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thesis entitled

A **Rationale** for the Origins of
Massif Anorthosites

presented by

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has been accepted towards fulfillment
of the requirements for

Ph. D. degree in Geology

A handwritten signature in cursive script, reading "Thomas A. Vogel". The signature is written in dark ink and is positioned above a horizontal line.

Major professor

Date August 8, 1974

ABSTRACT

A RATIONALE FOR THE ORIGINS OF MASSIF ANORTHOSITES

By

Graham Ryder

The origins of massif anorthosites cannot be simply explained by a single magma type, and two of the commonly proposed parents for anorthosites are andesites (quartz-diorites) and high-alumina basalts. This thesis proposes that these two magmas are the parents for two separate groups of anorthosites which include all massifs, and that the parents for any given anorthosite massif can be determined by the rock sequence associated with that massif.

Evidence from experiments and from phenocrysts in volcanics suggests that andesites crystallizing in the granulite facies would produce plagioclase cumulates at the base (anorthosites), followed by dioritic and acidic material, whereas high-alumina basalts would produce gabbros followed by anorthosite with very little succeeding acidic material. All massif anorthosites for which relevant data are available have one or the other of these stratigraphic sequences. Grouped according to these sequences

they coincide with two previously proposed groups, i.e., Andesine-type and Labradorite-type, whose characteristics are shown to be compatible with derivation from andesite and high-alumina basalt, respectively.

Two anorthosites which demonstrate the vertical sequence of rocks expected from the fractional crystallization and gravity settling of an andesite magma were studied as a test of the model. The San Gabriel anorthosite suite in California demonstrates a sequence in which the plagioclase composition, determined optically and with the microprobe, becomes more sodic from the anorthosite (mean approximately An_{48}) through diorite ($\approx An_{38}$) to monzonite and quartz-monzonite ($\approx An_{22}$). Cryptic stratigraphy is present in the major lithological units and there is no hiatus in the cryptic sequence, suggesting that the sequence is comagmatic. The San Gabriel anorthosite suite therefore has not only a lithological but also a cryptic stratigraphy very similar to that expected from the fractional crystallization of an andesite magma. The Langelier anorthosite suite in Quebec has a border zone sheared from the anorthosite proper, which therefore is probably diapiric. Although the measured plagioclase compositions indicate that the sequence is compatible with an andesite parent, there must be some doubt as to the validity of the results because of the diapiric nature of the pluton which puts the relations of the lithologies present in doubt.

The evidence suggests that andesitic and high-alumina basaltic magmas give rise to two independent groups of anorthosites. Because these two magmas are characteristic of present-day subduction zones, it is possible that anorthosite massifs are indicative of paleo-orogeny and paleo-subduction.

A RATIONALE FOR THE ORIGINS OF
MASSIF ANORTHOSITES

By

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A DISSERTATION

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This thesis is dedicated to

COLLEEN M. ROBICHAUD

. . . Every man of science whose outlook is truly scientific is ready to admit that what passes for scientific knowledge at the moment is sure to require correction with the progress of discovery; nevertheless it is near enough to the truth to serve for most practical purposes, though not for all. In science, where alone something approximating to true knowledge is to be found, mens' attitude is tentative and full of doubt.

- Bertrand Russell

"Ying tong iddle i poo."

- Spike Milligan

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INTRODUCTION

Anorthosites and gabbroic anorthosites, rocks composed predominantly of plagioclase, are found in three main geological environments: (1) large massif-type plutons; (2) layers, boudins and fault slices associated with aluminous metamorphic rocks; (3) layers in stratified basic intrusions (Anderson, 1969). This thesis is concerned with the origins of massif-type anorthosite.

Although plutonic massif-type anorthosite is well-known and widespread, its origin is problematical. Anderson and Morin (1969) have divided this anorthosite type into two groups based on lithological and mineralogical characteristics, and proposed that one type crystallized from a basic magma; the other was produced by remelting of the first group by a world-wide and probably catastrophic reheating event. The groups seem to have been accepted (e.g., Wynne-Edwards, 1972), but the model has not been widely accepted. There are indeed obvious flaws in the model: the catastrophic event could not have been synchronous and experimental evidence in general indicates that melting of the first group could not have produced the second. A world-wide heating event of the necessary intensity would have remelted much of the Earth's crust,

and this is not evident in the geological record--even the parent group plutons show no evidence at the present time of ever having undergone remelting.

This thesis proposes that a more generally acceptable model based on realistic and realizable magmas is desirable, and considers the possibility that each pluton of massif-type anorthosite is derived by the fractional crystallization of either an andesitic magma or a high-alumina basaltic magma under granulite metamorphic conditions.

MASSIF-TYPE ANORTHOSITES--

PRELIMINARY DISCUSSION

Massif-type anorthosites are found only in high-grade metamorphic terrains, usually of the granulite facies (Anderson, 1969). An attempt to explain the limited age variation of anorthosite (essentially Proterozoic), a preoccupation of many authors, is therefore inseparable from an attempt to explain the limited age variation in ages derived from the "mobile belts" (Anheusser et al., 1969) in which they are found. The ubiquitous associated presence of pyroxene granulite assemblages with anorthosite cannot be ignored. Heat flow from the Earth is unlikely to have been substantially greater one b.y. ago than it is at present (Lubimova, 1969), and the regional metamorphism is probably taking place today, for instance, deep in the crust in island arcs (Miyashiro, 1972). Thus the limited appearance of the granulite facies, and that of anorthosites, in the geological record since the Archean is most likely due to the level of erosion, and anorthosite-producing regimes may well exist at depth at the present time.

Although massif-type anorthosites are common (Anderson, 1969), anorthosite lavas have never been

reported. Experimental evidence lends little support to the possibility of the production of primary anorthosite magmas by partial melting of mantle or crustal materials. For instance, the Yoder and Tilley (1962) method of producing an anorthosite magma by the melting of basalt will in fact produce a magma approximately andesitic in composition (Holloway and Burnham, 1972). For these reasons, as well as the unreasonably high liquidus temperature of such a magma (Luth and Simmons, 1969; Isachsen, 1969), the possibility of magmas of anorthosite composition must be rejected. Most workers therefore agree that anorthosite is produced from the accumulation of plagioclase gravitationally either by floating or settling from a non-anorthositic magma. Many authors have favored a gabbroic anorthosite magma, generally charged with plagioclase crystals in suspension (Buddington, 1939, 1969; Bowen, 1971), or at least some form of high-alumina basalt (Emslie, 1965). Others have preferred to postulate an intermediate magma (Balk, 1931; Philpotts, 1966). These two magmas have generally been postulated for specific massifs, and then generalized by the author to all massifs.

Some plutons currently included in the category of massif anorthosite can be adequately explained as being a crystallization differentiate from a variant of high-alumina basaltic magma, and any radically different magma would not easily explain their chemical and mineralogical

nature and variations. Such massifs include the Michikamau, Labrador, intrusion (Emslie, 1965) which apparently has a chilled margin of high-alumina basalt, and the Kadavur, India, massif (Subramaniam, 1956). On the other hand, other massifs are extremely difficult to explain as being derived from a basaltic magma, mainly because of their high sodium contents and their lack of ultramafic materials, the latter being a necessary part of a differentiated basaltic sequence. These massifs include the Roseland, Virginia, massif (Herz, 1969a) and the Allard Lake, Quebec, massif (Hargraves, 1962).

Much of the problem concerning the parent magma of the massif anorthosites stems from the fact that two distinct anorthosite types have been traditionally treated as one group for which consequently no single magma type is compatible with all the evidence. For example, it is invalid to use evidence from the Michikamau to explain the evolution of the Marcy (Adirondacks) massif (Buddington, 1969). A genetic model for a specific massif must be built upon evidence obtained only from that massif until it becomes evident that other massifs are so petrologically and chemically similar that they must have a similar petrogenesis.

All massif anorthosites can, however, be produced from some form of high-alumina basalt or some form of andesite. It is the purpose of this thesis to evaluate

from experimental data what might be expected from the crystallization of the two magma types in the granulite facies of regional metamorphism, especially in terms of the sequences of mineral assemblages which would be evolved during fractional crystallization. This data is then compared with the petrological characteristics of anorthosite massifs. The first approach is to obtain such comparisons from data already available in the literature. The second is to use the model to make detailed predictions about two anorthosite massifs which, according to the model, have an andesitic parent and to evaluate, through field sampling and laboratory analysis, the comparison with the predictions.

The assumption is made here that plagioclase, and all other minerals, will sink and not float in the magma. Morse (1973) has discussed this problem and pointed out that even in a theoretically favorable instance for plagioclase flotation (Kiglapait), the plagioclase in fact settled. While by no means proven, the assumption is felt to be justified.

THE CRYSTALLIZATION OF BASALTIC AND
HIGH-ALUMINA BASALTIC MAGMAS IN
THE GRANULITE FACIES

Fractional crystallization trends of tholeiitic and alkali basaltic magmas are fairly well documented in terms of the field evidence (Wager and Brown, 1967). Plagioclase has not been found to develop at an early stage in plutonic sequences, and olivine is usually the earliest phase, succeeded by oxides and pyroxenes. The dominant phenocryst phase in basaltic volcanics is also olivine, indicating that it is the liquidus phase at the depth of first crystallization. Abundant experimental evidence from both melting and crystallization of basaltic magmas (Yoder and Tilley, 1962; Green and Ringwood, 1964, 1967; Holloway and Burnham, 1972; and others) shows that plagioclase is absent from the liquidus over a wide variety of pressures, water contents, and basaltic compositions. Only at very low pressures, approaching atmospheric, and with low water contents, approaching zero, can plagioclase be produced at a basaltic liquidus. At pressures above minimal but below about ten kilobars olivine is the liquidus phase; above this pressure it may be replaced by orthopyroxene (Green and Ringwood, 1964).

Experimental evidence indicates that in a high-alumina basalt, at least when the partial pressure of water is low, plagioclase is produced at or near to the liquidus between zero and 6.8 kilobars, but it is usually accompanied by both pyroxene and olivine (Green, Green, and Ringwood, 1967). Analogies with other compositions ranging from basalt to andesite indicate that the presence of water depresses the plagioclase crystallization temperature to below that of the mafic phases, and thus completely removes plagioclase from the liquidus of a high-alumina basalt.

