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NORITIC ANORTHOSITE BODIES IN THE SIERRA NEVADA BATHOLITH

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ABSTRACT

A group of small noritic plutons were intruded prior to the immediately surrounding granitic rocks in a part of the composite Sierra Nevada batholith near Lake Tahoe. Iron was more strongly concentrated in the late fluids of individual bodies than during the intrusive sequence as a whole. Pyroxenes are more ferrous in rocks late in the sequence, although most of the iron is in late magnetite which replaces pyroxenes. Both Willow Lake type and normal cumulative layering are present. Cumulative layering is rare; Willlow Lake layering is common and was formed early in individual bodies. Willow Lake layers require a compositional uniqueness providing high ionic mobility to explain observed relations.

The Sierran norites differ from those in large stratiform plutons in that (1) the average bulk composition is noritic anorthosite in which typical rocks contain over 20% Al_2O_3, and (2) differentiation of both orthopyroxene and plagioclase produced a smooth progressive sequence of mineral compositions. A plot of modal An *vs.* En for all the rocks in the sequence from early Willow Lake-type layers to late norite dikes defines a smooth non-linear trend from An_{88}-En_{76} to An_{43}-En_{54}. The ratio An/Ab decreased faster than En/Of until the assemblage An_{50}-En_{65} was reached and En/Of began to decrease more rapidly. Similar plots for large stratiform bodies show too much scatter to define single curves. Temperature gradients of 40°–50° C. within the magma chambers and variable convection patterns could account for the observed variations.

INTRODUCTION

A group of consanguineous intrusions crops out around Eagle Lake, just southwest of Emerald Bay, Lake Tahoe in the fifteen-minute Fallen Leaf Lake quadrangle, California. The rock types in the sequence, from oldest to youngest, are (1) noritic anorthosite and leuconorite, (2) hypersthene diorite, (3) hornblende quartz diorite and (4) hornblende-biotite quartz diorite with minor granodiorite. The two oldest groups of rocks will be called the Eagle Lake sequence; their generalized relations with other rocks is shown in Fig. 1. The noritic anorthosite-hypersthene diorite sequence comprises many small bodies with complex intrusive relations among one another. The bodies are not separated in Fig. 1.

The term noritic anorthosite is used for rocks with color index more than 10 and less than $22\frac{1}{2}$ (Buddington, 1939, p. 19), and plagioclase more calcic than An_{50}. Those rocks with plagioclase more sodic than An_{50} are called hypersthene diorites. The entire series is of interest because of its unusual composition considering its position in the composite Sierra Nevada batholith, its layered structures, and its consistent trend of mineral compositions with decreasing age.

The quartz diorite and minor granodiorite bodies listed as numbers 3 and 4 above intrude the noritic rocks. They are shown as younger intrusive rocks in Fig. 1. Many of the quartz diorite bodies have hypersthene grains rimmed with olive or brownish olive hornblende. The largest quartz diorite body contains local Willow Lake type combed layers as rims around inclusions and as thin sheets on internal intrusive contacts. The present volume of the earlier noritic rocks is only about 10 per cent of that of the later quartz diorites.

COMPOSITION AND TEXTURES

The rocks of the noritic sequence are much more feldspathic than the more common early gabbros and diorites of this part of the Sierra Nevada (Loomis, 1961). Compton (1961) and Taubeneck and Poldervaart (1960) have reported similar noritic rocks from the northern Sierra Nevada and the Wallowa batholiths, respectively, and rocks of this composition may prove to be more common than originally thought. The more leucocratic norites from the San Marcos gabbro of the Southern California batholith (Larsen, 1948) are also quite similar. All have similar textures and appear to be early relative to their immediate surroundings. Modes, chemical analyses, and norms of two hypersthene diorites are given in Table 1.

