THE SOOKE GABBRO

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ABSTRACT

The geology of the East Sooke peninsula comprises a core of olivine gabbro, peripherally uralitized and bounded on the north and east by upper Eocene Metchosin basalts of submarine origin. The gabbro intrudes the basalts which are unconformably overlain by sediments of the Sooke Formation of Miocene-Oligocene age.

The Sooke gabbro intrusion is an elliptical body of slightly differentiated olivine gabbro which is composed of calcic plagioclase and clinopyroxene with minor olivine and orthopyroxene. The gabbro does not exhibit any obvious cryptic or cumulate layering of the type which characterises many other layered basic igneous intrusions. Instead steeply dipping structures such as weak layering, foliation and lineation are believed to be flow structures.

Intensity of uralitization of the olivine gabbro increases near the margin of the intrusion and towards fractures which appear to have acted as channelways for a convective flow of hydrous fluids within and around the hot intrusion. Concentrations of copper sulphides, deposited from these fluids, are found in structurally favourable areas.

The gabbro intrusion is thought to mark the position of a volcanic neck or feeder, now exposed by erosion of a thick sequence of Eocene submarine basalts which built up from ocean floor in a manner similar to the Hawaiian chain of oceanic islands. An hypothesis of oceanic origin for the basalt and gabbro sequence is complemented by reinterpretation of the geophysical data from south Vancouver Island. The Metchosin basalts and gabbro intrusions are thought to represent an oceanic suite of rocks emplaced by obduction on the southern tip of Vancouver Island.

CONTENTS

FIGURES

TABLES.

MAPS

ACKNOWLEDGEMENTS

This thesis was undertaken under the supervision of Dr. K.C. McTaggart who instigated the study and made many useful suggestions. During the time of this study the author was supported by a National Research Council of Canada Postgraduate Scholarship.

INTRODUCTION

GENERAL STATEMENT

The aim of this thesis was to study a gabbro intrusion at East Sooke, Vancouver Island, and to consider the origin of the body in the light of recent advances in the understanding of layered and massive basic igneous rocks.

LOCATION AND ACCESSIBILITY

The map area, covering fifteen square miles of the East Sooke peninsula, is on Vancouver Island about sixteen miles southwest of Victoria (fig. 1). The peninsula is bounded on the south by Juan de Fuca strait and on the west and north by Sooke Inlet and Sooke Basin.

The northern part of the area is readily accessible from a secondary road which branches off Island Highway No. 14 about five miles east of Sooke village. Numerous logging roads traverse the area but many are overgrown by scrub and salal. A trail constructed in the summer of 1971 under the Opportunities for Youth Program provides access along the southern coast.

TOPOGRAPHY AND GLACIATION

Relief in the area ranges from sea level to almost 900 feet at Mt. Maguire and Babbington Hill (fig. 2). The area is cut by precipitous north and north-easterly trending valleys most of which are

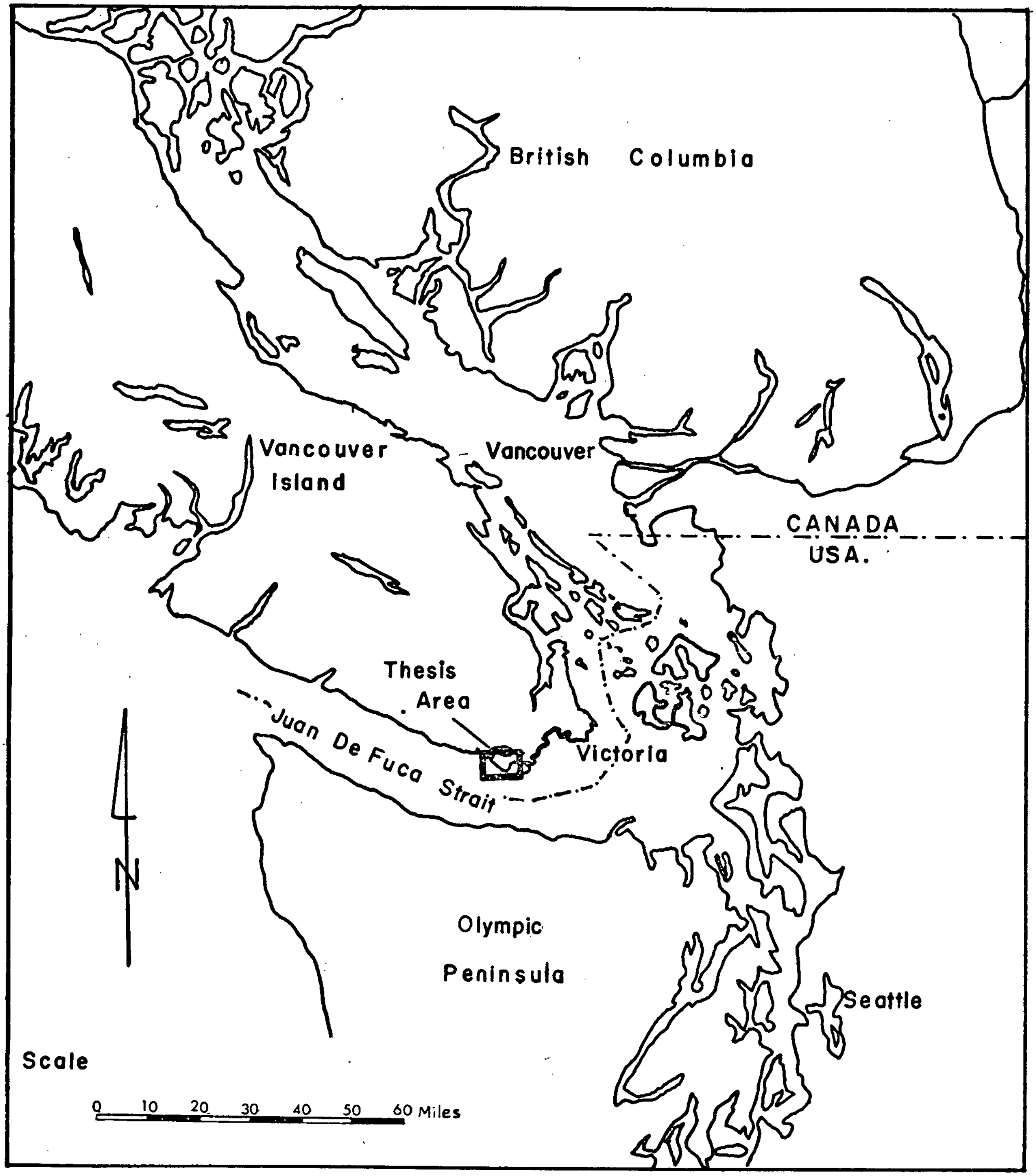


Figure I Location of Thesis Area.