With such experimental evidence as a base, it is possible to predict the course of fractional crystallization of a basaltic or a high-alumina basaltic magma in the granulite facies. Assuming that gravity settling is operative a basaltic magma will produce a vertical sequence with ultramafites at the base, with succeeding gabbro, some interlayered anorthosite, and diorite, followed by minor amounts of iron-rich acidic rocks. A high-alumina basalt under the same conditions and with a low water content will produce a sequence with minor basal ultramafites, succeeded by gabbro, much more gabbroic anorthosite, some diorite, and with minor acid differentiates at the top (Figure 1). In both cases the plagioclase becomes more sodic as the sequence evolved.

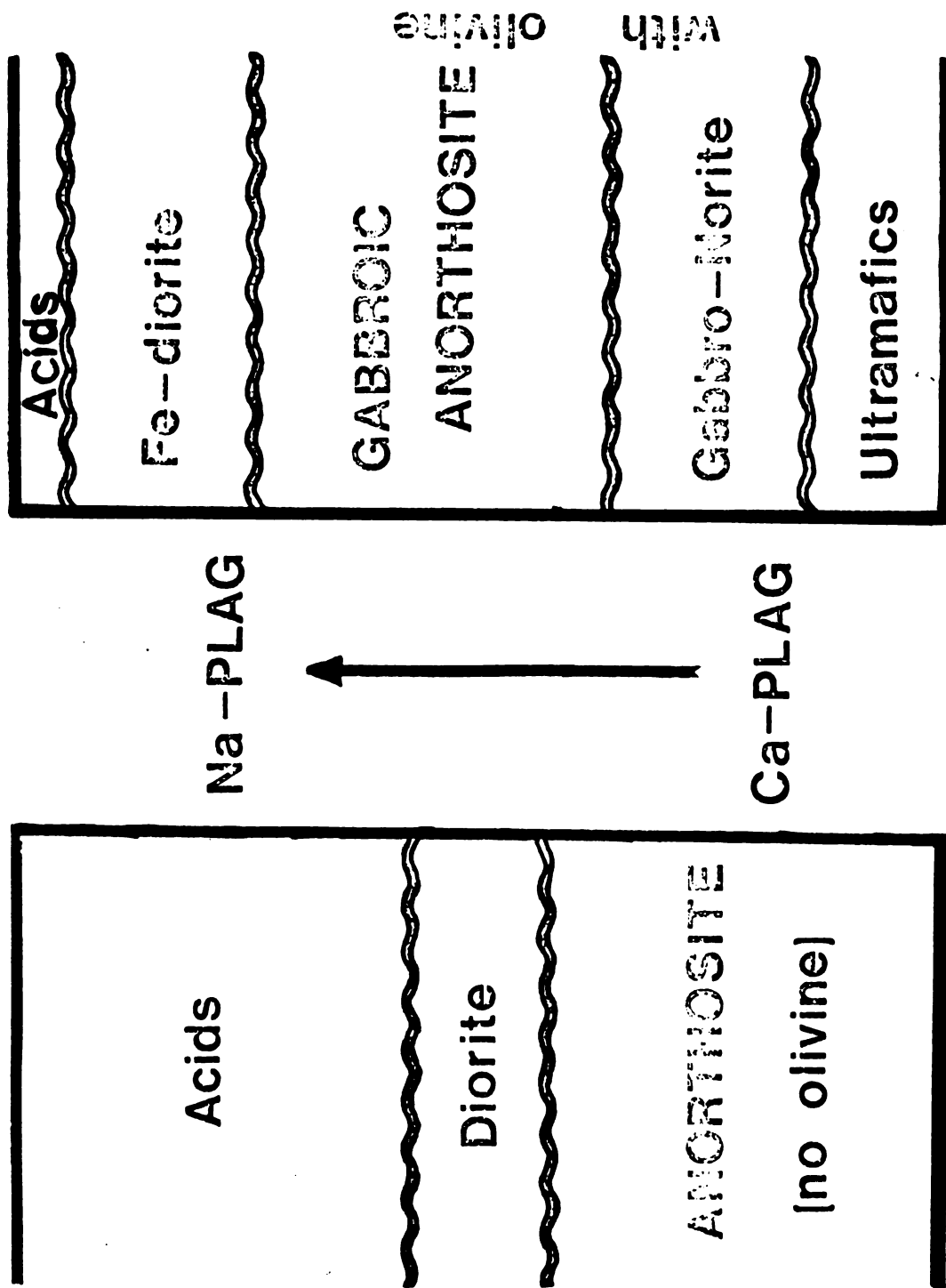


Figure 1.--Sequences expected from the crystallization of an andesite (left) and a high-alumina basalt (right) in the granulite facies.

THE CRYSTALLIZATION OF ANDESITE MAGMA IN THE GRANULITE FACIES

The most abundant phenocryst phase in calc-alkaline andesites is plagioclase (Green and Ringwood, 1968), indicating that plagioclase is the liquidus phase. In many cases andesite contains 50 to 70 per cent plagioclase as phenocrysts and groundmass. Settling of the plagioclase from these andesitic magmas at depth would produce anorthosite accumulations, as has been recognized by Green (1969).

Experimental evidence (Green, 1969, 1972) confirms that plagioclase is the liquidus phase in a dry andesite at pressures from atmospheric up to 13.5 kilobars, and remains the liquidus phase at 9 kilobars with up to two weight per cent water. Extrapolation of Green's data indicates that plagioclase is the liquidus phase at 6 or 7 kilobars with up to three weight per cent of water. Eggler (1972), in melting experiments on a Parícutin andesite, found that at 6 kilobars with up to at least 2.5 per cent water present, plagioclase was the liquidus phase.

With water contents from zero to two weight per cent, the mafics commence crystallizing from andesite magmas about 10° to 20°C below the liquidus, which lies above 1100°C in the experimental work (Green 1972; Eggler, 1972). The

sequence of mafic minerals produced during experimental crystallization includes orthopyroxene and clinopyroxene, and if water is present they are joined later by amphiboles. When 50 per cent of the dry melt has fractionally crystallized the products consist of anorthosite and dioritic anorthosite, while the remaining liquid is acidic (Green, 1969). It is unlikely that the addition of small amounts of water, such as the two per cent appropriate for a natural calc-alkaline andesite, would alter the proportions significantly.

If fractional crystallization occurs, then an andesite magma crystallizing in the granulite facies will produce a vertical sequence with anorthosite at the base, diorites in the middle, and abundant acidic rocks at the top. The plagioclase will become less calcic as the sequence evolves (Figure 1).

EXAMPLES OF THE TWO DIFFERENT SEQUENCES

Abundant evidence exists to suggest that the high-alumina basalt generated stratigraphic sequence is real, for instance the Bell River complex in north-western Quebec (Freeman, 1939). The Bell River complex is a deformed synclinal lopolith, with a basal norite zone, and succeeding zones of banded norite and noritic anorthosite (Figure 2). The banded norite consists of alternating 10 cm. bands of pyroxenite and anorthosite whose combined composition approximates that of the norite, and the plagioclase in the lopolith is bytownite and labradorite. Freeman (1939) noted the similarity of the rock sequence and rock types to that of the Stillwater and Bushveldt intrusions; it is evident however that the Bell River complex contains more anorthositic materials and probably was derived from a more aluminous magma. Quartz-diorites surrounding the lopolith were intruded after deformation, and cannot represent a contemporaneous, consanguinous magma. The sequence at Bell River, with the exception of an apparent lack of exposed basal ultramafic rocks which may have been obliterated during the intrusion of the quartz-diorite, is

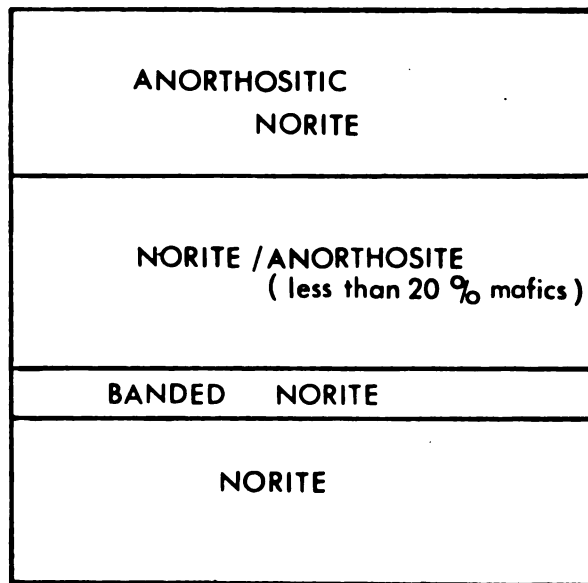


Figure 2.--Sequence at the Bell River Complex
(Freeman, 1939).

similar to that expected from the fractional crystallization of a high-alumina basalt.

On the other hand few authors have attempted more than cursorily to establish that the details of any anorthosite sequence are compatible with derivation from an andesite. In a number of cases exhibiting the broad outlines of an andesite-generated sequence, such a parentage has been denied on various grounds. One such example is the Honey Brook anorthosite, for which various models have been proposed (Bascom and Stose, 1938; Crawford et al., 1971).

The Honey Brook anorthosite of Pennsylvania is a domical, concentrically zoned pluton, varying gradationally from a core of anorthosite (plagioclase An_{55-48}), through dioritic anorthosite and anorthositic diorite, to banded diorite (plagioclase An_{42-35}) (Crawford et al., 1971). The dominant mafic mineral is hornblende, at least some of which is a replacement of augite (Bascom and Stose, 1938; Crawford et al., 1971). Bascom and Stose (1938) considered a surrounding envelope of quartz-monzonite to be consanguineous with the anorthosite. The quartz-monzonite consists mainly of microperthite with sodic plagioclases, with less important quartz, and with augite which has been altered to hornblende and chlorite. Thus the sequence seen in whole (Bascom and Stose, 1938) or in part (Crawford et al., 1971) consists of basal anorthosites, middle diorites, and upper acidic rocks with low quartz-contents, and is very similar to the sequence deduced to be produced from an andesite magma crystallizing in the middle or lower crust. The plagioclase becomes more sodic as the sequence evolves from anorthosite to quartz-monzonite.