Each body in the Eagle Lake sequence is structurally an individual intrusion with foliation which generally parallels contacts and truncates structures in older adjacent bodies. Combed Willow Lake-type layering (Taubeneck and Poldervaart, 1960) lies along many intrusive contacts within the complex, and may or may not be broken and deformed by later magmatic movements. Cumulative layering has been found in large blocky inclusions in younger noritic rocks. The foliate and lineate fabrics of indi-

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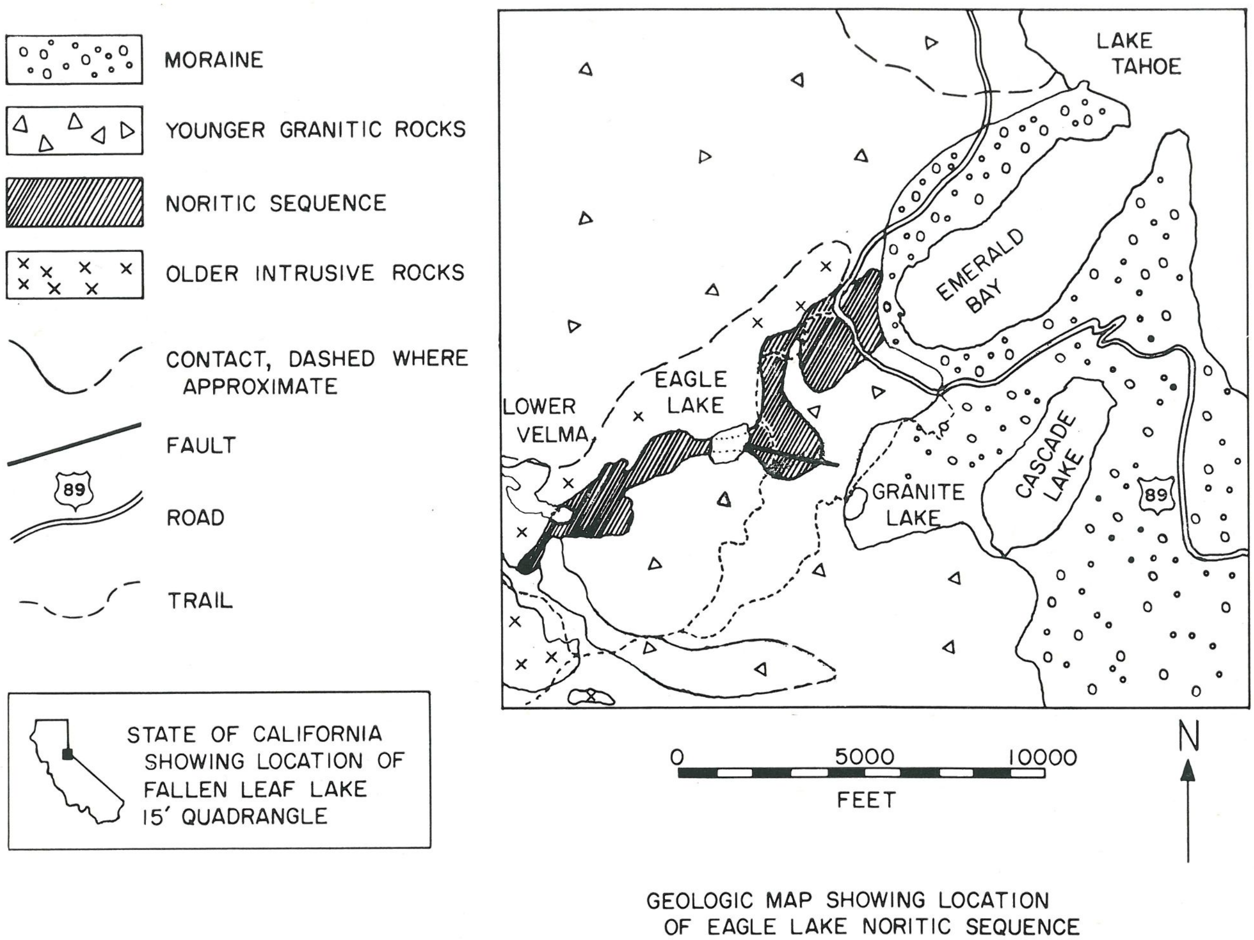

FIG. 1. Generalized geologic map of the northeast part of the Fallen Leaf Lake 15-minute quadrangle.