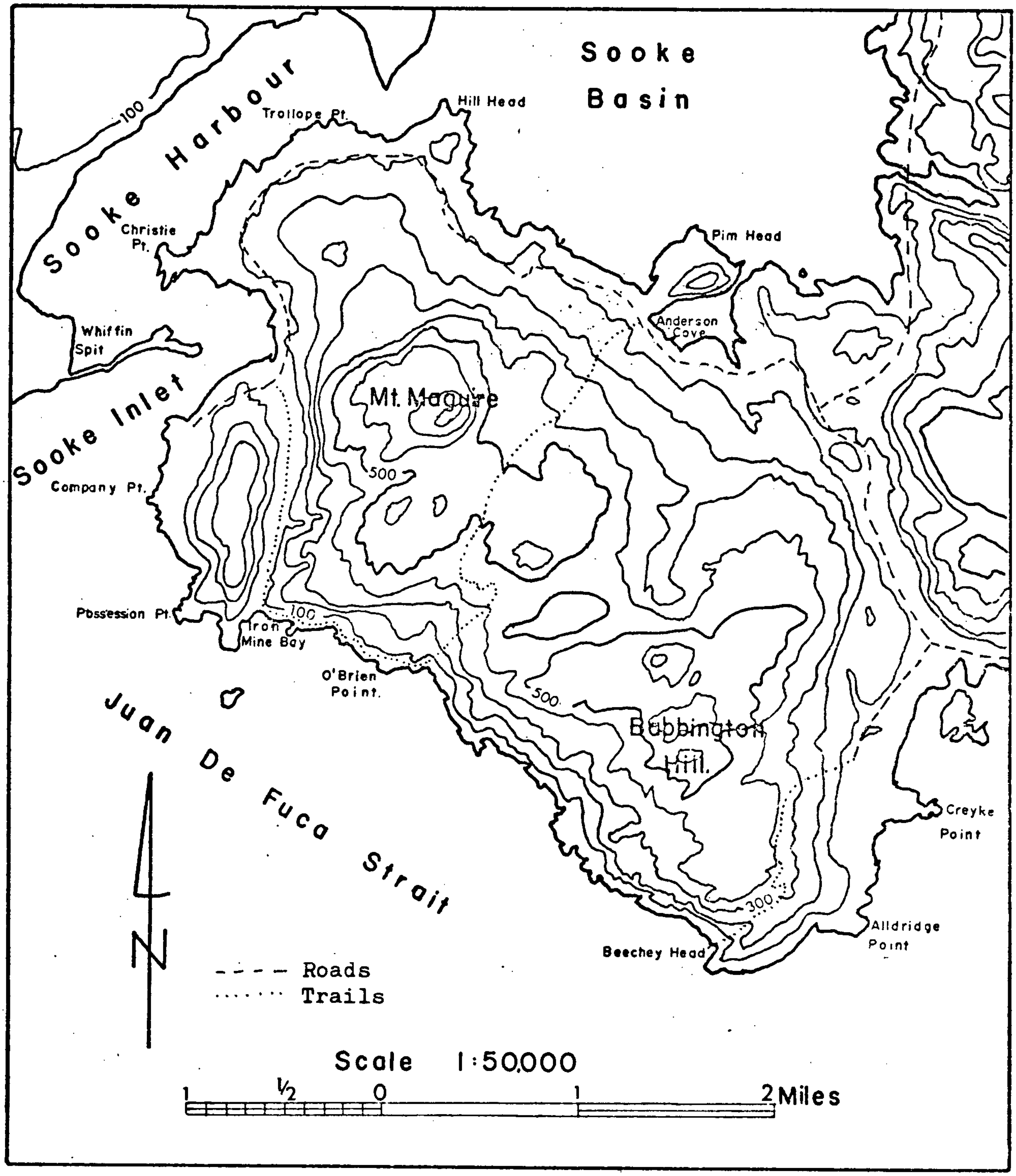


Figure 2 TOPOGRAPHIC MAP -EAST SOOKE PENINSULA.

the topographic expression of faults. The coastline along Sooke Harbour and Basin consists of silty beaches with little rock outcrop.

Much of the area is covered by variable thicknesses of glacial drift which consists largely of a mixture of yellow sand, gravel and bluish-grey boulder clay with numerous boulders and cobbles. The drift forms a thick blanket in the northeast part of the area where rock exposure is generally poor. Elsewhere the proportion of outcrop to drift is variable. Good exposures of bedrock are found along cliff and scarp sections on the south coast and ice-sculptured exposures of the roche moutonnée type are common on hills and ridges.

PREVIOUS WORK

Copper mineralization in the East Sooke gabbro was reported as early as 1893 but the geology was not described until 1912 when the Geological Survey of Canada published a memoir on southern Vancouver Island (Clapp 1912). Clapp described two stocks of basic plutonic rocks at East Sooke and Rocky Point. He also noted the presence of small gabbroic bosses along the coast northwest of Sooke Harbour. Clapp subdivided the gabbro into amphibole gabbro, fine grained augite gabbro, ophitic gabbro, olivine anorthosite, anorthosite and various pegmatites. He noted that the gabbro had suffered from "considerable metamorphism, rendering the rock gneissic and shearing it along well marked and often extensive shear zones". The age of the Metchosin basalts was at this time thought to be Triassic or Lower Jurassic. Consequently Clapp postulated an Upper Jurassic age for the intrusions as they could be seen to intrude the Metchosin rocks and to be much older and unconformably overlain by the Sooke and Carmanah formations.

H.C. Cooke, in a Geological Survey of Canada museum bulletin published in 1919, described the gabbro body of East Sooke. The bulletin is accompanied by a geologic map of the East Sooke peninsula. Cooke subdivided the gabbro into mappable units of olivine gabbro, augite gabbro, anorthosite and granite. He found a spatial relationship between these units in that the olivine gabbro occupies the centre and forms the main part of the East Sooke mass while the augite gabbro and granite lie on the periphery. Cooke believed that the differences in rock type were caused by "the processes of differentiation acting on an originally homogeneous magma whose composition was probably that of a rather basic basalt".

By this time the Metchosin basalts were recognized to be of Upper Eocene age. Therefore Cooke postulated a Lower Oligocene age for the Sooke intrusives.

Copper deposits of the East Sooke peninsula ensured a continuing interest in the area and reference is made to the deposits in British Columbia Minister of Mines Annual Reports of 1893, 1902, 1908, 1915, 1916, 1917, 1918, 1919, 1925 and 1931. In the Annual Report of 1948, Fyles summarised the economic history of the area and described some of the mineralised zones.

PRESENT INVESTIGATION

Field data for this thesis was collected in the fall of 1970 and the spring of 1971. The gabbro intrusion and the Metchosin basalts occurring on the East Sooke peninsula were mapped on a scale of 1:12,000. Other bodies of gabbro, although not mapped in course of the present study, were examined. Since the olivine and augite gabbros were virtually indistinguishable in the field, mapping was supplemented by microscopic examination of approximately one hundred specimens of the gabbro.

GEOLOGICAL SETTING

Basaltic pillow lavas of the Metchosin Formation form a westerly trending belt across South Vancouver Island. These Eocene basalts are part of a voluminous submarine volcanic assemblage of the Pacific North-west (fig. 3). Volcanic rocks of the Metchosin Formation are different from other Tertiary volcanics on the mainland of British Columbia which are, as a rule, subaerial flows similar to the Columbia River basalts.

A series of dyke- and stock-like gabbroic bodies known as the Sooke Intrusives, are intrusive into the Metchosin basalts. The largest of these gabbro masses is the elliptical body which forms the peninsula of East Sooke. Other gabbroic bodies are noticeably elongate in a northwesterly direction (fig. 4). Carson (1968) obtained a 43 million year K/Ar age (Upper Eocene) from the gabbro.

The gabbro is unconformably overlain by sediments of the Sooke and Carmanah Formations of Upper Oligocene - Lower Miocene age. The Sooke Formation, found in many places as downfaulted blocks within the gabbros or basalts, consists mainly of conglomerates with minor bands of yellowish sandstone. The conglomerates are derived directly from the Metchosin Formation and the Sooke Intrusives.

A distinct tectonic break, the Leech River Fault, separates the belt of Metchosin basalts from the schists of the Leech River Formation which lie north of the fault. Sooke gabbro intrusives are not known to intrude the Leech River Formation which is believed to be of Palaeozoic or Lower Mesozoic age. Thus the geology of Vancouver Island south of the Leech River Fault which shows clear affinities with the geology of the Olympic province to the south is distinct from that of the rest of the Island.

