanics, consist of alternating dark and light layers approximately one inch thick. The dark layers are primarily biotite, muscovite, and quartz, whereas the light layers are chiefly plagioclase and quartz. From stratigraphic studies it is apparent that these gneisses were initially shale. Analyses show that the chemical composition of the gneiss is not very different from that of shale. However, there has been some addition of soda and potash. It has been concluded that during metamorphism
soda and potash were introduced into the original shale (6, p. 927-932). Accompanying this, the dark and light constituents tended to segregate into alternating layers, generally parallel to the original bedding. Less than one per cent each of soda and potash has been added to the shale to produce these gneisses.

These gneisses pass imperceptibly into lighter-colored rocks that are difficult to distinguish from ordinary plutonic rocks. To form these rocks from shale, at least four or five per cent of soda, lime, and potash have been added. Plutonic rocks formed in this way occupy at least several square miles near the southeast corner of the Mt. Washington quadrangle (B4); they have been called Chatham granite on Fig. 1. But the Chatham granite of the North Conway quadrangle (C5) must be restudied before any conclusions as to its origin can be given.

**Problem of the “Domes.”** In the western part of New Hampshire, some ten miles east of the Connecticut River, the crest of a major anticline is occupied by a series of “domes.” In their essential features these domes, nine of which have been mapped, are remarkably similar (Fig. 10). A central oval-shaped core of plutonic rocks, ranging in composition from granodiorite through quartz monzonite to granite, has a foliation that dips outward. The plutonic rocks, overlain by Ordovician (?), Silurian, and Devonian strata, intrude the Ordovician (?) rocks in many localities and the Silurian rocks in at least one locality (10, p. 168). The upper contact of the plutonic rocks is at essentially the same stratigraphic horizon in all the domes, approximately 500 feet below the top of the Ammonoosuc volcanics, but ranges from the top to an horizon
1000 feet below the top. These overlying formations likewise participate in the domical structure (Fig. 10). The smallest dome, in the southeast corner of the Mt. Cube quadrangle (D1), is about ten miles long and two miles wide, whereas the largest dome, in the Mt. Washington quadrangle (B4) and adjacent quadrangles, is about 35 miles long and 12 miles wide. In the southwestern part of Fig. 1, and further south in New Hampshire, the long axis of each dome trends about north-south, whereas the anticline in which the domes occur trends N.20°E. The domes thus lie en echelon and toward the north each dome lies progressively further east.

It is clear that these domes have many of the features typical of laccoliths (Fig. 10), and C. A. Chapman (11) has advocated this interpretation. The present writer, however, has always preferred to use the more noncommittal term “dome,” realizing that there is no proof that these bodies have floors (5, p. 535). It was thought that the domes might equally well be the top of plugs that extend downward for many miles. In any case, the writer originally believed that the domical form was inherited from the time of intrusion, recognizing that some modification may have taken place in a subsequent period of folding.

The Mt. Clough pluton was considered younger than the domes. This interpretation presented no difficulties in the Moosilauke quadrangle (C2) so long as the bodies of Bethlehem gneiss west of the domes were believed to have risen from directly beneath. When C. A. Chapman extended the geologic mapping into the Mascoma quadrangle (E1) it became necessary to assume that the Mt. Clough pluton was able to rise up the east flank of the Mascoma dome and then move down the west flank (Fig. 8). This was rather difficult to believe. The mechanism is even more difficult, in fact impossible, to envisage if we grant that the bodies of Bethlehem gneiss west of the domes in the Mt. Cube (D1) and Moosilauke (E2) quadrangles belong to the Mt. Clough pluton. The domical structure must have developed after the intrusion of the horizontal sheet of Bethlehem gneiss.

The structural relations may be interpreted in one of two ways. The Oliverian magma series may be younger than the Bethlehem gneiss and have been intruded as laccoliths, “bottomless” plugs, or syntectonic phaccoliths; whatever their form, the plutons would dome up the overlying Paleozoic strata and
the horizontal sheet of Bethlehem gneiss. Unfortunately, no conclusive data have been found in the field to determine the relative age of the Oliverian magma series and the Bethlehem gneiss of the Mt. Clough pluton.

Another hypothesis was given serious consideration during the field work, although it has not yet been published. As field work extended into the Mt. Cube quadrangle, Hadley (27) considered the possibility that the Oliverian magma series was initially a single continuous horizontal sheet, bulged up into domes at some subsequent date. On this hypothesis the Oliverian magma series could be either younger or older than the Bethlehem gneiss. The en echelon arrangement of the domes would be explained by a gigantic horizontal couple, in which eastern Vermont was moving northward relative to central New Hampshire.

The origin of the domes of the Oliverian magma series is still an unsolved problem in New Hampshire geology. More field data, supplemented perhaps by petrofabric analysis, may aid in the solution. Moreover, similar domes in Massachusetts, just east of the Connecticut River, may contribute critical data.

SUMMARY.

The intrusive bodies of New Hampshire are varied in form and origin. The large concordant plutons, in the form of great sheets, lenses, and stocks, were forcefully injected. Rising during the Acadian disturbance, they are syntectonic or synchronous injections that jammed apart the older strata.

The ring-dikes, stocks, and batholith of the White Mountain magma series are post-tectonic or subsequent intrusions of Mississippian (?) age. The crust was in a neutral condition, under neither regional compression nor regional tension. The ring-dikes, composed chiefly of rocks ranging in composition from monzonite to quartz syenite, were intruded into arcuate or circular vertical extension fractures that formed above an upward-pressing magma reservoir. The ring-dikes composed of Albany quartz syenite surround cylindrical blocks resulting from surface cauldron subsidence, and the magma made room for itself largely by piecemeal stoping along the fracture zones. The ring-dikes older than the Albany quartz syenite were probably controlled by incomplete, arcuate fractures. There is no evidence of cauldron subsidence during the intru-
sion of these older ring-dikes. The magma made room for itself by piecemeal stoping, subsidence of arcuate blocks, and perhaps by pushing its walls apart. There is no evidence in New Hampshire that any of the ring-dikes occupy potential cavities caused by underground cauldron subsidence of a block with outward dipping walls.

The stocks, composed chiefly of biotite granite, formed in the last stages of the evolution of the White Mountain magma series. Underground cauldron subsidence was common, and the magma filled great potential cavities left by the sinking of large blocks with outward dipping walls.

Locally in New Hampshire, rocks that superficially appear to be plutonic are the result of atomic replacement of older metasedimentary rocks.

The concordant “domes” of western New Hampshire present an unsolved problem. Originally considered to be laccoliths or “bottomless” plugs that had bowed up their roof, it is possible that they all belong to a single great concordant sheet, originally horizontal, that has been buckled up during orogeny.

Future studies on the tectonics of the plutons of New Hampshire and other parts of the world must be based primarily on field work: hard, faithful, conscientious field work, that is not discouraged by the difficulties of the terrain. An accurate geological map, supplemented by all possible observations in the third dimension, is paramount. A judicious use of the methods of granite-tectonics and structural petrology is essential. Seismological and geophysical methods will undoubtedly become increasingly important. Laboratory experiments with scale-models may serve as important tests of theories evolved from field studies. But all this would be of no avail, without the vigor, enthusiasm, imagination, and sincerity exemplified by R. A. Daly.

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