TABLE 1. MODES, ANALYSES AND NORMS FOR TWO SPECIMENS FROM THE EAGLE LAKE SEQUENCE

Modes, Vol. %			*Analyses, Wt. %*			*Norms, Wt. %*		
	593	*600*		*593*	*600*		*593*	*600*
plagioclase	81.7	75.8	SiO_2	52.2	51.3	apatite	0.3	0.7
orthoclase	0.7	0.1	Al_2O_3	21.7	20.2	ilmenite	0.6	2.0
quartz	none	0.4	TiO_2	0.3	1.1	magnetite	4.9	5.6
hypersthene	9.5	8.4	Fe_2O_3	3.3	3.9	orthoclase	3.3	2.1
augite	2.7	1.7	FeO	5.2	4.3	plagioclase	77.1	70.8
hornblende	1.0	2.5	MnO	nd	0.12	diopside	2.3	5.3
biotite	0.3	1.1	MgO	3.8	3.6	hypersthene	11.1	12.7
magnetite	4.0	4.9	CaO	8.8	8.6	quartz	1.2	0.8
apatite	0.1	0.2	Na_2O	4.0	4.35			
calcite, chlorite	none	5.0	K_2O	0.5	0.35	normative An	50	47
			H_2O^+	nd	1.4	normative En	66	70
modal An	45	45	P_2O_5	0.1	0.30			
modal En	60	68	CO_2	nd	0.54			
density	2.88	2.84		——	——			
			Total	99.9	100.06			

Analysis *593* by Albert G. Loomis.
Analysis *600* by E. L. P. Mercy.

vidual plutons are not directly related to either type of layering.

Most of the plagioclase and orthopyroxene in the plutons crystallized before development of foliation. The bulk of the augite present crystallized after the bodies had been emplaced and the fabrics had been developed. Subhedral and euhedral plagioclase tablets define a flow foliation (exclusive of the layered structures) and *c*-axes of subhedral bronzite or hypersthene grains define a lineation in the foliation plane. Augite occurs both as discrete crystals or as jackets surrounding the orthopyroxenes. Much augite is poikilitic, enclosing several pyroxene and plagioclase grains. Olive-green to brownish-olive hornblende has jackted and partially replaced the pyroxenes and plagioclase. Hornblende rims are commonly continuous around several grains which are aligned in the fabric; therefore, most, if not all, of the hornblende crystallized after the internal movements of the bodies had ceased. Amounts of hornblende vary; amphibolization is described below. Magnetite crystallized subsequently or nearly contemporaneously with hornblende. It replaces pyroxenes and hornblende and is interstitial to plagioclase, pyroxenes, and hornblende. Late deuteric alterations are local. Common minerals include chlorite, actinolite, biotite, and calcite.

Figure 2 illustrates a common texture in the noritic anorthosite. Single hornblende grains surround pyroxenes and replace plagioclase. The bulk of the magnetite is late; it replaces and is interstitial to earlier phases. The small colorless grains in the ore are apatite. The amount of magnetite varies very little within the complex, generally forming 4 to 5 volume per cent of the rocks. The amount of hornblende is quite variable, however, as is the presence of deuteric alteration. The rocks are amphibolized particularly along contacts and fractures, as in Fig. 3. Figure 4 is a cumulative mode diagram of 14 specimens in varying states of alteration. The extent of actual replacement of plagioclase by hornblende, not only the reaction of pyroxene and plagioclase to hornblende, is illustrated by the changes from the fresh rock No. 593 to the amphibolized No. 622. Although the volume percentage of hornblende in-

FIG. 3. Irregular mode of amphibolization in hypersthene diorite near contact with another hypersthene diorite at lower left.