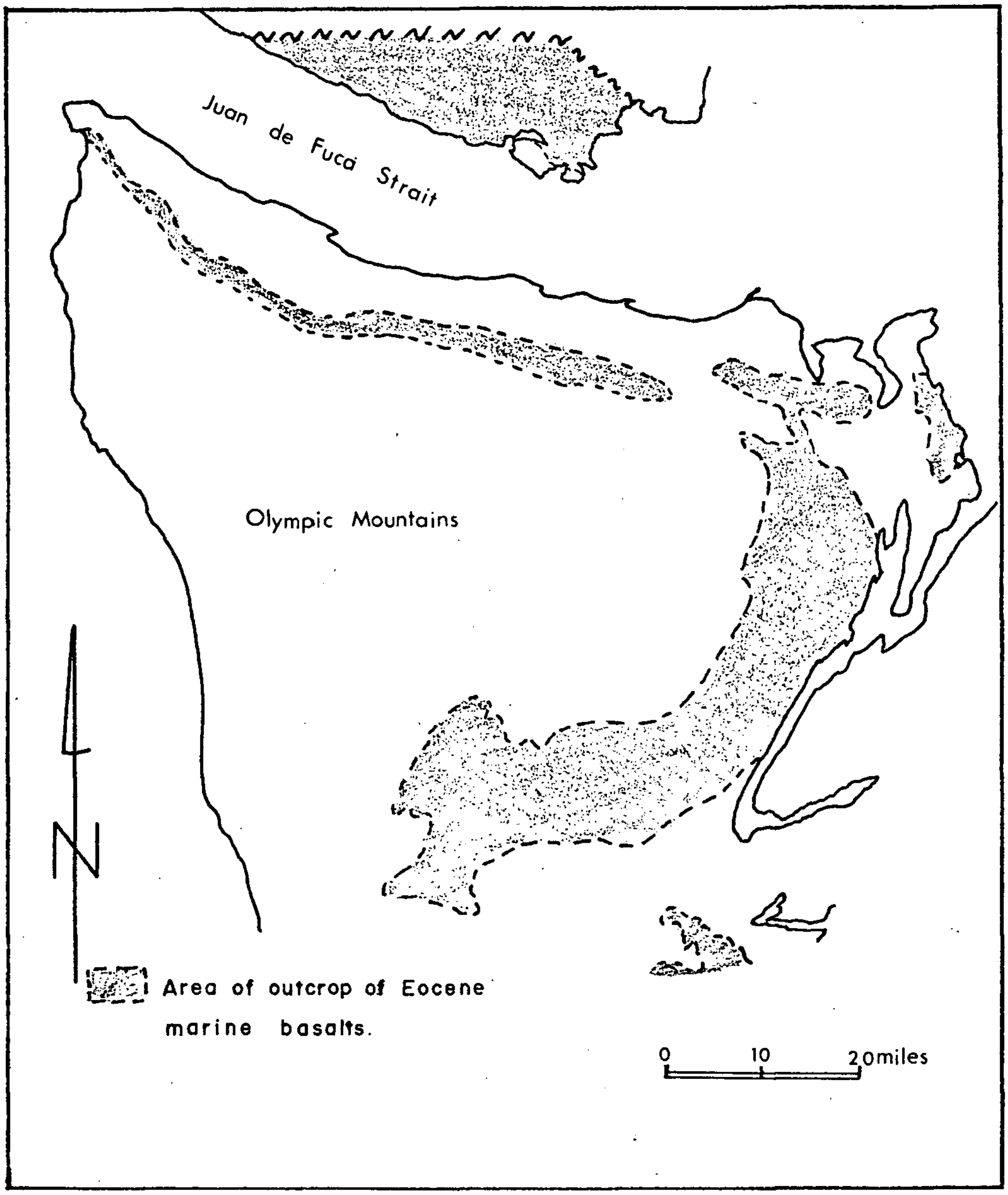


Figure 3. The distribution of Eocene marine basalts in the Olympic peninsula and Vancouver Is. after Danner 1955.

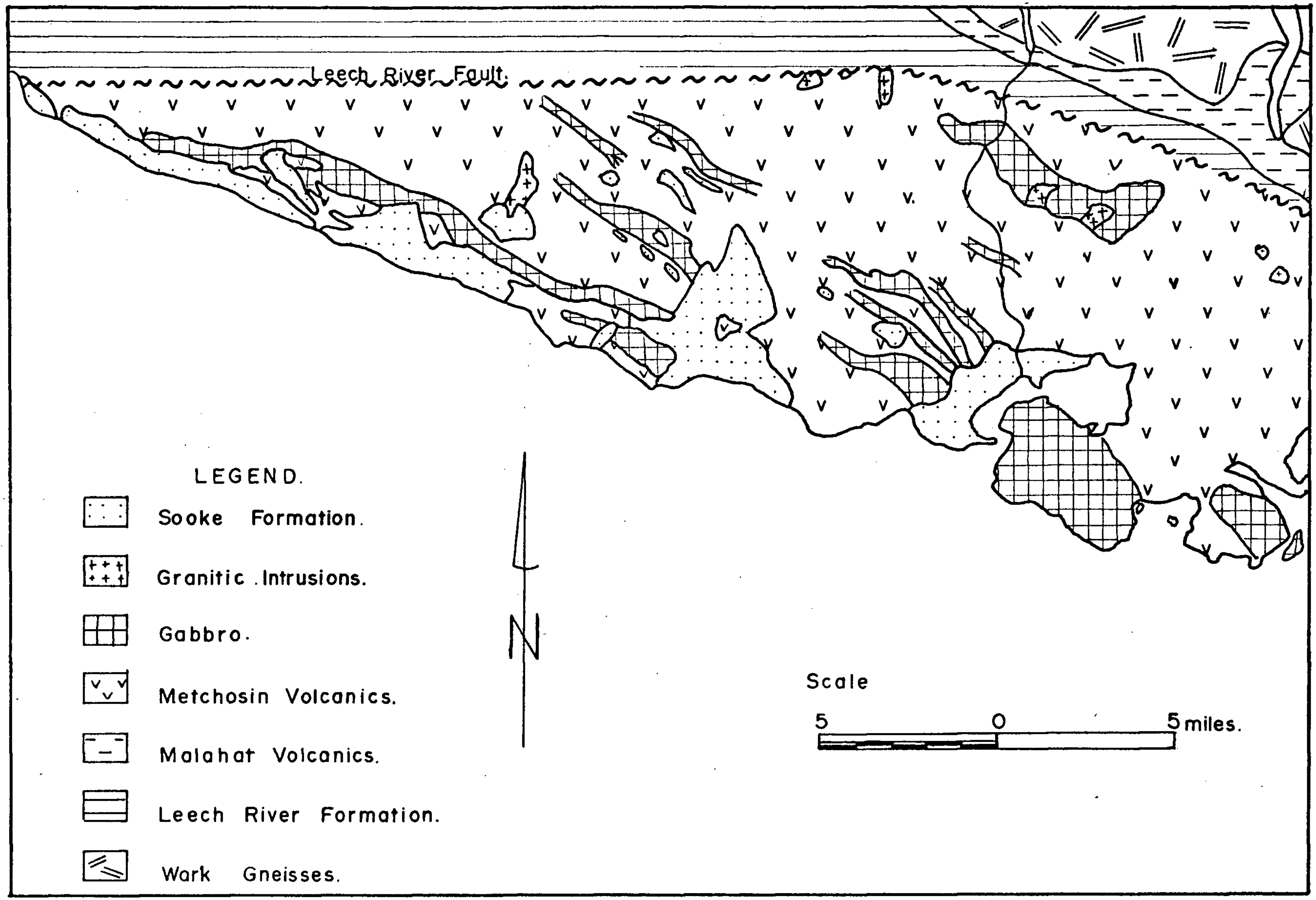


Figure 4. The geology of S. Vancouver Island (after Carson and Muller)

