THE CAULFEILD "QUARTZ-DIORITE":
MODAL DETERMINATION
and
PETROGRAPHIC OBSERVATIONS

by

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INTRODUCTION

In 1940, at the suggestion of Dr.C.O.Swanson, the writer began a petrographic study of the so-called quartz -diorite that underlies the Caulfeild area, a residential district situated about one mile and a half east of Point Atkinson on the north shore of Burrard Inlet. The work,based mainly on thin sections made from twenty-three carefully selected specimens, was carried out in the geological laboratories of the University of British Columbia under the supervision of Dr. Swanson.

ACKNOWLEDGEMENTS

The writer is grateful to Dr. Swanson for guidance and advice given during the preparation of the material for this thesis. The enclosed map is a tracing of one made by Dr. Gunning and students who carried out a geological survey of the area in 1940.

SUMMARY OF GEOLOGY

The geology, which needs only brief mention, is summarized from a report by one[1] of the students who examined the area with Dr. Gunning. The area is underlain by the southern extension of the Coast Range batholith which here surrounds a small, highly schistose roof-pendant known as the Caulfeild formation. The age of the batholith is possibly Upper Jurassic and that of the roof-pendant Triassic or late Paleozoic. These rocks are cut by aplite dikes and sills which grade into pegmatitic phases here and there. Post-Eocene(?) basic dikes comprise the final intrusive phase; they intrude the aplite. The reader is referred to the map for a more comprehensive picture regarding details.

SELECTION OF SPECIMENS

Twenty-three surface samples were chosen from an area of roughly 500 by 100 yards of the batholith; the locations are shown by numbers on the map and these correspond to those on the handspecimens and thin sections examined. Choice of material was guided largely by features not essentially characteristic of the rock. Thus no rock in contact with dikes, inclusions or shears was collected; strongly weathered samples were avoided. In a word, the material picked is as far as practicable representative of the rock as a whole. ?

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1 M.S. Lougheed

MEGASCOPIC DESCRIPTION

The rock is medium-grained, light grey to light tan where weathered and has a granitic texture. The minerals seen are plagioclase, quartz, orthoclase, biotite, chlorite, hornblende, magnetite and pyrite. The plagioclase occurs as rectangular crystals which show considerable variability in size, some exceeding 5mm. in length. Striated cleavage planes are common. A few of the crystals are altered at the centre to a white opaque substance. Both quartz and orthoclase are seen as irregular patches which appear to be interstitial to to the plagioclase grains. The colorless quartz reaches dimensions over 5mm.; the light pink orthoclase is about the same size at a maximum. Biotite, which is conspicuously plentiful, occurs as lustrous black plates that occasionally exceed 2mm. In general it is fresh but in places it has altered to green chlorite. Hornblende occurs sparingly as long black crystals. Examination under the hand-lens reveals the presence of a number of small magnetite grains. Pyrite is seen as occasional small grains and veinlets.

MICROSCOPIC DESCRIPTION

A brief description of the texture, grain size, alteration, minerals and the relations between them will be given. The statements made will have only general application to all the slides examined. Marked deviations from the general trend will be noted accordingly.

(a) Texture. With the exception of the plagio-

-clase which is generally subhedral to euhedral, the essential minerals are anhedral. The texture is therefore to be described as hypidiomorphic.

(b) Grain size. For the purpose of comparison, measurements were taken along the greatest dimension of plagioclase, quartz, orthoclase and biotite grains. Dimensions taken in this manner show that the average plagioclase crystal in each of the slides falls between 2.2mm. and 1.3mm, the average of all the slides being 1.7 mm. Similarily for quartz these limits are between 2.4 mm. and 1.4 mm., the average being 1.9 mm.; for biotite, between 1.6 and 0.8, the average 1.1. The orthoclase was not averaged but it has a definite tendency towards a size larger than the other minerals. Often it exceeds 7mm. and in slide #23 it reaches nearly 12 mm. The conclusion, then, is that the rock as a whole shows a rough uniformity in the size of its individual minerals.