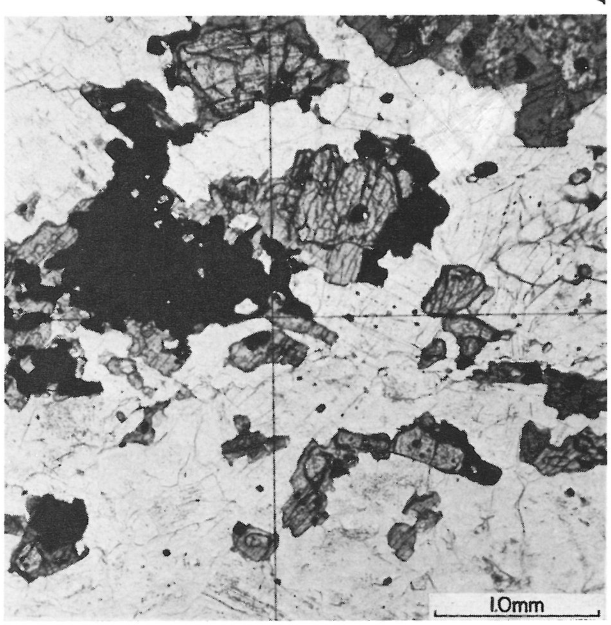

FIG. 2. Noritic anorthosite specimen 622. Olive-green hornblende rims pyroxenes. Magnetite, commonly with apatite inclusions, is late, fills voids, and replaces pre-existing mafic grains.

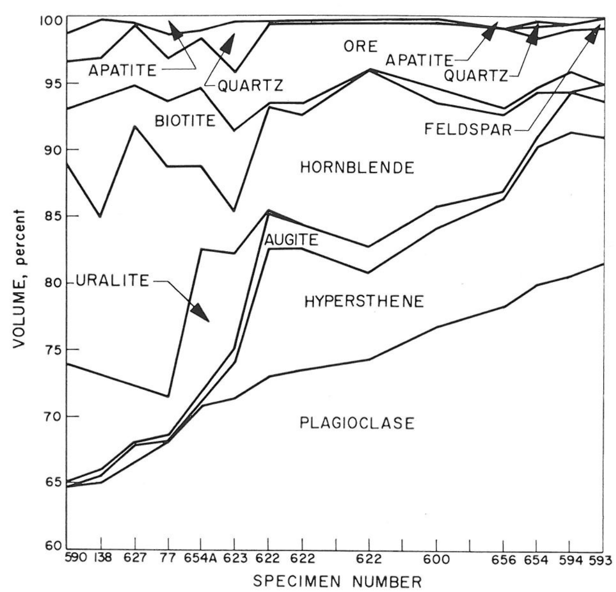

FIG. 4. Cumulative modes of 14 noritic anorthosites and hypersthene diorites which had very similar modes prior to amphibolization and deuteric uralite, quartz and biotite.

creases from a minimum of zero per cent to a maximum of 13 per cent, the volume of the pyroxene shows a complementary decrease of 4 per cent or less. The volume now occupied by green hornblende was originally occupied mostly by plagioclase. The pyroxenes remaining after the amphibolization and introduction of late magnetite were uralitized locally, and some deuteric biotite and quartz formed. These alterations took place mainly near contacts with older plutons and where the rocks were intruded by the surrounding quartz diorites.

Iron was more strongly concentrated during the crystallization of any one body than during the entire intrusive sequence. The late magnetite in each body is more important than the effect of the iron increase due to changing orthopyroxene composition during the whole sequence. Somewhat more than half of the bulk iron in the rocks exists in the late magnetite. As each individual body crystallized, the iron was strongly concentrated in the late fluid. The entire sequence comprises many small intrusions, and the Fe/Mg ratio increased slowly throughout the sequence as will be described below. But iron enrichment was much more extreme within each small body of magma after it separated from the main mass and crystallized independently.