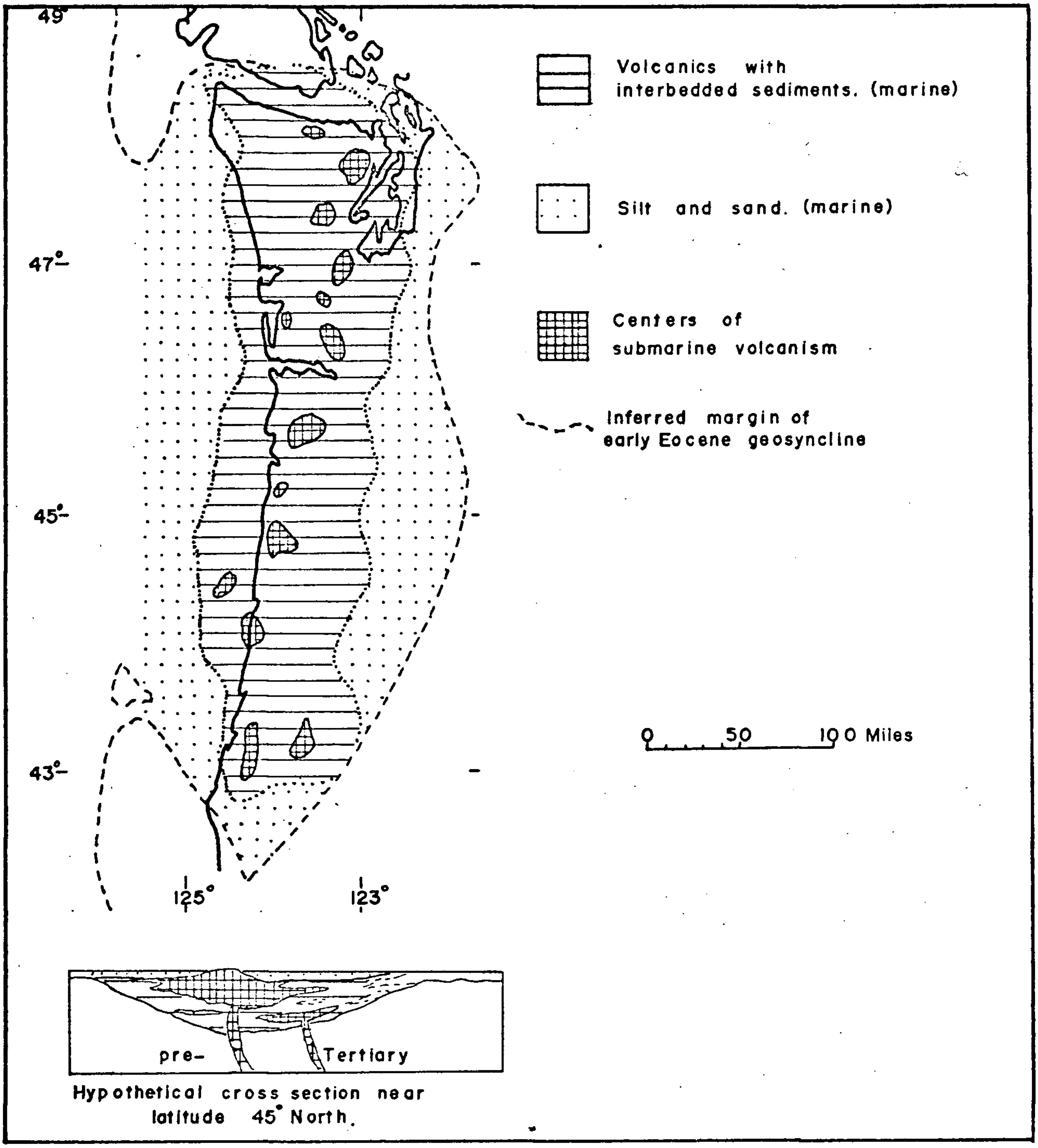


Figure 5. Paleogeologic map of western Oregon and Washington in early Eocene time. (after Snavely and Wagner 1963)

THE METCHOSIN FORMATION

INTRODUCTION

The Metchosin basalts in the area comprise part of an extensive tract of Eocene pillow lavas exposed on south Vancouver Island and on the Olympic Peninsula (fig. 3). The volcanic assemblage consists mainly of submarine, basaltic lavas erupted on to ocean floor occupying the area which is now the Olympic Peninsula and south Vancouver Island (fig. 5).

The lavas are estimated to cover more than 60,000 square miles. In the northeastern Olympic area the lavas are more than 15,000 feet thick (Snavely and Wagner 1963) and Clapp (1917) considered a thickness of 7,500 feet to be a moderate estimate of the Metchosin volcanic pile on south Vancouver Island. The volume of Eocene basalt erupted is estimated as being at least 40,000 cubic miles (Waters 1955). A figure of 100,000 cubic miles of Eocene basalts is quoted by McKee (1972).

Volcanism was largely submarine and pillow lava-palagonite complexes dominate the volcanic pile. Some of the basaltic flows are spilitized (Park 1944). Waters (1955) postulated that "water, alkalis, silica and other easily removable constituents stewed from the slowly metamorphosing root of geosynclinal sediments as it was downbuckled to form a tectogene" caused the "spilitization" or albitisation of the basalts.

The basalts interfinger complexly with cherts and marine tuffaceous sedimentary rocks containing pelecypod and gastropod faunas.

Submarine eruptive centres appear to have been intermittently active over most of the Eocene and early Oligocene (Snavely and Wagner 1963). Sites of underwater basalt or sediment accumulation shifted from place to place, and because of slight differences in age, the Eocene basalts have been given many different local formational names. In western Washington, the Eocene lava is known as the Crescent Formation. The same strata on Vancouver Island, across the Strait of Juan de Fuca, constitute the Metchosin Formation. Other names are used in the Coast Range of Oregon - Tillamook Volcanic Series in the northern part of the range, Siletz River Volcanics in the central part, and the Umpqua Formation toward the south end of the range.

THE METCHOSIN BASALTS OF EAST SOOKE - DISTRIBUTION AND DESCRIPTION

Metchosin rocks outcrop on the north and northeastern edge of the East Sooke peninsula and are distributed peripherally to the gabbro which forms the central core of the area. Although there is no outcrop of Metchosin basalt on the southwest part of the peninsula facing Juan de Fuca Strait, large fragmented screens and xenoliths of baked and partly remelted basaltic rocks are there enclosed by the gabbro. It seems probable therefore that the southerly contact between the gabbro and the basalt lies just offshore.

The Metchosin basalts exposed in the north and northeast are dark grey, commonly weathered reddish brown.

The basalts exhibit a range in textures from aphanitic or fine-grained types to distinctly porphyritic varieties.

Microscopically, the fine-grained basalts are holocrystalline and generally exhibit a diabasic or sub-ophitic texture in which aggregates of pyroxene crystals enclose long laths of plagioclase. The basalts consist of almost equal parts of plagioclase and pyroxene with subordinate magnetite, apatite and possibly ilmenite. Various amphiboles, jarosite, chlorite, epidote and scapolite are secondary alteration minerals. The plagioclase of the basalt is labradorite (An 60-70) and is normally zoned. In some of the more altered rocks the margins of the plagioclase crystals are albitic, and hairline veins which cut the crystals are filled with albite, epidote and uralitic amphibole. The pyroxene is a brownish coloured augite which is slightly pleochroic and is generally altered, at least in part, to uralitic amphibole. The alteration, where not pervasive, generally takes place along crystal margins or along fractures and cleavage planes within the crystal. Fresh augite contains dust-like inclusions of magnetite or ilmenite arranged in parallel lines nearly perpendicular to the prismatic cleavage.