The size of the plagioclase crystals varies from tiny grains to those that commonly exceed 4 mm. in length; no one crystal was observed to go beyond 6 mm., however. Likewise quartz and orthoclase show a wide range in dimensions. Biotite tends to be more uniform, in general not deviating as greatly from its average dimensions.

(c) Alteration. The rock as a whole is fairly fresh. Where alteration has taken place it is confined mainly to the plagioclase. Here it is frequently restricted to the core of the feldspar in dense masses but more often it has affected the entire feldspar in varying degrees . In a single slide only a few of the plagioclase crystals may be altered while the remainder may be comparatively fresh. The alteration products comprise epidote chiefly, sericite, kaolin, and calcite rarely. These minerals occur singly or together in varying proportions in the plagioclase. Quartz is practically unaltered. Orthoclase has been lent a brownish turbidity by the presence of very fine-grained material, probably kaolin. Biotite has been changed in varying degrees to chlorite but the total extent of alteration is quite small. Titanite shows more or less alteration to leucoxene.

(d) Essential minerals.

(i) Plagioclase. This mineral occurs as elongated to equidimensional crystals which commonly show corroded outlines, especially in contact with orthoclase. Reaction rims are common and several may be present in a single feldspar. Zoned crystals with andesine cores and oligoclase rims are frequently seen but much of the plagioclase is also not zoned. Albite twins are by far the most abundant; Carlsbad-albite and pericline types are observed occasionally.

The composition of the plagioclase was determined largely from the extinction angles on albite twins. Unfortunately, some of the slides, particularily #14,15,17,20 and 21, do not contain enough suitable albite twins to permit the identification of the plagioclase with certainty. In these cases the determination of the indices of refraction by means of oils of known refractive indices was resorted to and the identity of the feldspar deduced from Tsuboi's chart.[1] The plagioclase composition for all the slides averages out to $Ab_{69}An_{31}$ and individual crystals fall within the limits $Ab_{74}An_{26}$ and Ab64An36.

(ii) Quartz. Occurs as irregular, equi-dimensional patches to elongated forms which act as a ground-mass for the other minerals. Now and then it contains inclusions of corroded plagioclase as well as other minerals. But for rare sericitization and some dust-like inclusions, it is clear and fresh. Undulating extinction is quite common.

(iii) Orthoclase. Occurs much in the same way as quartz in that it occupies the spaces between the other minerals. In slides #11 and 15 it forms tiny veinlets which follow cleavage planes and fractures in the plagioclase. Often it exhibits a poikilitic relationship to the other minerals; slide #23 illustrates this structure exceptionally well, the orthoclase serving as host to scattered crystals of plagioclase, magnetite, apatite and biotite. Occasionally the plagioclase has been strongly corroded by the orthoclase mass and in some instances is almost completely dissolved. In slides #5,6,14, 21, where orthoclase is in contact with the plagioclase the periphery of the latter shows under high magnification what appears to be fine myrmekitic texture.

What has up to this point been called orthoclase shows in part properties that are foreign to this mineral. For instance, in slides #1,3,5,7,8,14,16,19,20, this feldspar

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1 Rogers and Kerr, Thin Section Mineralogy, p.213,1933.

exhibits twinning in the form of a single set of fine lines which may be long and straight or short and scattered. Moreover, 2V is often too large or small for orthoclase; in sections #2,7,13, it is in some cases about 50 degrees and in other sections it appears to be definitely greater than 72 degrees, the maximum for orthoclase. From this data it is evident that in addition to orthoclase, microcline and anorthoclase are also present in the rock in proportions that the writer did not try to determine. In this paper the term orthoclase will always include anorthoclase and microcline.

Another very common feature of the orthoclase is the presence of small,irregular patches whose properties are not readily determinable. Rough parallel orientation of the more elongated grains in some cases suggests incipient microperthite.

(e) Secondary and accessory minerals

(i) Biotite and Chlorite. The biotite is a dark brown normal variety which usually shows subhedral outlines. Often it is altered to chlorite which forms long wedges that penetrate the cleavage; or it may be altered at its boundaries with the development of fringes of chlorite. Only in a few cases has complete replacement taken place. Practically all the chlorite in the rock is pseudomorphous after biotite. The chlorite, which is a rather dark green, is always length fast and has anomalous interference colors of very low order. It is probably the variety penninite.Both biotite and chlorite commonly contain inclusions of apatite and titanite.