Layered Structures

The noritic rocks contain both normal cumulative layering which was formed early in the sequence, and Willow Lake-type layering which formed early in each individual body. The cumulative layers are now seen largely as inclusions in younger norites. They have very good foliation defined mainly by plagioclase tabular on (010). Rhythmic compositional

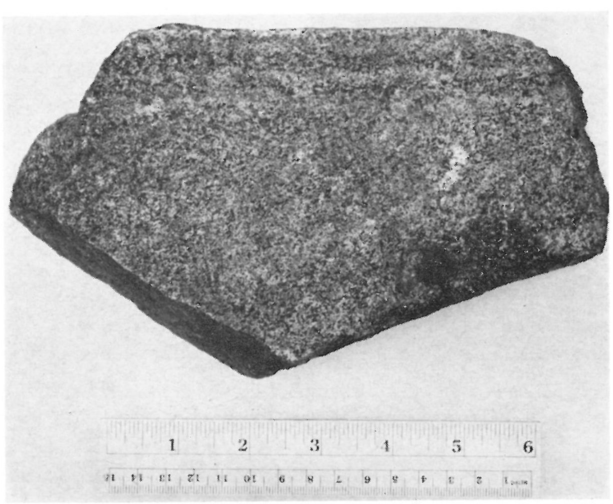

Fig. 5. Hand specimen with cross-laminated cumulative layers.

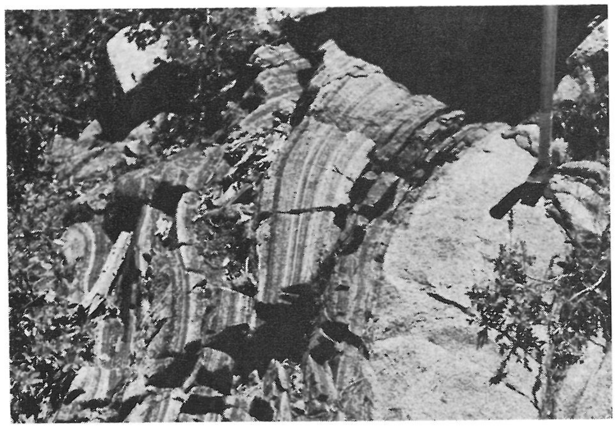

Fig. 6. Combed layers along intrusive contact (covered at left). Hammer is in foliation plane of younger rock which contains layers.

layering is very subtle and is only expressed by changes in color index over thicknesses on the order of 1 cm. Cross-bedding indicating current deposition is present locally and in any one outcrop the tops are consistent. Figure 5 shows bedding dipping 20° to the left truncated at the top by horizontal layers. The cumulative layers contain the most magnesian orthopyroxene and most calcic plagioclase in the sequence. No olivine has been found. Augite is much less abundant than the bronzite, as is the case in normal rocks later in the sequence. The Willow Lake-type layers, however, have much more clinopyroxene than orthopyroxene.

The Willow Lake layers (Fig. 6) lie along intrusive contacts and form rims around inclusions which may be of Willow Lake layers themselves. The crystals stand normal or at high angles to the plane of the layering. The plane of the layering is commonly vertical. The thickness of most individual layers is 0.1 to 2 inches. Groups consist of 5 to 20 individual layers and average about one foot thick, although some are 5 feet thick. When followed along strike, a group of layers may diverge smoothly, include a lens of normal rock, and reconverge. A given group normally contains the same number of individuals no matter how much its thickness varies; the individuals thicken or thin together as the group thickens or thins. The variation in thickness of a group is the result of the crystals in the layers having varied in length in the same way in all of the layers. The Willow Lake layers are distinguished from the better known harrisitic structures in that the latter are upward growth from previously deposited cumulate layers. Descriptions of harrisitic rocks indicate that nucleation takes place on accumulated grains; the large crystals grow upward but commonly become

FIG. 7. Branching bytownite crystals from Willow Lake layer. Note discontinuous, bladed albite twins.

highly poikilitic and reach sizes of several inches to a foot (Brown, 1956).