Phenocrysts in the porphyritic varieties of the Metchosin basalt are bytownitic plagioclase, the anorthite content ranging from An 86 to An 78. The plagioclase phenocrysts exhibit normal zoning. Olivine, though usually absent from the Metchosin basalts, is a minor constituent in some of the more porphyritic varieties. Aggregates of olivine alteration products, mainly serpentine and chlorite, commonly pseudomorph the original mineral.

CHEMISTRY

The chemical composition of four Eocene Metchosin basalts from the Olympic Peninsula is shown in column 6 of Table V. Although the analyses of the Metchosin basalts are not identical to those of the average ocean tholeiites, they show generally low values of K_2O, TiO_2 and P_2O_5. The Metchosin basalts also exhibit high Al_2O_3 and CaO values and a high Na/K ratio. These features are supposedly characteristic of ocean tholeiites (Cann 1971). The analyses of the Metchosin basalts are also characterised by relatively high silica and lime and low alkalies as are the tholeiitic basalts of the Hawaiian area (column 7).

STRUCTURE

There is no obvious folding of the basalts in the East Sooke area other than a local steepening of dip near the gabbro contacts. Basalts close to the contact dip northeasterly at approximately fifty degrees and the dip decreases rapidly away from the gabbro.

Pillowed sequences are found within the basalts. The pillows are irregular bulbous and tubular masses commonly broken by subsequent fracturing. Porphyritic varieties of the basalt,(fig.9), generally found close to the gabbro intrusion, interdigitate complexly with the fine grained basalts. Immediately north of the Sooke Basin, sill-like bodies of medium-grained rocks which are gabbroic in aspect grade distally into fine grained volcanic rocks.

The basalts are extensively fractured on all scales from minor fractures to wide shear zones. There is a dominant north-easterly trend of shears and fractures, many of which extend into the gabbro.

The contact between the gabbro and basalts is a sharp intrusive contact with no evidence of faulting. A steeply dipping foliation developed in the basalts close to the gabbro contact is parallel to the gabbro contact and is formed by a parallel alignment of metamorphic amphibole, plagioclase laths and by trains of magnetite grains. The foliation is probably caused by reorientation and recrystallization of the original basalt fabric to correspond with the stress system imposed by the intrusion.

METAMORPHISM

The Metchosin basalts have been subjected to thermal metamorphism at the contacts with the Sooke Gabbro. The typical doleritic texture of the basalts gradually disappears towards the gabbro contact. The mineralogy is unchanged but feldspars become more equant and, along with pyroxene, form an interlocking equigranular mosaic indicative of recrystallization.

Hydrothermal alteration of the basalts is most extensive along fractures near the contact with the gabbro. Hydrated phases are common. Pyroxene is progressively replaced by hornblende. Veins of chlorite, epidote and actinolite are common. Plagioclase is saussuritized especially along fractures in the crystals. Near the veins and fractures in the rock the plagioclase laths are strongly zoned and margins of some crystals show low or negative relief indicating an albite-oligoclase composition. Scapolite is seen mainly as a vein mineral although on occasion it appears to replace plagioclase near the veins. The intensity of hydrothermal alteration is always greatest along shear zones and it is obvious that the fractures acted as channelways for hydrothermal fluids. The hydrothermal activity is probably caused by a convective flow of heat and fluids around the slowly cooling gabbroic stock (cf. Norton 1972). This concept is discussed more fully in a later section on hydrothermal activity.

AGE OF THE BASALTS

The Metchosin basalts are part of the voluminous sequence of submarine basaltic lavas in the Pacific Northwest which are Eocene in age. A potassium argon age of 44±6 million years from hornblende in altered Metchosin Basalts is given by Kirkham (G.S.C. 70-63).

THE GABBROS OF EAST SOOKE

INTRODUCTION

The gabbros comprise an elliptical body occupying the major part of the East Sooke peninsula. The major axis of the intrusion is almost five miles in length; the minor axis is approximately half this length. The gabbros can be subdivided into different members of the gabbro family on the basis of mineralogy. Two main groups are distinguished, an olivine gabbro which forms the core of the area and a uralitized gabbro which lies on the periphery. The olivine gabbro grades into the uralitized gabbro by gradual disappearance of olivine and fresh pyroxene with concomitant increase in amount of secondary amphibole. Other varieties such as plagioclase - or olivine - rich 'gabbros' are minor in extent and are believed to represent layered phases of the gabbro. Leucocratic quartz diorites are intrusive into the gabbros and are thought to represent late differentiates.

OLIVINE GABBRO

The olivine gabbro underlies the major part of the area and forms the elliptical core of the intrusion (Map A). The average unaltered olivine gabbro is a dark grey or black rock, composed of approximately 45% plagioclase, augite clinopyroxene and normally less than 20 per cent olivine. Accessory minerals are apatite, sphene, ilmenite and magnetite. Sulphide minerals are generally absent from the olivine gabbro.

The plagioclase is purplish or black giving rise to the dark, almost ultramafic aspect of many of the gabbros. In the fresh olivine gabbro the anorthite content of the plagioclase is consistently high (Table I and Map B). Unzoned cores of the plagioclase crystals consist of calcic bytownite. Normal zoning towards a slightly more sodic plagioclase is seen at the margins of the crystals. The unzoned core generally comprises around 80 to 90 per cent of the area of plagioclase crystal and measurements using the Universal stage indicate that the anorthite content of the marginal zones of the crystals does not differ greatly from that of the core. The maximum measured differences of anorthite content from core to margin are of the order of 10 to 15 per cent An.

There is no noticeable difference in the composition of the cores of the plagioclase crystals in the unaltered olivine gabbro either laterally or with elevation. The intrusion therefore does not seem to exhibit the cryptic layering characteristic of many basic intrusions.

The structural state of the plagioclase within the olivine gabbro is generally low. Slow cooling of plagioclase after crystallization is believed necessary to permit structural rearrangements which lead to the formation of the more ordered structure of the low temperature feldspars.

Plagioclase crystals are invariably twinned. Albite twinning is most common. Combined albite-carlsbad, carlsbad, pericline, manebach and acline twins occur in progressively decreasing incidence. Certain gabbros showing evidence of strain such as deformation lamellae in olivine contain plagioclase with a higher incidence of "rare" twin types. In such crystals the structural state also shows slight variations away from the ordered or low temperature state.

The predominant pyroxene in the olivine gabbro is an augitic clinopyroxene which has generally crystallized later than both olivine and plagioclase. Usually the clinopyroxene forms large poikilitic crystals which enclose plagioclase and olivine (fig. 6).

Inclusions and thin irregular exsolution lamellae of a calcium-poor pyroxene are common within the augite crystals, giving rise to a schiller texture. Lamellae are generally exsolved parallel to the (100) plane of the augite and are probably hypersthene.

Unaltered clinopyroxene shows a very slightly pink pleochroism. The crystals also show a compositional zonation towards the margins.

Compositions of a number of augite crystals were determined optically by the Universal Stage, and although optical data on the clinopyroxenes are not completely reliable, reasonably reproducible results were obtained using unaltered, twinned crystals with few exsolution lamellae. The compositional zonation of the augite crystals was too small to be determined by optical methods. Compositions of the clinopyroxenes are shown on the pyroxene quadrilateral (fig. 7). The clinopyroxenes are mainly diopsidic augites but an overall iron enrichment trend can be observed.