(ii) Epidote. This mineral occurs in two ways: one as as fine-grained alteration product of plagioclase, and the other as comparatively large grains which may occur with any of the minerals in the rock. In the first type of occurrence, where it is always associated with plagioclase, it is seen as small, more or less clear, irregular grains scattered throughout the plagioclase and as dark,dense masses concentrated at the cores of the plagioclase crystals; in this latter case it frequently shows a characteristic nondescript greyish interference color of low order. In general there is a certain amount of sericite and kaolin(?) associated with these masses. In the second, coarser type the epidote occurs as equidimensional to elongated forms that are usually well under 5 mm. The mineral is colorless to lemon yellow, rarely orange, and shows slight pleochroism.

As in the case of orthoclase, the term epidote very likely includes related minerals, namely, zoisite and clinozoisite. Small grains of these minerals are difficult to distinguish from one another in thin section.

(iii) Titanite,rutile,leucoxene.These minerals, almost invariably associated, are largely confined to biotite. The titanite, which is more or less altered to leucoxene, often displays a marked tendency to parallel the biotite cleavage as long irregular grains; it is also seen to follow along biotite peripheries in the form of thin ragged rims. Rutile could not be identified with certainty except in one or two instances where the characteristic twinning, color and relief could be more clearly discerned under high magnification. The mineral occurs very sparingly as tiny needles and plates.

(iv) Magnetite and apatite. Occur sparingly throughout the slides. Magnetite occurs as anhedral masses to well-formed crystals that seldom exceed 0.5 mm. As a rule it is fresh but occasionally it is completely or partially altered to hematite. The apatite is of the ordinary well-crystallized variety; crystals are usually well under 0.3 mm.

(v) Hornblende. This mineral was noted in ten of the slides but only in #5,21",22, does it attain proportion of any importance. It is dark green and has a maximum extinction of about 30 degrees. The crystals are subhedral to splendidly euhedral and range over 5.5mm.

(vi) Sericite and kaolinite. While these minerals are common to most of the plagioclase, the average amount is very small. Only in a few cases, as in slides #10,13, does the feldspar display marked alteration of this type; in these instances epidote, the dominant alteration mineral in the rock, is either absent or present in small quantities only. Kaolin tends to be a little coarser grained than the sericite. The fine-grained brownish material so frequently observed in the orthoclase is whitish and opaque in transmitted light, and may well be kaolin.

(vii) Zircon. This mineral is distributed scantily throughout the slides. The crystals are stout and rounded, and are usually under 0.5 mm. When in biotite they are sometimes surrounded by pleochroic haloes.

(viii) Calcite, pyrite, hematite and limonite. All of these are comparatively rare in the rock. Calcite has probably originated through the alteration of plagioclase with which it is associated. In slide #23, the only place where it is at all conspicuous, it occurs as numerous small, irregular grains in some of the plagioclase. One exceptionally large grain here reaches 0.4 mm., but the average is much smaller. Pyrite is seen as the odd grain or two in some of the thin sections. It may or may not be rimmed by hematite which also replaces a little of the magnetite. Weathering of the mafic minerals has produced occasional limonite stains.

MODAL DETERMINATION

The percentages of individual minerals in each of the slides was determined by means of the Rosiwal method. No one slide has an area one hundred times as great as the area of the largest grains that are present to the extent of one per cent of the rock, a condition required for accuracy within one per cent in the modal determination of rocks.[1] This rule has special bearing on the orthoclase, which often occupies unusually large areas. It is to be expected, there-

[1] Larsen, E.S. and Miller, F.S., "The Rosiwal method and the modal determination of rocks", Amer. Min., XX, 1935

-fore, that the mineral compositions of individual slides will vary considerably and that a single slide cannot be taken as representative of the rock as a whole. This point is best illustrated by the analyses (see below) of slides #21', 21", 21"', all of which were taken from handspecimen #21. However, if all the slides are pictured as combined into a single large area, then this area has the proportion(in relation to the largest grains that comprise one percent of a slide) required for one per cent accuracy, provided the rock is uniform. Now if individual slide compositions are considered as parts of this imaginary slide, totalled and averaged, the resulting composition should represent the rock as a whole. The analyses below have thus been treated, the average of each constituent taken to be representative of the entire rock. This data was then used as a basis for the classification of the rock.Because of the fine-grained nature of some of constituents and uneven distribution of others, most of the small percentages given in the table below are approximations rather than exact calculations. Dashed lines in the columns signify either absence of the mineral or its presence toan extent of less than 0.1 percent.