The plagioclase, augite and hornblende crystals in the Willow Lake layers are long and feathery. Sheaves of crystals are commonly plumose above discrete centers at the base of the layer. Longer branching crystals truncate shorter ones as they diverge from the base of the layer. Figure 7 shows a common habit of plagioclase. Albite and Carlsbad twinning predominate; many albite twins are discontinuous along the length of the crystal and in three dimensions are curving blades up to 10 mm long. Some plagioclase grains are zoned primarily along their length, and a wave of progressive extinction passes along the bladed albite lamallae on rotation of the stage.

The primary mineralogy of the layers is plagioclase; plagioclase-augite; plagioclase-augite-hypersthene; and brown hornblende-plagioclase. The brown hornblende is primary in some layers. Figure 8 is a photomicrograph of primary brown hornblende and plagioclase with minor augite and magnetite. The hornblende does not contain partially digested remnants of pyroxenes and the pyroxenic layers immediately above and below are quite free of hornblende. The texture of the hornblende is unlike the textures of augite in these layers. The hornblende crystals have a greater length to width ratio and tend to form clusters of branching crystals. The elongated augites are commonly curved. Both species are commonly repeatedly twinned on (100). Augite is much more abundant than bronzite and forms feathery crystals whereas bronzite does not. The preferential occurrence of augite, which is subordinate to orthopyroxene throughout the rest of the sequence, suggests that special conditions obtained during crystallization of the combed layers. Presumably, crystals which could nucleate and grow quickly were favored. The combed texture suggests, but does not prove, rapid crystallization on solid surfaces. The sympathetic thinning or thickening of several layers (shortening or elongation of crystals) indicates that several layers could grow while some local environmental condition on the order of several feet tended to promote or retard growth. The occurrence of primary hornblende layers indicates that water pressure became high at times. The occurrence of pyroxenes in layers adjacent to hornblende layers and small amounts in hornblende layers themselves suggests that water pressure was maintained close to the amphibole-pyroxene phase boundary by crystallization of either phase.

Taubeneck and Poldervaart (1960) have attempted to explain combed layering as the result of undercooling. The main objection to this hypothesis is that if undercooling is the sole explanation, why do such structures not occur in other types of rocks, or in those of equivalent composition that show some evidence of chilling against contacts? Combed structures are restricted in the Fallen Leaf Lake quad-

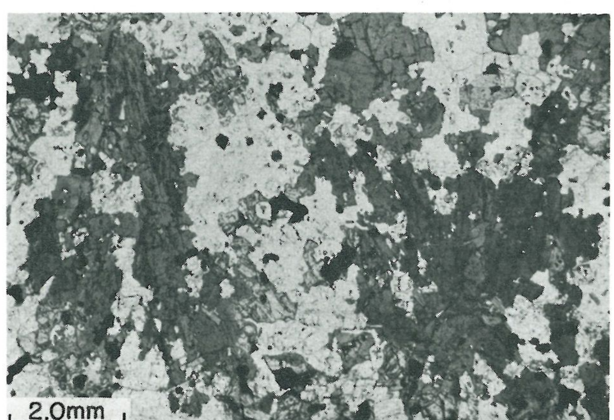

FIG. 8. Primary brown hornblende forming Willow Lake layer. Pyroxenes in adjacent layers are not amphibolized.

rangle to the noritic rocks and the adjacent quartz diorites which are derivative from them. They do not occur in the older gabbro and diorite bodies which were intruded earlier at this level into presumably cooler, wetter surroundings. Neither do they occur in the quartz diorite, granodiorite, and other bodies composing the rest of the batholith.