Evidence in support of the concept that the sequence is more compatible with derivation from an andesitic magma than from a more basic magma is provided by plots of the cumulate rocks on ternary diagrams in the field $MgO-FeO_t-CaO-Alkalis$ (Figure 3). The diagram provides a comparison of the solid accumulation trends calculated from

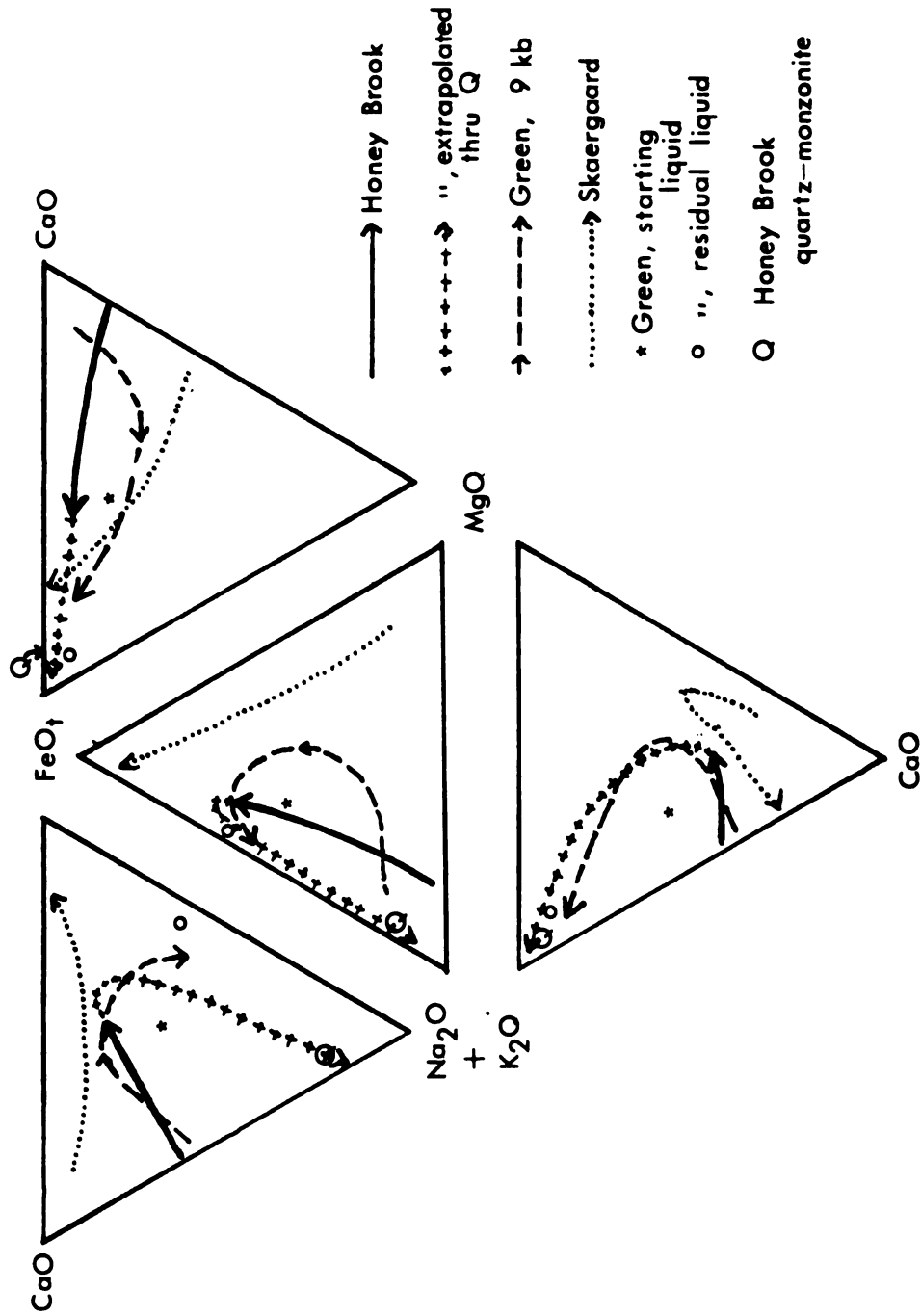


Figure 3.--CaO-MgO-FeO-Alkalis diagram ($\text{FeO} = \text{Fe}_2\text{O}_3 + \text{FeO}$) to show the compatibility of the Honey Brook Anorthosite with an andesite magma. (See text.)

Green's (1969) crystallization of a synthetic andesite at 9 kilobars, with that of the Honey Brook (from Crawford et al., 1971), and with that of the Skaergaard intrusion, calculated from Wagner and Brown (1967).

Green's synthetic andesite trend is extrapolated beyond the experimental data on the basis of the plots of both the parent liquid and the residual liquid. The early stage of the experimental trend shows a deflection towards magnesium compared to the Honey Brook trend and compared to the parent liquid. This is due to the difficulty of analyzing the iron-bearing phases and the trend must curve back towards and around the parent liquid, away from the MgO apex according to simple mass balance principles, during the later stages. It should be noted that at 13.5 kilobars the early part of the trend is further from the starting liquid than it is at 9 kilobars; therefore presumably it is closer to the starting liquid at 6 to 7 kilobars, the expected pressures of the granulite facies, and even closer at lower pressures which conceivably apply to the crystallization of the Honey Brook anorthosite suite.

The Honey Brook trend is quite close to the trend demonstrated for the synthetic andesite, and if the plagioclase compositions of the rocks can be taken as an indicator of the direction of crystallization, then the direction is also appropriate. This trend is valid for about 50 per cent of crystallization of the synthetic liquid; the

remainder at Honey Brook might well be represented by the quartz-monzonite, and if so then the curving trend is even closer to that of the synthetic andesite.

The trend for the Skaergaard basaltic cumulates is very different. Although superficially the trends in the fields of CaO-MgO-FeO_t and $\text{CaO-FeO}_t\text{-Alkalis}$ appear similar to the other trends, the rocks being compared at similar stages are very different: peridotites at Skaergaard compared to anorthosites at Honey Brook and in the synthetic products. It is therefore unlikely that the Honey Brook anorthosite suite represents crystallization from a basaltic magma.

The synthetic andesite magma experiment showed that the liquidus plagioclase at 6 kilobars would have a composition of about An_{55} , and the maximum anorthite content of plagioclase at Honey Brook is of this composition. The sequence of rocks at Honey Brook is therefore very close in its characteristics to the sequence expected from the crystallization of an andesite magma at pressures equivalent to high grades of metamorphism. The quartz-monzonite at Honey Brook is likely to be consanguineous, an hypothesis which might be tested by geochemical methods.

TWO GROUPS OF MASSIF ANORTHOSITE

If massif anorthosites do in fact fall into two groups, one derived from an andesitic magma and the other derived from a high-alumina basaltic magma, then their vertical sequences, as outlined in the previous sections, should be distinctive. It should then be possible to divide massif anorthosites into two groups using the two different sequences as discriminators, and a given massif should fit easily into one or the other of the groups even if only a part of the sequence is visible. This assumes in practice that the vertical sequence is derivable from and available for a given massif. The two groups, if they exist, can then be further investigated to see if their features are in fact compatible with the proposed magmas.

There is a lack of information concerning the internal variability and compositional variations within many anorthosite massifs, and many bodies, such as the Matamec (Greig, 1945), may be too deformed to allow objective assessments of their pre-tectonic vertical sequences. However, the sequences for 16 massifs have been gleaned from the literature. Nine massifs have sequences similar to that expected from an andesite magma crystallizing in the granulite facies, while the other seven

massifs have sequences as expected from a high-alumina basalt under similar conditions (Figure 1). Thus positive grouping based on igneous stratigraphy does occur. The massifs are listed in Table 1. Two more plutons, including the Matamec, may have andesitic sequences, and are included in Table 1.

Anderson and Morin (1969) divided massif anorthosites into two groups, on criteria not including the vertical sequence. Their division is based essentially on the plagioclase compositions, the predominant rock types present, the types of ferromagnesian, and the types of oxide minerals. Their Labradorite-type consists mainly of gabbroic anorthosite, and contains labradorite, clinopyroxene, olivine, and titaniferous magnetite. Their Andesine-type is characterized by more true anorthosite, by andesine, by orthopyroxene with no olivine, and by hemo-ilmenite. The andesine-type is generally domical while the Labradorite-type is frequently irregularly deformed.

The plagioclase of a massif anorthosite derived from an andesitic magma should be more sodic than the plagioclase in a gabbroic anorthosite derived from a more basic high-alumina basaltic magma. Table 1, showing plagioclase compositions as listed in the literature, indicates that the "andesitic" group has mainly andesine, and the "high-alumina basaltic" group has mainly labradorite. This immediately suggests that there may be some correlation

TABLE 1.--Anorthosite massifs grouped according to their vertical sequence of rock types, i.e., stratigraphy.

Massif	Type*	% An in Plagioclase	Reference
ANDESITIC SEQUENCE:			
Adirondacks	(A)	46-52	Davis, 1969; De Waard, 1970
Allard Lake	(A)	40-52	Hargraves, 1962
Bethoulat		55	Neale, 1965
Bjerkreim-Sogndal		-	Michot & Michot, 1969
Honey Brook	(A)	38-55	Crawford <u>et al.</u> , 1971
Labrieville	(A)	35-53	Anderson, 1966
Langelier		-	Rondot, 1961
Morin	(A)	47-56	Philpotts, 1966
St. Urbain	(A)	45	Mawdsley, 1927
?Matamec	(A)	45-50	Greig, 1945
?Wilkinson	(A)	45-53	Harrison, 1944
HIGH-ALUMINA SEQUENCE:			
Angola	(L)	50-80	Simpson and Otto, 1960
Bell River	(L)	60-65	Freeman, 1939; Freeman and Black, 1944
Kadavur	(L)	50-55	Subramanian, 1956
Lofoten	(L)	50-60	Romey, 1969, 1971
Michikamau	(L)	54-72	Emslie, 1969
Nain	(L)	34-58	Wheeler, 1960
Vital	(L)	53	Blais, 1960

* A = Andesine-type; L = Labradorite-type (Anderson & Morin, 1969).

between these groups and those of Anderson and Morin (1969). Anderson and Morin list 10 plutons as being of Labradorite-type and 15 as being Andesine-type. The relationship between their classification and the classification proposed here, based on a petrogenetic model, and using predicted vertical sequences as discriminators, is shown in Table 1. It is evident that the two independent sets of criteria lead to identical groupings, as all "andesitic" group plutons which are also listed by Anderson and Morin are included in their Andesine-type and vice versa. Similarly all "high-alumina basaltic" group plutons which are also listed by Anderson and Morin are included in their Labradorite type and vice versa. No mis-classifications occur. (The Bell River and Angola complexes satisfy the criteria for Labradorite-type and have been included as such.)