Calcium-poor pyroxenes are present in small amounts in only some of the olivine gabbros. These normally occur as rims bordering olivine crystals or in small crystal aggregates associated with amphibole, serpentine and magnetite which appear to be replacing the olivine. Orthopyroxene does not appear to have crystallized directly from the magma, but it is not possible to tell whether the orthopyroxene and abundant magnetite represent oxidation of the olivine or a reaction replacement. Optical data from a number of orthopyroxenes indicate that

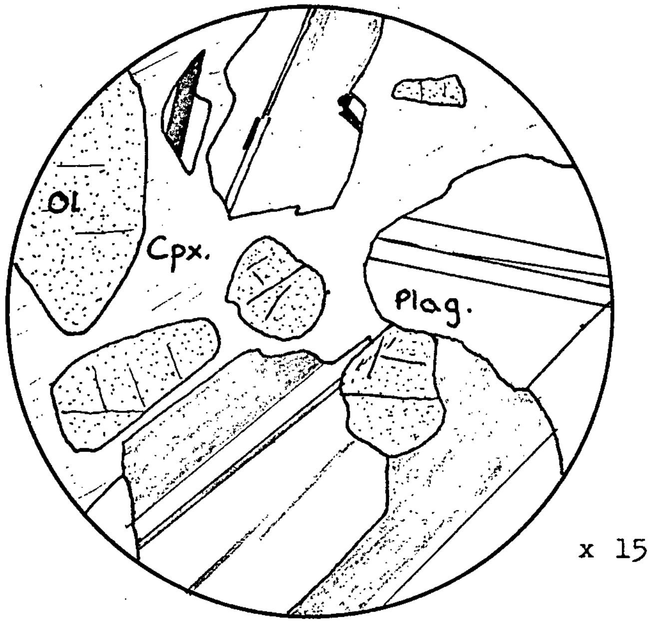


Figure 6. Plagioclase and olivine poikilitically enclosed in clinopyroxene.

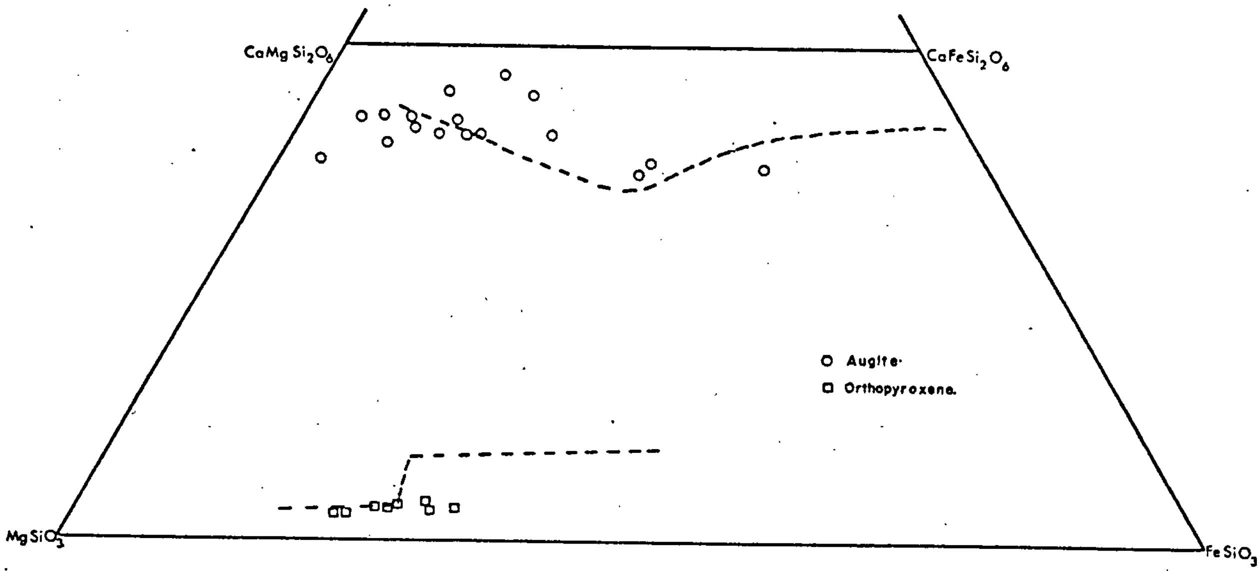


Figure 7. Pyroxene compositions - trends of Skaergaard pyroxenes are shown by the dashed lines.

they vary in composition from bronzite to a relatively magnesian rich hypersthene (fig. 7).

Olivine in the gabbro does not normally constitute more than 15 per cent of the rock. Olivine has crystallized early and apparently almost coeval with early formed plagioclase. Olivine occasionally encloses small laths of this early plagioclase all of which is a very calcic bytownite (Table II). In the fresh rock the olivine forms subhedral crystals which are commonly embayed at the margins. Deformation lamellae in olivines are common in gabbros containing complexly twinned plagioclase. Most olivine present in the gabbro shows various stages of reaction and alteration ranging from a slight exsolution of magnetite and rimming by orthopyroxene to crystals which are completely pseudomorphed by aggregates of iddingsite, chlorite, serpentine and various other olivine alteration products. The composition of the olivine in the gabbros is forsteritic. Samples analysed by X-ray methods range from Fo.82 to Fo.67 (Table III).

Small amounts of magnetite are present in the olivine gabbro. Textural relations indicate that some of the magnetite which occupies interstitial spaces has crystallized late from the magma. Other clots and blebs of magnetite are derived, as previously noted, from the breakdown of olivine. Ilmenite, recognised in polished samples, is present in very minor amounts. Other accessory minerals found in the olivine gabbro are apatite, zircon and rare sulphide. An analysis of olivine gabbro is given in column 1 of Table V.

Microscopic textures in samples of the East Sooke gabbro clearly demonstrate that there is a definite sequence of crystallization of the main mineral phases. Olivine is commonly enclosed by both plagioclase and clinopyroxene. Only in a few samples does olivine enclose small laths of extremely calcic bytownite. Pyroxene is commonly interstitial to both plagioclase and olivine and usually encloses both these minerals poikilitically (fig. 6). Olivine appears to have crystallized first, closely followed and somewhat overlapped by the crystallization of plagioclase. Clinopyroxene which has crystallized contemporaneously with most of the later formed plagioclase, has persisted late in the crystallization sequence. Magnetite, which has crystallized late, occupies interstitial spaces between the silicates but seldom grows large enough to produce a poikilitic texture. There is little evidence that a cumulus mechanism has operated on a large scale within the magma chamber as true cumulus textures are seldom seen, except in the olivine-rich gabbro.

URALITIZED GABBRO

Olivine gabbro, which forms the core of the intrusion, grades into uralitized gabbro at the margins by gradual disappearance of olivine and gradual increase in the intensity of uralitization. The mapped distribution of uralitized gabbro corresponds in general with the augite gabbro mapped by Cooke. The change from olivine gabbro to uralitized gabbro can be distinguished in hand specimen as a progressive replacement of greenish olivine by brown alteration products.

Microscopic examination shows that, though the uralitized gabbro is texturally similar to the olivine gabbro, the mineralogy exhibits certain differences. Plagioclase cores in the uralitized gabbro are less calcic than those of the olivine gabbro and range between

An. 65 and An. 70 in composition (Table I). The plagioclase is also more strongly zoned in the uralitized gabbro.

Almost all the augite is altered to a hornblende amphibole and only relict cores or blebs of pyroxene remain within the amphibole. The amphibole is invariably an alteration mineral and has not crystallized as a primary magmatic mineral.