Furthermore, the occurrence of combed layers at interpluton contacts and around inclusions shows that the cause of the combed textures could not have been local, but must have affected entire bodies nearly simultaneously. Thermal transfer to a heat sink by convection would seem to be too inefficient a process to require crystallization of the combed layers rather than normal crystal growth, especially if the concentration of water was sometimes high enough to cause precipitation of primary hornblende. Relatively rapid cooling in a small body with a high surface to volume ratio should be expected; the combination of a normally quick cooling rate and a compositional peculiarity producing high ionic mobility might produce the effect. If water pressure was close to load pressure, sudden lowering of water pressure might produce rapid isothermal crystallization. Opening of fractures in wall rocks during rapid emplacement of wet magmas from a lower level is the type of structural control envisioned. An attempt to produce similar combed textures and their variations experimentally will begin shortly.

Mineral Composition Sequences

Figure 9 is a plot of modal An and En mol percentages in coexisting plagioclase and orthopyroxene from 25 specimens from the Eagle Lake sequence.

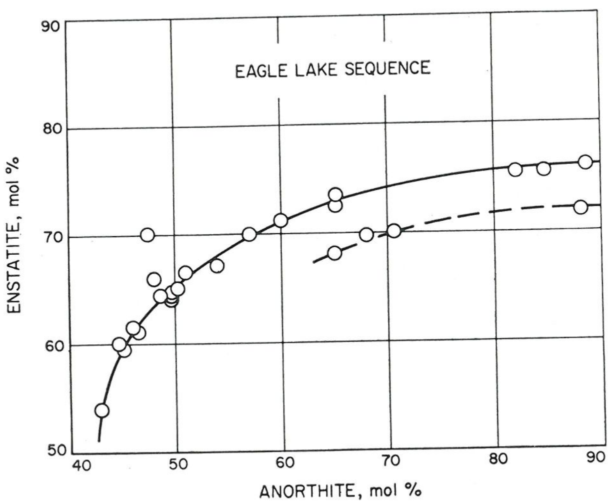

Fig. 9. Modal compositions of coexisting plagioclase and orthopyroxene from rocks of the Eagle Lake sequence.

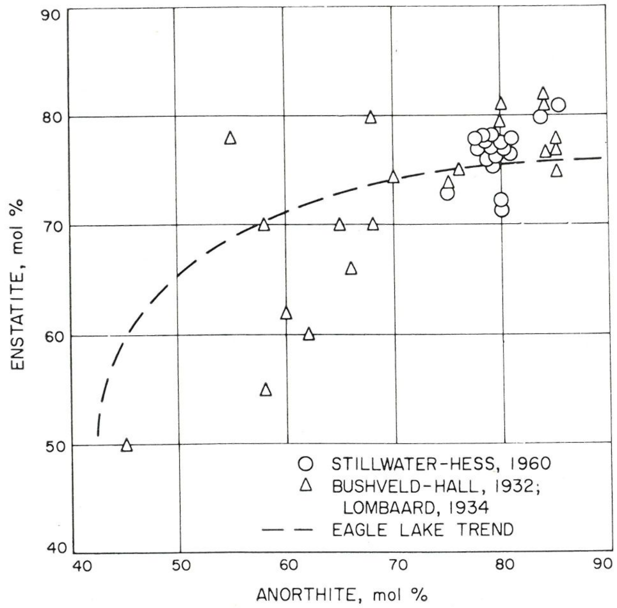

Fig. 10. Compositions of coexisting minerals from literature for large stratiform bodies.

Two of the points with plagioclase more calcic than An_{80} are from Willow Lake layers and two are from large inclusions of cumulative layers. Several of those with plagioclase between An_{53} and An_{70} are also from combed layers. The rest are from normal plutonic rocks and late norite dikes intruded into individual noritic anorthosite bodies. The points define a main trend and a (dashed) subsidiary trend. The mineral compositions were determined optically using optic angle for the orthopyroxenes and Rittmann and Turner methods with a universal stage for the plagioclase. Neither the plagioclase nor the pyroxene is zoned enough to affect the results.