Since the two methods of classification lead to identical groupings, the conclusion must be that two fundamentally different types of massif anorthosite exist. The groups can be distinguished not only on vertical sequence, but also plagioclase composition, the types of ferromagnesians and oxides, and dominant rock types.

Labradorite-type anorthosites are mineralogically similar to basaltic rocks, and many authors have postulated basic magmas as the parent of individual plutons which belong to this group. Anderson and Morin (1969), in their discussion of the group, relate Labradorite-type anorthosites to a

basaltic parent. The ubiquitous olivine may in particular be evidence of basicity. The Michikamau massif seems to be a clear example of a basic pluton in that it has a chilled margin of basalt, and Emslie (1965, 1969) has proposed a basaltic parent magma. The lack of associated acid derivatives would be expected from a basic magma. The Nain massif, with its associated suite of adamellitic rocks (Wheeler, 1960) seems to be an exception, but there is evidence (below) that the adamellite was a later intrusion, and not comagmatic with the anorthositic rocks. Morse (1972) has proposed, on petrological grounds, that the parent of the Nain anorthosite was a high-alumina basalt, and that the adamellitic rocks originated in a separate and later event.

A number of authors have proposed intermediate magmas for specific Andesine-type anorthosites. Balk (1931) proposed a dioritic parent for the Adirondacks suite, Oakeshott (1937) proposed a similar parent for the San Gabriel massif, and more recently Philpotts (1966) has proposed an acid dioritic parent for the Morin Series in Quebec. Overall bulk compositions for anorthosite-syenite suites are estimated to be generally dioritic with no unusual chemical characteristics, e.g., Buddington (1939, p. 235), Barth (1936, p. 301) and Philpotts (1966, p. 51), and therefore are compatible with an andesitic magma as the parent.

The plagioclase of Andesine-type anorthosite is generally andesine (Table 1) and is also typically antiperthetic. The orthoclase mol per cent is frequently of the order of 6 to 8. This is compatible with derivation from an andesite magma which contains about 10 to 11 per cent of orthoclase constituents (McBirney, 1969), but is not compatible with derivation from a basaltic magma.

Compared with layered basaltic plutons, anorthosites have a high mol per cent enstatite in orthopyroxene/mol per cent anorthite in plagioclase ratio (Anderson, 1969). No adequate theory exists for this feature (Anderson and Morin, 1969), but Green's (1969) anorthositic materials produced from a synthetic andesite has compositions and ratios similar to those of Andesine-type anorthosites (Figure 4). Empirically, therefore, the feature is compatible with an andesitic parent for the group. Similar data on experimental high-alumina basalt does not exist.

While the precise nature of the parental magmas of the massif anorthosites must remain a matter of conjecture with the available descriptive information, there appear to be no petrological obstacles to proposing a high-alumina basaltic magma for the Labradorite-type massifs, and to proposing an andesitic parent for the Andesine-type massifs.

POSSIBLE TESTS OF THE MODEL

The most obvious tests of the model are those in which its predictions are tested both in the field by mapping and by detailed petrological studies. With such data as plagioclase composition, oxide composition, and the variability in mafic mineralogy available, the grouping into either the Andesine-type or the Labradorite-type is possible. The sequence, including the presence or absence of a substantial comagmatic syenite suite, is predictable and testable through mapping and sampling which provides the compositional variations. Conversely, if the sequence is known, then the mineralogical variation is predictable and testable, since the sequence supplies the categorization as Andesine-type or as Labradorite-type.

The model proposes that all Andesine-type anorthosites have an abundant consanguineous suite of acidic rocks averaging approximately quartz-syenite in composition (Green, 1969). Any consanguineous acidic rocks associated with the Labradorite-type anorthosites must, however, be minor, and if acidic rocks are abundant in their vicinity they cannot be consanguineous according to this model. Proof of consanguinity or otherwise will therefore be a powerful test of the model, though this factor has been a

controversial point for models in which anorthosites are assumed to belong to a single group. Field evidence is frequently inconclusive, and geochemical studies may be a more fruitful line of approach.

Rb and Sr isotopic studies on anorthosite-syenite suites have been reported by Heath and Fairbairn (1969). Four massifs were investigated, two of which, the Nain and Sept-iles, were of Labradorite-type, and one of which, the Adirondacks, was of Andesine-type; the other is at present unassignable to either category. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio for the two Labradorite-type acid associates are different from, and outside of experimental error of the initial ratios for the anorthosites, indicating that if the system has remained closed since formation, the acids are not consanguineous with the anorthosites. The Adirondack syenites have initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios within experimental error of the initial ratio for the anorthosite, showing consanguinity to be a possibility. These results are predicted by the models proposed in this paper, and thus the model is supported by the data.

Rare-Earth Elements (REE) have been proposed as another reasonable approach to the problem of consanguinity, or otherwise, of the anorthosite-syenite suites (Philpotts, Schnetzler, and Thomas, 1966; Green, Brunfelt, and Heier, 1969, 1972). The REE distribution in the anorthosites and in the syenites should be complementary if consanguinity

is present. Conversely there should be no relationship if consanguinity is not present. Philpotts et al. (1966) studied an anorthosite from the Lac St. Jean massif (Labradorite-type) and a mangerite from Grenville Township, Quebec, and which is therefore presumably associated with the Morin Series (Andesine-type anorthosites). Therefore, that they do not seem to be consanguineous (Philpotts et al., 1966) is not surprising, if only because the samples were from different massif associates. The model proposed in this paper predicts that the Lac St. Jean anorthosite has no abundant associated syenites and is derived from a different type of magma than is the Morin Series.

The present model predicts no consanguinity between the anorthosite and the syenites at Lofoten, since the massif is of the Labradorite-type. The REE distribution studies of Green et al. (1969, 1972) supports this conclusion. No other massifs have yet been investigated in a similar manner but such investigations could be a powerful test of the model, especially if used in conjunction with Rb and Sr isotopic studies.

FIELD TESTING OF THE MODEL:

APPROACH

Having shown that the available data support the model, it becomes necessary to use the model to make predictions for testing. Because the high-alumina basaltic generated magma seems to be well-established, it is felt that a concentration on the more controversial and less well-documented andesitic parent is desirable. The model requires that in an andesite-generated sequence (Figure 1) the plagioclase in the anorthositic rocks is more calcic than the plagioclase in the mafic mineral-bearing rocks (diorites). This is the opposite relation to that seen in the high-alumina generated sequence and thus provides a critical distinction between the two groups of anorthosite.

Testing of the model in the present study is by means of establishing an andesitic sequence in some massif, i.e., with rocks containing mafic minerals lying above the anorthosite, and then assessing whether the mafic rocks follow the prediction and contain more sodic plagioclase than do the anorthosites. Acid rocks associated with the massif should have even more sodic plagioclase, if plagioclase is indeed present in such rocks.

Two massifs were chosen for field sampling and laboratory analysis, the choices being made after an investigation of the literature. The three basic criteria for selection were that the massif show an andesite-generated lithological stratigraphy (Figure 1), that plagioclase variation was not established or documented, and that the massif be accessible to comprehensive sampling. Two anorthosites were chosen: the San Gabriel anorthosite suite in California, and the Langelier anorthosite in Quebec.

THE SAN GABRIEL ANORTHOSITE
SUITE, CALIFORNIA

The San Gabriel anorthosite suite underlies about 250 km² of the Western San Gabriel Mountains in the Transverse Ranges of California, and has been described by Miller (1934), Higgs (1954), Oakeshott (1958) and by Carter and Silver (1972). It is pre-Cambrian (1220 $\pm$ 10 m.y.; Silver et al., 1963), has a domical form, and it was intruded into a pre-existing granulite gneiss. Earlier authors referred to it as having anorthosite and gabbroic (mafic) rocks, with no appreciable difference of plagioclase compositions either within or between different lithologies. Carter and Silver (1972), however, recognized a syenite phase, composed of mafic minerals and mesoperthites, which they placed stratigraphically between the anorthosite and the other mafic mineral-bearing rocks (see Figure 5), and suggested that the plagioclase in the mafic rocks was more sodic than in the anorthosites.