Small clots of chlorite, amphibole and iddingsite surrounded by orthopyroxene are common in many of the least altered gabbros. Occasionally small remnant cores of olivine occupy the centres of the clots. These rounded clots are therefore considered to be pseudomorphs formed by the alteration of olivine.

The uralitized gabbro therefore appears to be an altered equivalent of the olivine gabbro of the core area. The alteration is believed due to hydrothermal activity and is discussed more fully in a later section.

PLAGIOCLASE- AND OLIVINE-RICH PHASES OF THE GABBRO

Plagioclase- and olivine-rich phases of the normal olivine gabbro constitute only a small part of the gabbro intrusion and are gradational into the olivine gabbro. Although most of the plagioclase-rich gabbros are in the vicinity of Mt. Maguire, they also occur elsewhere as minor bands and pods within the olivine gabbro.

The plagioclase-rich gabbro is not a true anorthosite but is rather a feldspathic phase of the olivine gabbro. Plagioclase in the rock seldom exceeds 65 per cent (Table IV). Many plagioclase-rich varieties of the gabbro are coarse-grained. Large plagioclase crystals and minor olivine are poikilitically enclosed by large interstitial clinopyroxenes which are commonly uralitized.

A strong foliation caused by a planar alignment of tabular feldspars and occasionally of other minerals is usually developed in the plagioclase-rich gabbro. The foliation, evident both in hand specimen and thin section, is invariably steeply dipping or vertical.

Olivine-rich gabbros or hornblende peridotites occur near the eastern margin of the intrusion. These contain as much as 50 to 60 per cent olivine. Pyroxene and minor plagioclase make up the remainder of the rock. The plagioclase is a calcic bytownite approaching anorthite in composition. Olivine forms the cumulate framework of the rock while plagioclase and pyroxene have crystallized in the interstitial spaces. Pyroxene, as in the normal olivine gabbro, has crystallized last and poikilitically encloses the other mineral phases. A platy mineral foliation in the olivine-rich gabbros is also steeply dipping but is less obvious than that seen in the plagioclase-rich gabbro.

LEUCOCRATIC QUARTZ DIORITES

Small bodies of leucocratic quartz diorite, previously mapped as granites and aplites by Cooke, are intruded into the gabbro. Most of these are dykes and pods which irregularly cut across the gabbro and are too small to be shown on the geological map. The largest area of leucocratic quartz diorite, on the western edge of the peninsula, is an irregular dyke-like pod which cuts across the foliation in the gabbro. It therefore appears to have been intruded after the main mass of the gabbro had solidified.

The leucocratic quartz diorites consist mainly of plagioclase and quartz with minor amounts of green amphibole. The plagioclase which makes up approximately half the rock is strongly zoned from cores of andesine composition to albite-oligoclase margins. Fractures which cut the plagioclase are bordered by a thin band of sodic plagioclase. Quartz forms up to 20 per cent of the rock. The amphibole is hornblende and is generally present only in minor quantities. In decreasing order of abundance, magnetite, epidote, sphene and zircon are the accessory minerals.

The leucocratic quartz diorite is thought to represent a late differentiate product of the gabbroic magma.

BASALTIC DYKES

Many narrow, fine-grained basaltic dykes intrude the gabbro cutting across both foliation and layering. Although most of these are less than twelve inches wide, are sharply bounded by matching walls and show no chilling at the margins, there are exceptions. A number of dykes have irregular embayed contacts with the gabbro and show metasomatic relations. In these the gabbro is depleted in ferromagnesian minerals for up to two inches away from the dyke contact (fig. 8).

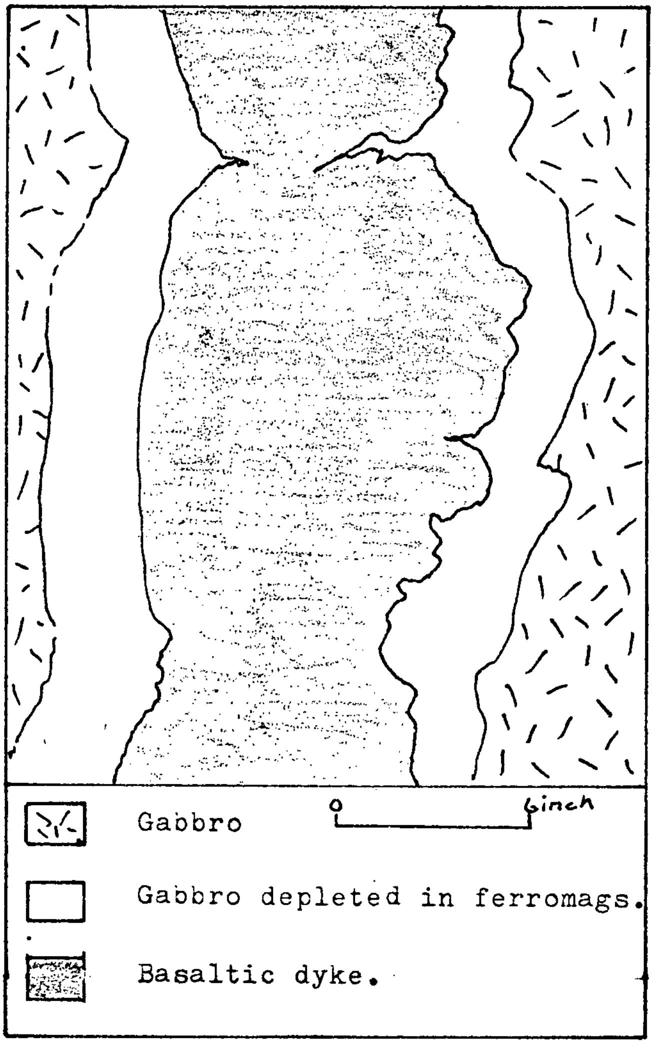


Figure 8 Metasomatic reaction at dyke contacts.

STRUCTURAL RELATIONS OF THE INTRUSIVE ROCKS

Internal structures - Xenoliths.

In the southwestern part of the area the gabbro encloses many xenoliths and screens of basaltic Metchosin country rock. Some of the inclusions are large, with dimensions in the order of a few hundred feet. Others are small angular fragments with a matrix which is generally gabbroic but in certain areas is the late leucocratic quartz diorite.

The mineralogy of the inclusions is similar to that of the gabbro except that in the inclusions, olivine is lacking and magnetite is more abundant. Like the gabbro, the inclusions have undergone variable uralitization. There are however distinct textural differences between the inclusions and the gabbro. In the least recrystallized inclusions the diabasic texture or porphyritic fine-grained texture of the basalts is retained. These least recrystallized rocks are generally found near the periphery of the intrusion as large screens. Some of the xenolithic blocks have become extremely coarse-grained at the margins in contact with the gabbro and show a gradational decrease in grain size from the margins towards the centres of the xenoliths. In other inclusions the distinct porphyritic texture of the porphyritic volcanics is preserved. Smaller inclusions further away from the probable gabbro-basalt contact have been more extensively recrystallized and have become almost as coarse-grained as the gabbro. Microscopically, the recrystallized inclusions show a medium- to fine-grained mosaic of interlocking plagioclase and pyroxene crystals. In the porphyritic varieties containing large bytownite plagioclase phenocrysts, the matrix consists of small, equant plagioclase and pyroxene crystals (fig.10). Some of the most completely recrystallized basalt inclusions exhibit unusual graphic plagioclase and pyroxene intergrowth textures (fig. 12). A sequence of recrystallization textures from the moderately recrystallized basalts to almost completely reconstituted rocks which are as coarse-grained as the gabbros can be observed microscopically (figs.10 - 12). In figure 11 the pyroxene crystals are beginning to coalesce giving rise to a texture which is believed to be the precursor of the graphic texture shown in figure 12.