TABLE OF

SLIDE ANALYSES

Slide	Plag. %	Qtz. %	Or. %	Bio. %	Chlo. %	Mag. %	Ap. %	Hn-bld. %	Epi. %	Rut. Tita. Leuc. %	Sericite Kaolin Pyrite Hematite Calcite Limonite
1.	58.9	17.2	14.5	6.6	0.2	0.4	0.2	0.8	0.1	0.3	0.8
2.	54.7	28.7	6.5	3,9	1.4	----	----	----	2.8	1.3	0.7
3.	48.9	29.0	9.1	7.9	----	1.9	0.5	0.9	1.0	0.4	0.4
4.	44.0	31.1	19.6	3.0	0.3	----	----	----	0.9	0.8	0.3
5.	34.5	39.3	12.2	7.9	0.5	0.8	0.2	3.0	0.6	0.5	0.5
6.	53.8	24.7	13.5	5.4	0.1	1.4	0.1	0.5	0.1	0.1	0.3
7.	51.7	28.1	11.4	5.5	0.3	1.1	0.4	----	0.8	0.1	0.6
8.	60.9	25.8	7.7	2.1	0.3	0.4	0.1	----	1.8	0.1	0.8
9.	49.0	26.7	10.7	8.0	0.5	2.9	0.5	----	0.7	0.3	0.7
10.	36.3	26.3	23.3	1.9	3.9	1.4	0.4	1.3	2.5	1.0	1.7
11.	39.8	26.9	14.4	8.1	5.3	1.0	0.1	----	3.0	1.0	0.4
12.	45.5	31.2	15.6	1.6	2.9	0.3	0.3	----	0.9	1.4	0.3
13.	43.0	27.2	20.7	1.5	0.7	0.4	----	----	4.2	0.8	1.5
14.	46.0	29.0	13.5	8.6	1.0	0.6	0.2	----	0.4	0.4	0.3
15.	48.8	34.6	10.9	2.0	1.1	1.6	0.3	----	0.2	0.3	0.2
16.	68.0	15.6	11.9	1.4	0.7	0.3	0.1	----	1.3	0.3	0.4
17.	52.9	32.4	8.5	2.2	1.3	1.0	0.1	----	0.2	1.0	0.4
18.	51.5	31.3	11.0	3.8	1.1	0.2	0.1	----	0.5	0.2	0.3
19.	25.3	49.7	19.2	3.7	0.6	0.7	0.1	----	0.4	0.2	0.1
20.	44.9	34.7	13.9	4.6	0.3	0.2	0.1	----	0.7	0.5	0.1
21'.	42.1	20.1	30.3	6.3	0.2	0.2	0.2	0.6	---	-------	----------
21''.	48.0	31.1	16.2	3.7	0.1	0.6	0.1	-----	0.1	0.1	----------
21'''.	44.6	31.7	13.2	5.5	0.1	0.4	0.1	3.6	0.4	0.4	----------
22.	36.7	38.3	18.1	3.6	0.4	0.1	---	2.2	0.4	0.2	---------
23.	48.1	24.1	18.4	6.4	0.1	0.8	2.2	-----	0.4	0.4	1.9
Av.	47.1	29.4	14.6	4.6	0.9	0.7	0.2	0.5	1.0	0.5	0.5

CLASSIFICATION

According to Lindgren[1], "The truly characteristic feature of the granodiorites is that the soda-lime feldspar, which is always a calcareous oligoclase or an andesine, is at least equal to double the amount of the alkali feldspar. The latter may be taken to vary from 8 to 20 per cent" in a rock with an assumed feldspar content of 60 per cent. The Caulfeild plutonic, which is about 60 per cent feldspar, has about three times as much andesine($Ab_{69}An_{31}$) as orthoclase, as well as an abundance of quartz. The rock may therefore be classed as a granodiorite, in Lindgren's sense of the word. In the classification by Johannsen[2] which includes the monzonites, it is intermediate between quartz monzonite and tonalite(quartz-diorite) and is hence given the name monzotonalite. The two terms are synonymous since they refer to the same rock, and either may be applied correctly to the Caulfeild intrusive.