The sequence as described is broadly anorthosites (below) and mafic mineral-bearing rocks (above). The sum of the previous work suggested that the San Gabriel suite was a suitable locale to test the sequence of the andesitic parent model in some detail, using the plagioclase

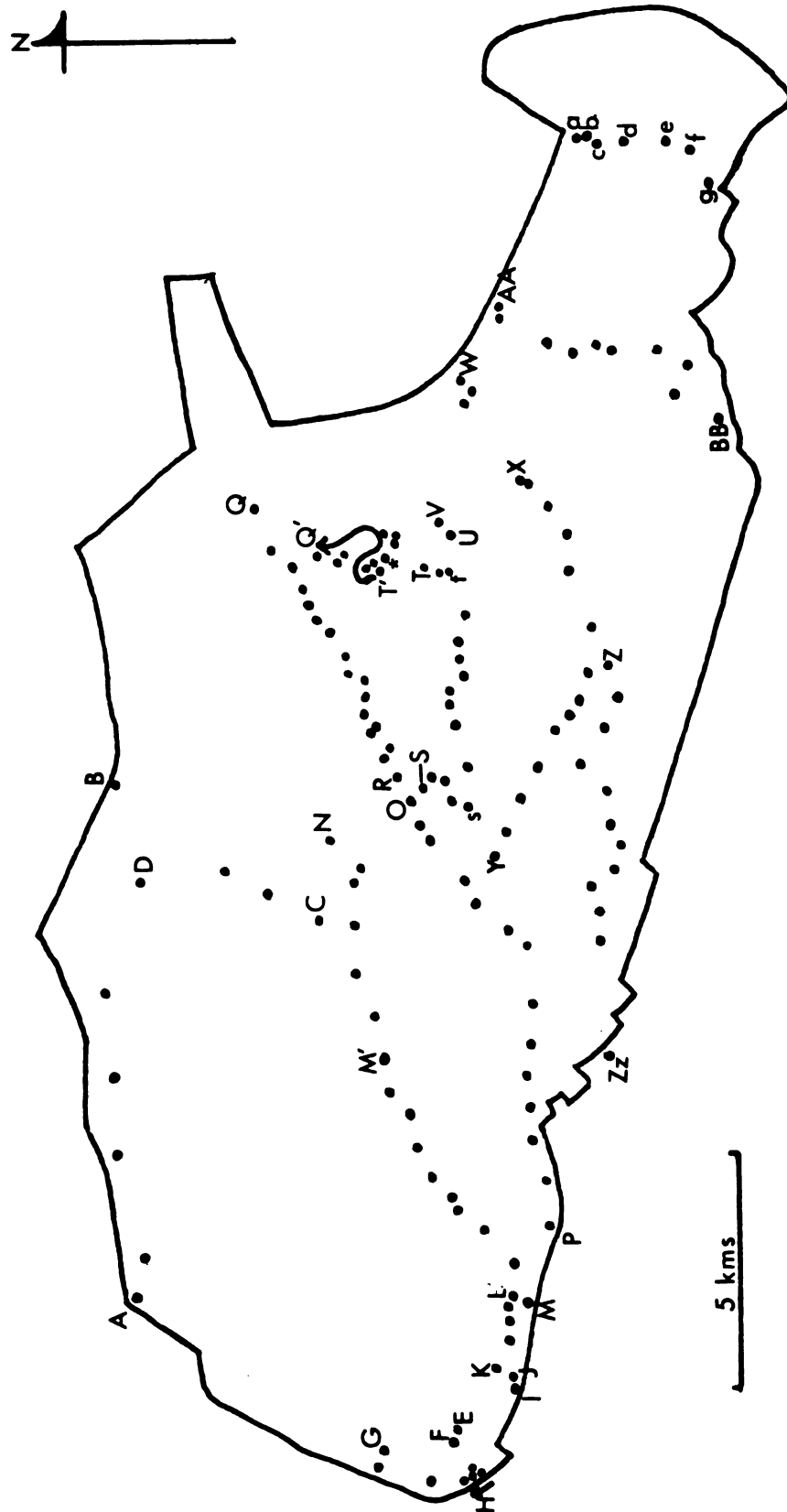
composition as an indicator of the crystallization sequence, and assuming that the whole suite was comagmatic.

Sampling was conducted, to encompass all the major lithologies present and a total of 168 fist-sized samples were collected, geographically distributed over most of the massif. The outcrops sampled were mainly those along or near to the truck trails because of their comparative ease of access; mobility off the trails was extremely restricted by the environment, and sampling would have required an inordinate amount of time. However, a comprehensive collection was made, and the sample localities are shown as Figure 6. A locality map for the field area is shown as Figure 7.

In the field the lithologies sampled comprised anorthosites (almost purely plagioclase), diorites (plagioclase and mafics), syenites (untwinned feldspars and mafics), ultramafites (black and dense), and a hornblende plagioclase rock with a distinctive crescumulate texture which has been termed Willow Lake type by Taubenbeck and Poldervaart (1960). Thin section studies showed that the samples could be grouped according to their major primary mineralogy in the following manner:

Figure 6.--San Gabriel Anorthosite: Sample Localities.

A-B	168-163	*	4-7
C-D	123-126	S-s-t-T	38-42-53-55
E	132-135	U	56-58
F	136-137	V-W	59-62
G	138-139	X-Y	109-122
H	14-17	Z-Zz	151-162
I	64-66	AA-BB	141-150
J	67	a	101
K-L	127-131	b	103
M-N	68-86	c	102
M'	77-80	d	104
O-P	87-100	e	106,107
Q-R	18-37	f	105
T'-Q'	1-13	g	108'



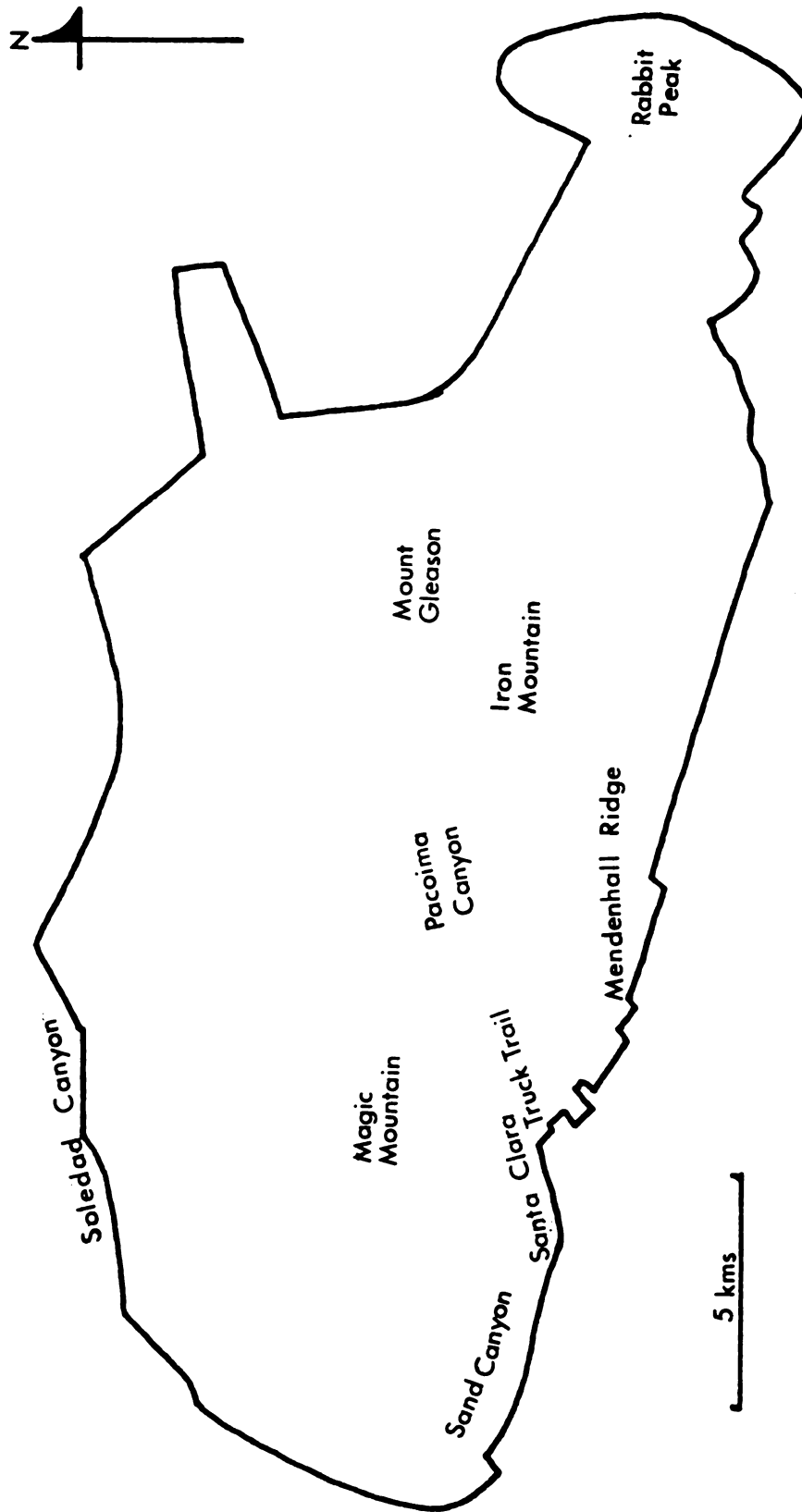


Figure 7.--San Gabriel Anorthosite: Locality map.

1. Anorthosites--plagioclase.
2. Diorites (Jotunites*)--plagioclase, pyroxenes largely altered to hornblende, mesoperthites.
3. Monzonites** (Syenites*)--mesoperthites, pyroxenes largely altered to hornblende, minor plagioclase, quartz.
4. Ultramafites--metallic ores, apatite, olivine (?)
5. Hornblende Gabbro--hornblende, bytownite.
6. Diabase--bytownite, labradorite, pyroxenes, hornblende, olivine, biotite.

representative figures of these rock types are shown in Figure 8, A to F. Groups 5 and 6 were omitted from the analysis because they do not appear to be intimately related to the other rocks in the massif. Both of these groups are extremely fresh compared to the anorthosites, diorites and monzonites. The hornblende gabbro intrudes the anorthosite zone at Mount Gleason, at Rabbit Peak, and in the eastern border zone in contact with Mesozoic granites, and may itself be of Mesozoic age. The diabase intrudes the diorites on the southwest side at Sand Canyon and on the Santa Clara Truck trail as a broad inhomogeneous (Figure 9) dyke-like formation and has a very fresh recrystallized mineralogy. The direct relation of these

* Terminology of Carter and Silver, 1972.

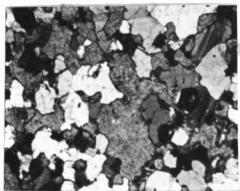
** Microprobe scan shows that the plagioclase in the mesoperthite is An 20, and thus the rock is more appropriately termed a monzonite.