The ratio An/Ab decreased faster than En/Of until the point An_{50}-En_{65} was reached and En/Of began to decrease more rapidly. Similar plots for most larger stratiform bodies show much more scatter. Figure 10 is a plot for Stillwater and Bushveld with the Eagle Lake trend from Fig. 9 added for comparison. Stillwater rocks show little progression; Bushveld shows a good deal of scatter. Both curves are drawn for coexisting early cumulative phases that are zoned slightly, if at all.

Figure 11 shows plots for Skaergaard, Rhum and the Great Dyke. Modal compositions were used where possible, but normative points are included as well as olivine compositions where orthopyroxene data are lacking. Skaergaard nicely illustrates a broad variation that diverges more and more with more highly differentiated rocks. The increased divergence from a single line of points, expressed as a

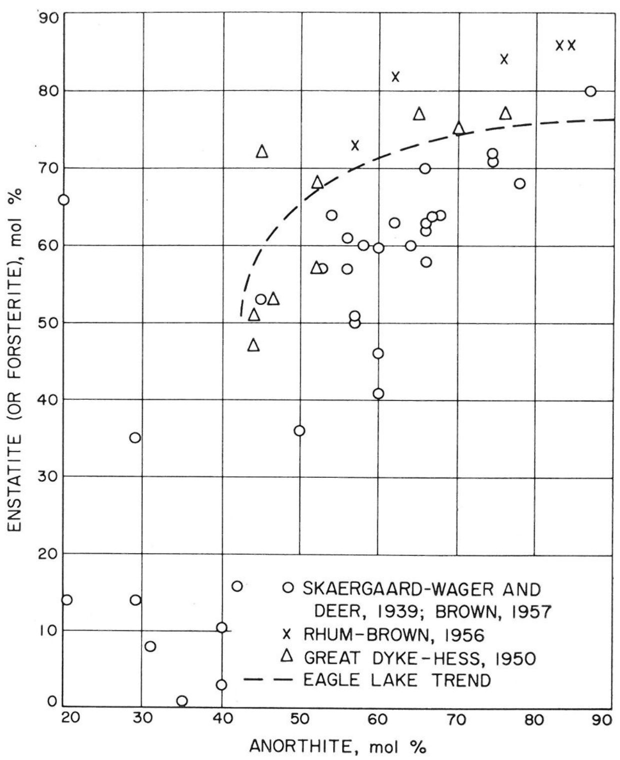

FIG. 11. Compositions of coexisting minerals from literature for large stratiform bodies.

broadening of the envelope containing the points at the low-temperature end, is to be expected. The slopes of the experimentally determined solidus surfaces in systems containing plagioclase, orthopyroxene and olivine decrease for the lower temperature phases. Therefore, a given temperature change in a magma should produce progressively a greater difference in crystal composition as differentiation progresses. The amount of compositional variation in the Skaergaard assemblages is equivalent to that which would be caused by temperature gradients of 40°–50° C. as estimated from the experimental phase diagrams.

In the Eagle Lake rocks, minerals which are found together crystallized and remained together during emplacement. The larger stratiform bodies cooled more slowly and contained temperature and composition gradients. In a large body, convection currents probably would sweep out different parts of the magma at different times, depositing separate layers which did not crystallize in the same place in the chamber. Temperature and consequent composition gradients would be produced locally during relative quiescence of some parts of the chamber with respect to others. As deposition proceeds and the height through which a current can operate becomes smaller with respect to the lateral dimension of the chamber, a larger number of cells with smaller diameters will become operative, increasing the chances for producing sizeable temperature and composition gradients. Any extensive lateral movement of convecting cells or discontinuity in the pattern would bring together and deposit layers which would be only in apparent disequilibrium.

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