OBSERVATIONS AND CONCLUSIONS

(a) General nature of the rock. In most respects the granodiorite is a normal variety with a little more quartz and plagioclase and less mafic minerals than the average. Its average grain size is somewhat smaller than that common to most granodiorites. A comparison between Lindgren's[3] normal

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[1] Waldemar Lindgren, "Granodiorite and other intermediate rocks" Amer.Jour.Sci., IX, 1900, p.277.

[2] Albert Johannsen: "A descriptive petrography of igneous rocks" University of Chicago Press, Chicago, Ill., 1932, II, p.320

[3] Lindgren, op. cit., p.274-275 & 282.

granodiorite and that of the Caulfeild area is shown below.

Lindgren's granodiorite	Caulfeild granodiorite
(i) light-colored, granular rocks	Ditto
(ii) composed of quartz, oligoclase or andesine, biotie and/or hornblende, orthoclase, titanite, magnetite, apatite, zircon	Ditto
(iii) decomposed rock never sets free Fe_2O_3 to impart red color to the rock	Ditto
(iv) hypidiomorphic texture	Ditto
(v) biotite & hornblende are sometimes, plagioclase nearly always partly idiomorphic	Ditto
(vi) these minerals usually cemented together by later mass of orthoclase & qtz.	Ditto
(vii) orthoclase may assume form of microcline; perthitic growth may be present in small amounts	Ditto
(viii) plagioclase range Ab_{70} to Ab_{56}	Ab_{74} to Ab_{64}
(ix) biotite, dark brown normal variety	Ditto
(x) hornblende, green or brownish green; maximum extinction about 18-20 degrees	green; maximum extinct. about 30 deg.

Mode %	Plag.	Qtz.	Or.	Mafic
Lindgren	44.0	23.0	14.0	14.0
Caulfeild	47.1	29.4	14.6	6.0

(b) Effects of assimilation. As well as enclosing the Caulfeild roof-pendant, the granodiorite contains many other much smaller inclusions. These have been greatly metamorphosed and in some cases only vague outlines or "ghosts" of them now remain in the plutonic. It is evident, then, that assimilation taken place to some degree. For this reason it might well be suspected that absorption of foreign material by the original magma may have been considerable, and that as a consquence local effects and variations should be seen in the rock. However, the microscope show the rock to be uniform in most respects throughout the area. The conclusion, therefore, is that neither the roof-pendant nor the inclusions have been assimilated to such an extent as to have exerted an important effect on the composition of the magma.

(c) History of the magma. At its beginning, prior to the onset of crystallization, the state of the magma was one of high temperature and pressure. The field evidence - partial absorption of inclusions and possibly the highly altered character of the roof-pendant - points clearly to such a condition. The magma was presumably produced by processes of fractional crystallization from a more basic source-magma, according to the theory of magmatic differentiation.

The course of crystallization and ultimate solidification of the granodiorite magma as outlined below has been interpreted from the nature of crystal boundaries of individual minerals and other features in the slides.

The magma began crystallization with the precipitation of small amounts of widely-scattered crytals of zircon, apatite, magnetite and titanite. The early formation of these minerals is proven by the fact that they occur as inclusions in later minerals. Of them, apatite and zircon were earlier than magnetite which is occasionally observed to enclose them. After the magma had cooled somewhat, hornblende began to settle out, probably in small quantity, from the liquid until equilibrium between the two was established. At this stage began the production of plagioclase in the form of a few small crystals scattered thinly throughout the magma. Further cooling and adjustment in equilibrium brought about reaction between the liquid magma and hornblende and the resultant formation of biotite, some of which began to envelope the odd small crystal of plagioclase as well as apatite etc. as it grew. Evidence for these latter developments is seen in the slides. In slide #5, for example, a crystal of hornblende is rimmed by biotite and in other slides it is intergrown with the biotite. Not infrequently do small crystals of plagioclase occur as inclusions in the biotite.