Figure 8.--Photographs of rock types in the San Gabriel suite:

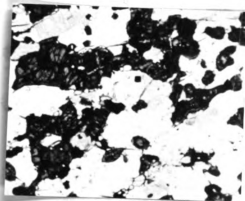
- A - Anorthosite
- B - Diorite
- C - Monzonite
- D - Ultramafite
- E - Hornblende gabbro
- F - Diabase



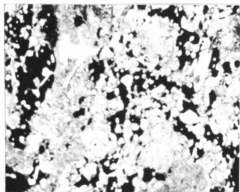
A. Crossed Polarizers
1mm



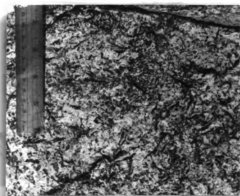
B. Crossed Polarizers
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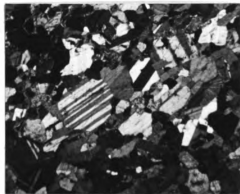
C. Plane Polarized
1mm



D. Plane Polarized
1mm



E. Outcrop



F. Crossed Polarizers
1mm

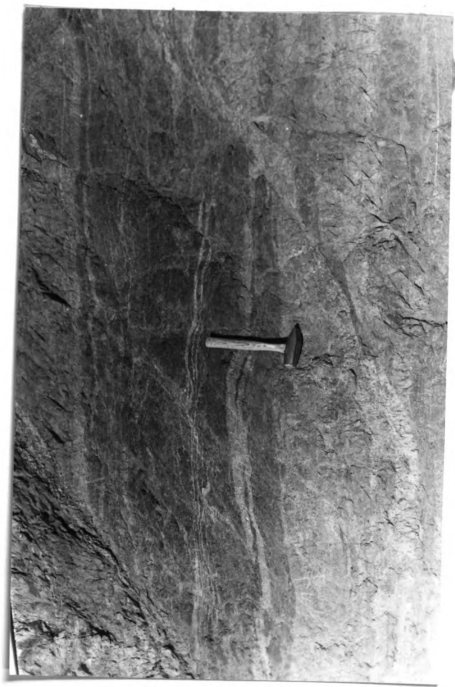


Figure 9.---Photograph of the inhomogeneous diabase at sample sites 63-67.

two groups to the anorthosite suite is unlikely. Group 4, the ultramafites are of a rock type commonly associated with anorthosite. They are assumed to be comagmatic with the anorthosite suite, probably separating during an immiscible stage, as has been suggested by Anderson (1966) for those at the Labrieville anorthosite. They have no bearing on the present study because of their lack of plagioclase.

ANALYTICAL METHODS FOR PLAGIOCLASE COMPOSITIONS

Plagioclase compositions were determined on crushed samples using the revised Tsuboi Dispersion Method (Morse, 1968), because it is both rapid and precise (Morse, 1968), and because of its superior accuracy over other optical methods (Vogel, unpublished data). Approximately 20 grains per sample were determined and the mean value accepted. Precision in this study was such that the standard error for a sample was equivalent to less than 2% Anorthite, and usually about 1% Anorthite.

Microprobe analyses were made for two reasons. The first was to check the accuracy of the optical determinations, and the second was to obtain compositions for the small grains of rare primary plagioclase in the monzonite, a task beyond the capability of the optical method. All microprobe determinations were made using an Applied Research Laboratories EMX instrument. The analyses were made using an accelerating potential of 14.5 Kv. and with a sample current of 0.02 μ amps. Albite, Orthoclase, and Anorthite (An 95) were used as standards, and corrections were made using the method of Smith and Ribbe (1966). Because the data required in this study was essentially

anorthite mol per cent, the corrected data was recalculated to 100% (Or + Ab + An). The microprobe results for samples also determined optically are shown in Table 2, and demonstrate that the optical data is consistently 2-3% An greater than the microprobe determinations. For the comparative purposes of this study, this difference can lead to no significant error.

TABLE 2.--Comparison of the optical and microprobe data.

Sample	Optical		Microprobe	
	Mean An%	Range*	Mean An%	Range*
SG-36	22	21½-22½	21	19-23
SG-44	11	10-12	9	4-14
SG-78	47½	46-49	45	43-47
SG-79	50	49-51	47½	45½-49½
SG-134	33	31-35	30½	28½-32½

* As one standard error on each side of the mean.

RESULTS AND DISCUSSION

The optical data are displayed in Table 3, and the complete microprobe data in Tables 2 and 4. The data is also shown in histogram form in Figure 10, and in a hand-contoured form in Figure 11. A trace across a typical mesoperthite from group 3 is shown as Figure 12, and demonstrates that the rock is appropriately termed a monzonite rather than a syenite because its feldspar is at least 50% plagioclase containing more than 5% anorthite.

The results demonstrate conclusively that the plagioclase in the anorthosite suite varies continuously from being more calcic in the anorthosite, to less calcic in the diorites, to even less calcic in the monzonites. This suggests that the crystallization sequence was anorthosite, followed by diorite, and finally by monzonite. The variation is continuous rather than disjunct (Figure 10), suggesting that differentiation from a common magma is likely. The sizes of the individual modes are insignificant except insofar as they represent the sampling and therefore the outcrop area, and there is no certainty that the outcrop area represents the relative volumes of the rock types differentiated from the common magma. The diabase and the hornblende gabbro both plot separate from

TABLE 3.--Optically derived plagioclase compositions
(see text).

Sample	An%	Rock	Sample	An%	Rock
1	43	A	46	51	A
2	51½	D	47	41½	A
3	51	A	48	44½	A
4	52	A	49	41	A
5	52	A	50	40	A
6	50	A	51	43	A
7	52	A	52	49½	A
8	49½	A	53	44	A
9	44	D	54	53½	A
10	50½	D	55	49	A
11	0	A	56	53	A
12	44	A	57	-	H
13	49	A	58	75	H
14	28	D	59	43	A
15	31	D	60	46	A
16	27½	D	61	47	A
17	25½	D	62	46	A
18	46½	A	63	-	W
19	47	A	64	-	W
20	50	A	65	-	W
21	47	A	66	75	W
22	47	A	67	-	W
23	45	A	68	41	D
24	49	A	69	39½	D
25	46	A	70	35	D
26	50	A	71	35	A
27	42½	A	72	-	M
28	43½	A	73	40	A
29	50	A	74	39	A
30	40	A	75	41	A
31	41	A	76	42	A
32	-	M	77	45	A
33	-	M	78	47½	A
34	-	M	79	50	A
35	-	M	80	49½	A
36	22	M	81	41	A
37	-	M	82	46½	A
38	-	M	83	49	A
39	-	A	84	-	Albitite
40	-	U	85	49	A
41	-	M	86	50	A
42	-	M	87	49	A
43	-	M	88	-	M
44	11	M	89	-	M
45	-	M	90	29	D

TABLE 3.--Continued.

Sample	An%	Rock	Sample	An%	Rock
91	31½	D	130	-	U
92	35	D	131	-	W
93	35½	D	132	36	D
94	-	D	133	36½	D
95	38	D	134	33	D
96	40	D	135	38	D
97	42	D	136	-	D?
98	40½	D	137	-	U
99	43	D	138	-	?
100	-	D	139	39	D
101	52	A	140	-	?
102	51	A	141	49	A
103	75	H	142	-	?
104	47½	A-D	143	49	A
105	53½	A	144	-	?
106	53½	A	145	49½	A
107	54	A	146	54	A
108	46½	A	147	55	A
109	45½	A	148	-	A
110	34	D	149	55½	A
111	49	A	150	49	A
112	-	M	141	49½	A
113	-	M	152	-	M
114	48	A	153	-	M
115	47½	A	154	-	M
116	36	A	155	-	M?
117	-	M	156	26	D
118	35½	D	157	41	A
119	-	M	158	-	A
120	-	M	159	30	D
121	-	M	160	-	?
122	-	M	161	31	D-A
123	50	A	162	33½	A+Quartz
124	40	A	163	43½	A
125	47½	A	164	47½	A
126	39	A	165	40	A
127	-	W	166	45	A
128	-	@	167	42½	A
129	-	W	168	41½	A

A - Anorthosite/Leuconorite

D - Diorite

M - Monzonite or Quartz-monzonite

U - Ultramafite

H - Hornblende Gabbro

W - Diabase

TABLE 4.--Microprobe-derived plagioclase compositions
(see text).

Sample	Grain	An%
35	1	20.9
36	1	21.3
36	2	22.0
36	3	21.0
38	1	22.5
38	2	21.0
43	1	27.1
43	2	23.6
44	1	10.1
44	2	8.7
44	3	8.4
78	1	44.6
78	2	45.5
79	1	45.9
79	2	49.0
79	3	48.0
88	1	27.0
88	2	20.3
122	1	20.3
134	1	29.2
134	2	30.4
134	3	30.5