The magma now began the simultaneous production of biotite and plagioclase slowly but on a large scale. The contemporaneity of these two minerals is shown by the fact that their crystal outlines often exhibit mutual interference in development, one forming indentations in the other. Contin-crystallization finally exhausted the magma of these two constituents.

At this point in the process of consolidation the magma had become a hot mush of crystals which were separated by interstitial liquid of highly silicious,granitic composition. Falling temperature then caused the solidification of this liquid into orthoclase and quartz masses whose shapes were largely governed by the disposition of the previously formed crystals . Under the microscope these masses are seen as irregular patches or anhedra.

In the ordinary course of crystallization in granitic magmas, the formation of orthoclase precedes that of quartz. Here, however, to a considerable extent the reverse is true. In some of the slides(#6,9,11,16,19,22,23) the ~~quartz~~ orthoclase extends tongues or veinlets into the quartz, or partially encloses or completely engulfs quartz grains. Slide #23 affords a particularily good illustration of the last relationship. The quartz, then, is in no small measure younger than the orthoclase in its formation. Moreover,there is a general tendency for the quartz to approach euhedral form than in the case of orthoclase; this is to be taken as additional evidence of the earlier crystallization of quartz. There is,nevertheless, evidence similar to that in the case of orthoclase that some of the quartz is later than the orthoclase. It is plain that there was a large overlap between the crystallization periods of quartz and orthoclase and that the two were precipitated simultaneously for a time.

By now all the major constituents of the magma had been successively precipitated and solidified in accordance with changing physical and chemical conditions in the cooling melt. The magma had become a body of hot, solid rock. It remained only for the effects of gases and solution - the end products of crystallization trapped in the hot rock - to bring the history of the magma to a close. Such emanations soaked through the body of the rock, attacking and partially replacing plagioclase and biotite chiefly. This action is responsible for the formation of all the chlorite, epidote and sericite, some of the titanite and possibly some of the magnetite in the rock.

Thus a good deal of the accessory minerals in the rock owes its origin to deuteric or hydrothermal action rather than to direct precipitation from the magma. The criteria supporting this conclusion are far from abundant. They are as follows: (1) some of the epidote, magnetite and titanite occurs as vein-like forms and in irregular shapes which replace other minerals

(2) the confinement of a particular type of alteration to a particular mineral, e.g. chlorite to biotite

(3) these minerals are not products of weathering by surface solutions or other superficial agencies. In connection with the last point, the most noteworthy feature is that the amount of chlorite, epidote and sericite is not proportional to the degree of weathering in the rock.

Very fresh specimens, for example, often contain more of these minerals than do those that are relatively altered.

(d) Temperature conditions in the magma. The general uniformity in texture and composition in the rock testify to uniformity in temperature conditions during the cooling of the magma. The fall in temperature was undoubtedly slow and gradual throughout. Evidence of this is seen in the following (1) the common occurrence of zoning and reaction rims in plagioclase crystals

(2) the absorption and corrosion of plagioclase borders by orthoclase and quartz. These features are hardly to be expected under any conditions other than slow cooling.

(e) Pressure conditions in the magma. The slow consolidation took place under static pressure. Except for occasional slightly warped crystals of plagioclase and biotite, strained quartz and tiny fractures, there is no evidence whatever in the rock of important movement having taken place in the magma during its solidification.

SUMMARY

The Caulfeild plutonic is not a quartz-diorite but normal variety of granodiorite. Throughout the area sampled it is uniform in both texture and mineral composition. There is no evidence of it being transitional to either quartz -diorite or granite. It does not seem to have been influenced greatly by assimilation of the numerous inclusions it contains. Its genesis is normal. With the exception of orthoclase, which crystallized abnormally late, the paragenesis is regular.

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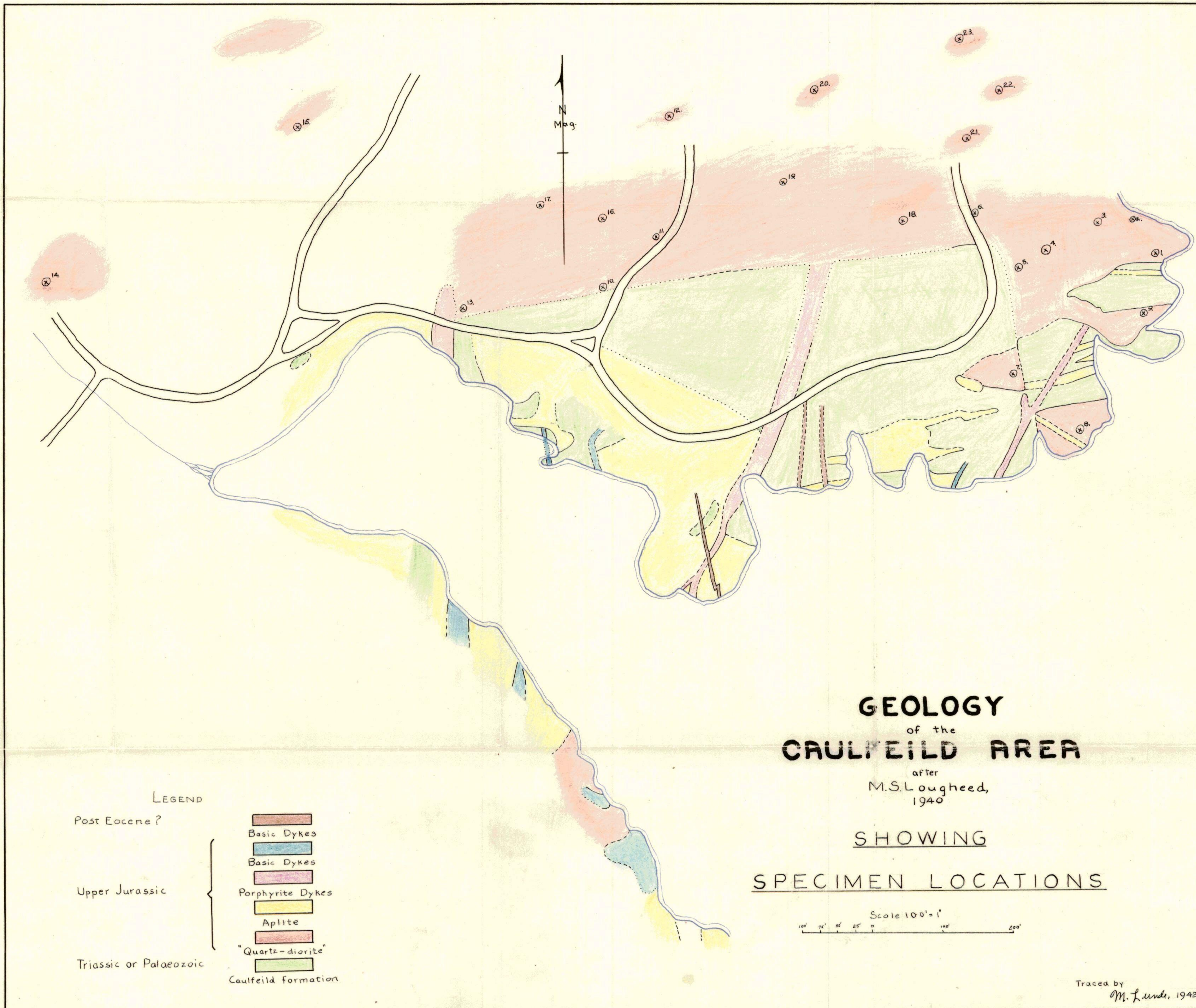
GEOLOGY
of the
CAULFEILD AREA
after
M.S. Lougheed,
1940
SHOWING
SPECIMEN LOCATIONS
Scale 100' = 1"
N
Mag.
LEGEND
Post Eocene?
Basic Dykes
Upper Jurassic
Basic Dykes
Porphyrite Dykes
Aplite
"Quartz-diorite"
Triassic or Palaeozoic
Caulfeild formation
Traced by
M. Lunde, 1942