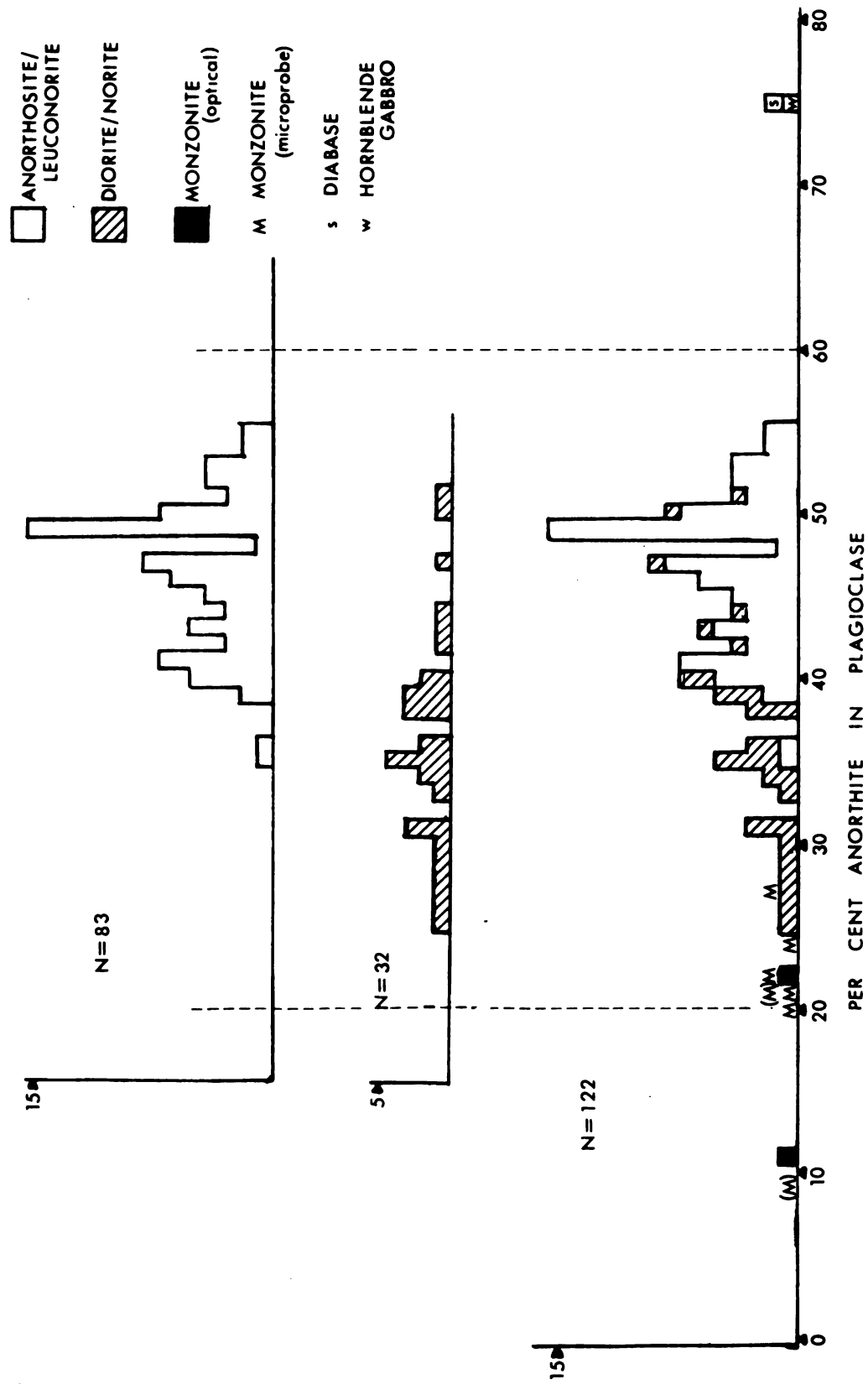


Figure 10.--San Gabriel: Histogram of plagioclase compositions.

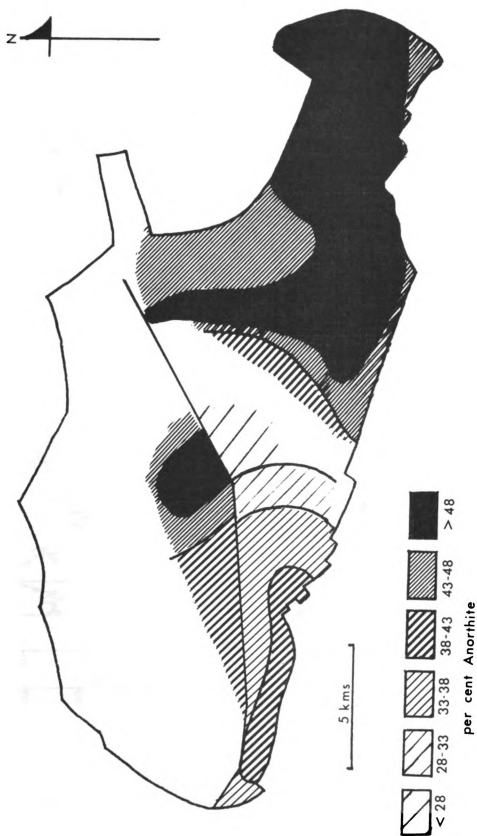


Figure 11.--San Gabriel: Contour map of plagioclase compositions.

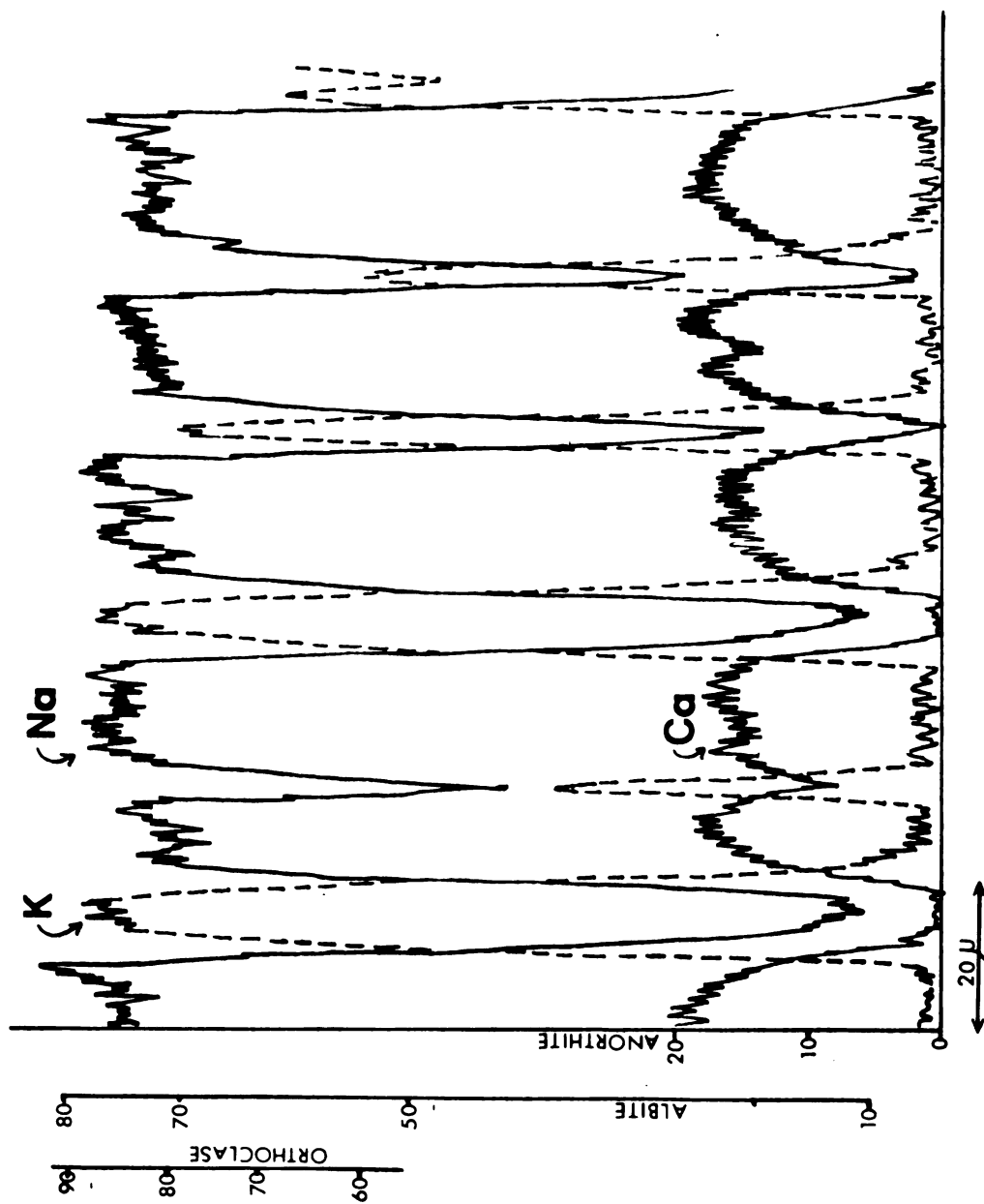


Figure 12.--Microprobe trace of a mesoperthite from sample SG-35 (Monzonite).

the other rocks, supporting the belief that they are not consanguineous with them.

Not only does the crystallization sequence at San Gabriel agree with the predicted andesite sequence (Figure 1) but the absolute values of plagioclase composition are in close agreement. The average plagioclase at San Gabriel must be about An_{40-45} , which is in good agreement with an andesitic parent, but not with any type of basaltic parent. In addition, Greens' (1969) experiments showed that at 9 kilobars the plagioclase crystallizing at the liquidus of an andesite (synthetic quartz-diorite) has a composition of An_{55} , similar to the most anorthitic of the plagioclases in the San Gabriel anorthosite. An increase in pressure would reduce the calcic components in the liquidus plagioclase, whereas a decrease in pressure would increase the calcic components in the liquidus plagioclase (Green, 1969). This suggests that the pressure of crystallization of the San Gabriel anorthosite suite would have been less than 9 kilobars insofar as its earliest plagioclase is at least An_{55} . Greens' experiments were anhydrous, and the San Gabriel would have had some water present, but it is not known how this would affect the compositional relationship.

The freshest monzonite sample, SG-38, is quite rich in primary quartz, indicating that the parent liquid of which the monzonite is a residual, was silica over-saturated, such as an andesite of a calc-alkaline nature.

The sequence and plagioclase compositions at San Gabriel are very similar to those at the Honey Brook anorthosite (p. 14), and the major difference may be in the pyroxene phases originally present. It is reasonable, however, to postulate that the parent magmas were similar.

The contoured map (Figure 11) is undoubtedly an overgeneralization, but the data clearly supports the existence of cryptic stratigraphy within the lithologies, and there seems to be no doubt of the cryptic stratigraphy within the jotunite unit along Pacoima Canyon, and continuously into the monzonite. This data leads to a different conclusion concerning the structure of the massif than has hitherto been proposed, because both the anorthosite and the diorite have increasing albite components in the plagioclases as the monzonite is approached. The contact between the anorthosite and the monzonite is sharp but is not faulted, and the contact between the monzonite and the diorite is gradational. This suggests that the monzonite intrudes the anorthosite, and this must be due to contemporaneous faulting within the magma chamber while the residual monzonite liquid was still mobile (Figure 13). This concept of intrusion is supported by the fact that the monzonites contain large anorthosite xenoliths. Such an interpretation explains the stratigraphic situation of the monzonite above the anorthosite without invoking the crystallization of the monzonite immediately after the

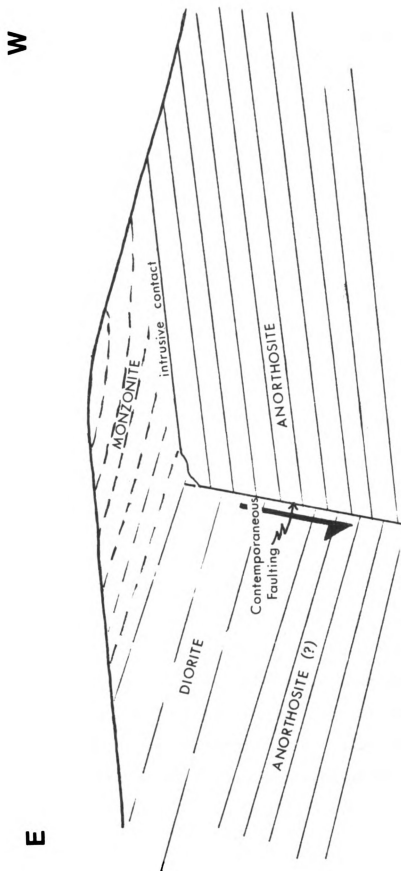


Figure 13.--Postulated reconstruction of the structure of the central part of the San Gabriel massif.

crystallization of the anorthosite. The latter has been proposed by Carter and Silver (1972), but is obviously not supported by the plagioclase data. The interpretation also indicates that the tectonic environment of emplacement was not as passive as has been previously assumed. In addition, the cryptic stratigraphy supports the contention, derived from the earlier mapping of the major units, that the Lone Tree Transmission Line fault is a left lateral offset of several kilometers (Figure 5).

In summary, the data clearly indicate that the massif differentiated from a common parent, with anorthosite accumulating first, followed by diorite, and ultimately by monzonites. Mineralogically the succession was labradorite, andesine, mafics (probably mainly pyroxenes), oligoclase, and finally alkali feldspars. This is close to the sequence predicted to be derived from an andesitic parent magma, such as the model sequence of Green (1969). A crucial point is that plagioclase crystallized alone from the magma at first. This severely limits the possible parent magma types and crystallization conditions, but is compatible with an andesitic magma crystallizing at depths corresponding to high grades of metamorphism. The San Gabriel anorthosite (Anderson and Morin, 1969) displays in detail the petrology predicted for an andesite-generated sequence.

THE LANGELIER ANORTHOSITE,
QUEBEC

The Langelier anorthosite, which underlies about 100 km² of Quebec County, Quebec, has been briefly described by Rondot (1961) and is shown on the map of Laurin and Sharma (1972). The pluton is domical with a circular outline and is surrounded by a sheath of green mafic rocks; the whole sequence intrudes the surrounding gneisses (Figure 14). The literature indicated that the rocks displayed an andesite-generated sequence. However, in the field it was observed that the contact of the anorthosite and mafic rocks was extremely sheared on all sides, and that the massif had been intruded as a solid diapir, such that the relation of the anorthosites to the surrounding rocks or to any other rocks was in doubt. The coarse grain of the anorthosites also contrasted sharply with the fine grain of the mafic rocks. However, 43 fist-sized samples of the suite were collected, and plagioclase determinations were made on 35 of them using the Tsuboi dispersion method (Morse, 1968). The results are displayed on the map (Figure 14). The plagioclase of the anorthosite varies from An₅₆ to An₄₇, with a slight tendency for the central zone to have more calcic plagioclase than the

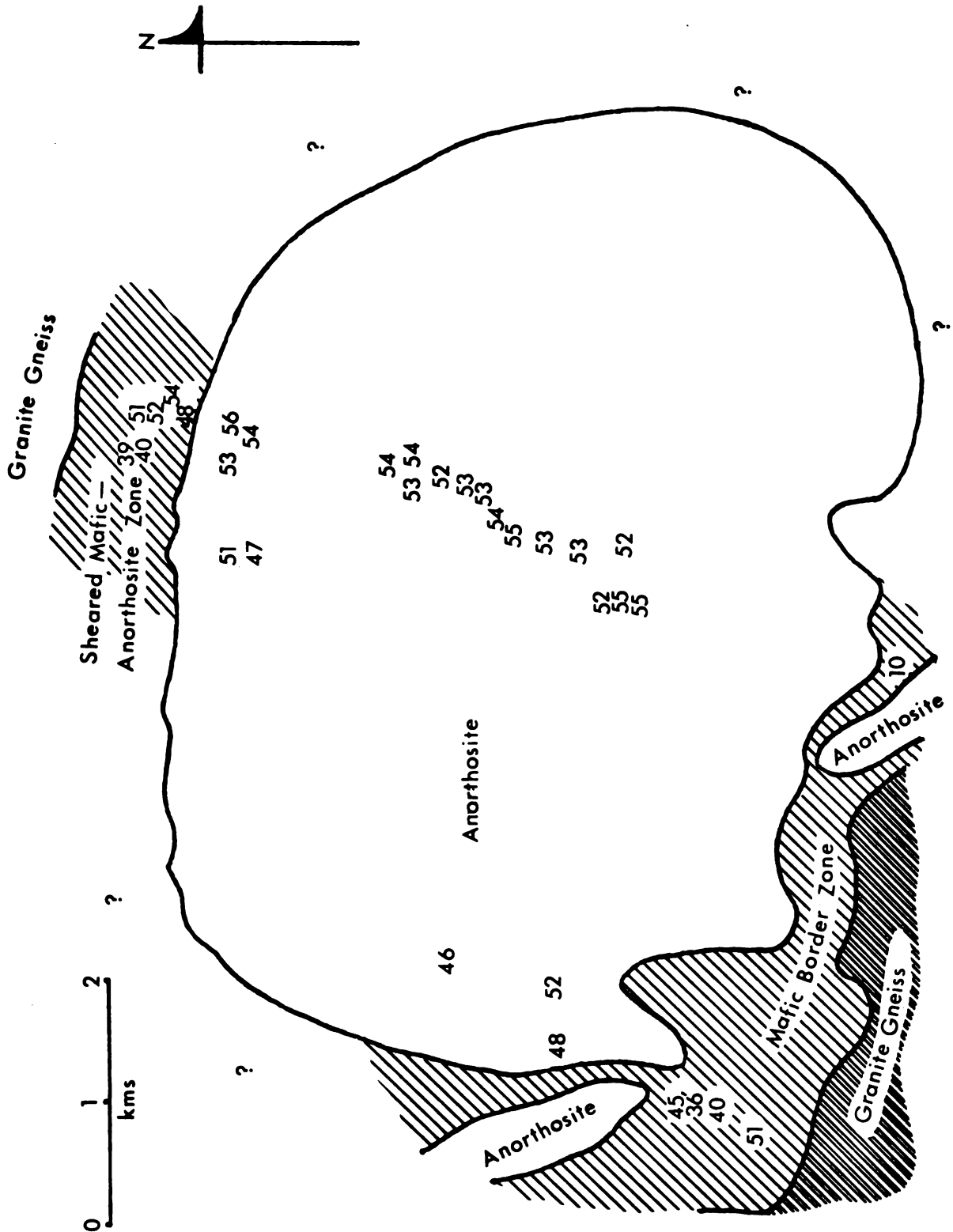


Figure 14.--Generalized map of the Langelier Anorthosite.

outer zones, and these in turn to have more calcic plagioclase than the bordering mafic rocks. Although this broadly supports the andesitic magma sequence, it is felt that little weight can be put on the results owing to the dissociated nature of the anorthosite and its sheath.

CONCLUSIONS AND SPECULATIONS

The two groups of massif anorthosite described by Anderson and Morin (1969), the Andesine-type and the Labradorite type, are compatible with derivation from an andesitic and a high-alumina basaltic magma, respectively. This conclusion is based on comparisons of the igneous stratigraphy of plutons with predictions made from published experimental work, on general petrological characteristics of massifs, and on a study of Andesine-type anorthosite, in particular the pluton at San Gabriel, California.

The evidence demonstrates that the parent magma of an Andesine-type anorthosite crystallizes plagioclase alone on the liquidus, while the parent magma of a Labradorite-type anorthosite crystallizes olivine and pyroxene on the liquidus. Plagioclase in the latter anorthosite-type is an early, but not a liquidus, phase. Under reasonable conditions of temperature and pressure for the crystallization of anorthosites, as shown by field evidence, only an andesite magma can crystallize plagioclase first; the other characteristics of Andesine-type anorthosites, such as the plagioclase compositions and the silicic rocks associated with the suite, are also compatible with an andesite magma. The plagioclase

compositions and the crystallization of olivine and pyroxene early in the development of a Labradorite-type anorthosite, together with the lack of silicic rocks and the overall high-alumina nature of the plutons, make a high-alumina basaltic magma compatible as a parent.

The conclusion is satisfactory because it demonstrates that actualistic magmas can be called upon to adequately explain anorthosite origins; there is no necessity of invoking unusual circumstances. The possibility of andesitic and high-alumina basaltic magmas as parents for anorthosites also leads to some speculation concerning the tectonic environment of the petrogenesis of anorthosites. Herz (1969b) pointed out that massif anorthosites occur in at least three linear belts in pre-Cambrian reconstructions. Present-day evidence shows that continental linear belts are generally the sites of subduction zones, or are continental collision zones, marking the compressional edges of plates. They are dominated by calc-alkaline andesite volcanism, and high-alumina basalts are of common occurrence.

The Grenville province of Ontario has recently been interpreted as a plate tectonic feature, associated with a subduction zone and ultimately with a continental collision, on the basis of its being a paired metamorphic belt (Chesworth, 1972). A similar origin has been proposed for the pre-Cambrian paired metamorphic belt containing

anorthosite massifs which includes Africa, Madagascar, Ceylon, the Eastern Ghats, Antarctica, and the Australian Wheat Belt (Katz, 1972). Emslie (1973) proposed that the high potassium content of anorthosite suites relates them to orogeny, possibly on the flanks of orogenic zones.

Regional metamorphism occurs behind and above subduction zones (Miyashiro, 1972); it is likely that andesite magmas and high-alumina basaltic magmas will crystallize as plutons in such environments, and produce massif anorthosites. It may well be that the presence of anorthosite signifies the presence, therefore, of a paleo-subduction zone and that plate tectonics has been active for at least two b.y.

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