The structural states of a number of plagioclase phenocrysts from the inclusions were determined optically. Cores of these phenocrysts generally exhibit high intermediate structural states, typical of the disordered structure of quickly quenched volcanic rocks while the margins of the phenocrysts show the low structural state more typical of intrusive rocks. It seems strange that the structural state of the cores did not change also. It is possible that a chemical control as well as a temperature difference is reflected in the ordering of domains near the crystal margins.

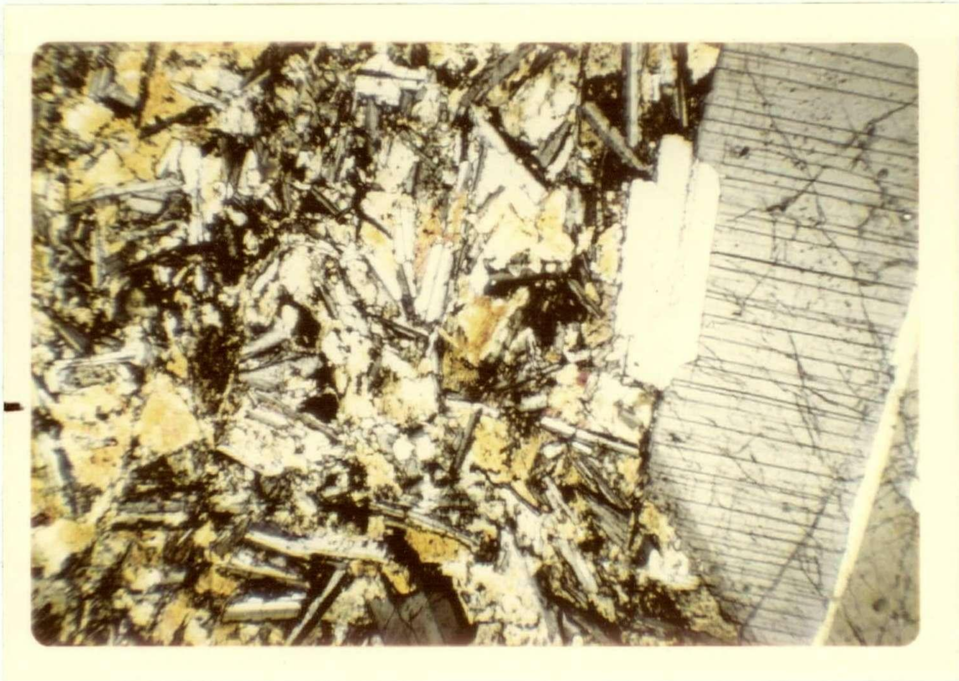


Figure 9. Porphyritic basalt - phenocrysts of plagioclase set in a groundmass of plagioclase and amphibole.

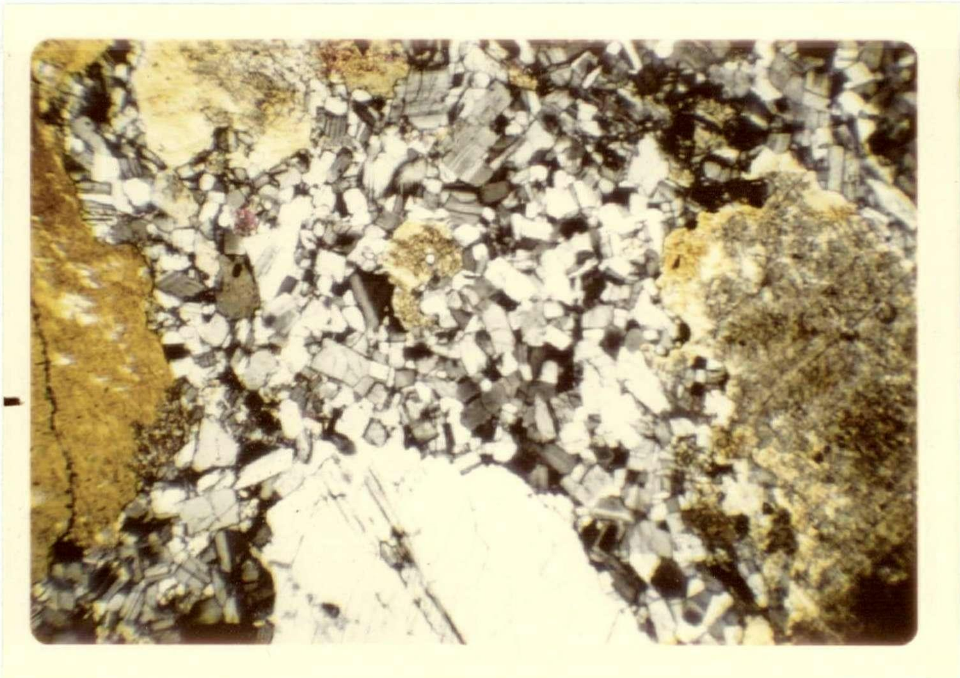


Figure 10. Partially recrystallized basalt; uralitized pyroxene - brownish-yellow and plagioclase - grey and white.

Figure 11. Recrystallized basalt; plagioclase - greys, clinopyroxene - blue green.

Figure 12. Recrystallized basalt, graphic intergrowth of plagioclase and clinopyroxene.

- Foliation, lineation and layering.

There is no obvious layering or banding of cumulate nature within the gabbro, but at numerous localities a mineral lineation and foliation are well developed. A common feature of the gabbro is a steeply plunging lineation which is produced by a linear arrangement of ferromagnesian minerals and occasionally tabular plagioclase. Foliation is shown by a planar orientation of individual plagioclase and pyroxene crystals and in some areas intergrades with a thin banding or layering of the gabbro. The layering is caused by the partial separation of leucocratic and melanocratic crystals into thin layers which give the rock a fine banded appearance (fig. 13). Foliation and layering are almost everywhere steeply dipping or vertical (Map C). In some localities the foliation is parallel to the contact between the gabbro and the basalt but this is not a general rule as the foliation swings around in an irregular manner. Foliation, and in some places layering are seen to wrap around discrete autolithic blocks of gabbro which contain no structure. Some of these blocks are round and the margins frequently show evidence of assimilation by the enclosing gabbros. In other places gabbroic rocks of slightly differing texture and mineralogy exhibit complex intrusive relations with each other, implying injection of magma subsequent to at least the partial crystallization of earlier gabbro.

Figure 13. Thinly banded gabbro.

- Shear Zones.

The gabbros are extensively fractured on all scales from minor jointing to extensive shear and fracture zones which show up as marked topographic lineaments. Map D, prepared directly from air photographs, shows the distribution of these lineaments. A strong north and northeasterly trend is evident. A strike frequency diagram (fig. 14) based on 739 measurements of strikes of fractures and shear zones shows a predominant northeasterly trend. An indistinct northerly trend of fractures can also be distinguished.

Shear zones are now represented by wide areas of highly altered rock. Movement has taken place even after the alteration as secondary hornblende is in many cases fragmented and granulated. Certain shear zones within the gabbro are not strongly amphibolitized. These may be later or may not have opened enough to allow the passage of hydrothermal or deuteric solutions. In these shear zones flaser gabbros show extreme microbrecciation and mylonitization of fresh pyroxene and plagioclase which in some cases are preserved as angular fragments within the microcrystalline sheared rock. The mylonitic zones vary in extent from microscopic bands of crush material which cuts across strained but unaltered rock to zones of mylonitic gabbros up to ten feet wide. Jointing is common throughout both gabbro and basalt. Joint patterns are varied and complex and no regularity could be determined even among conjugate joint sets.

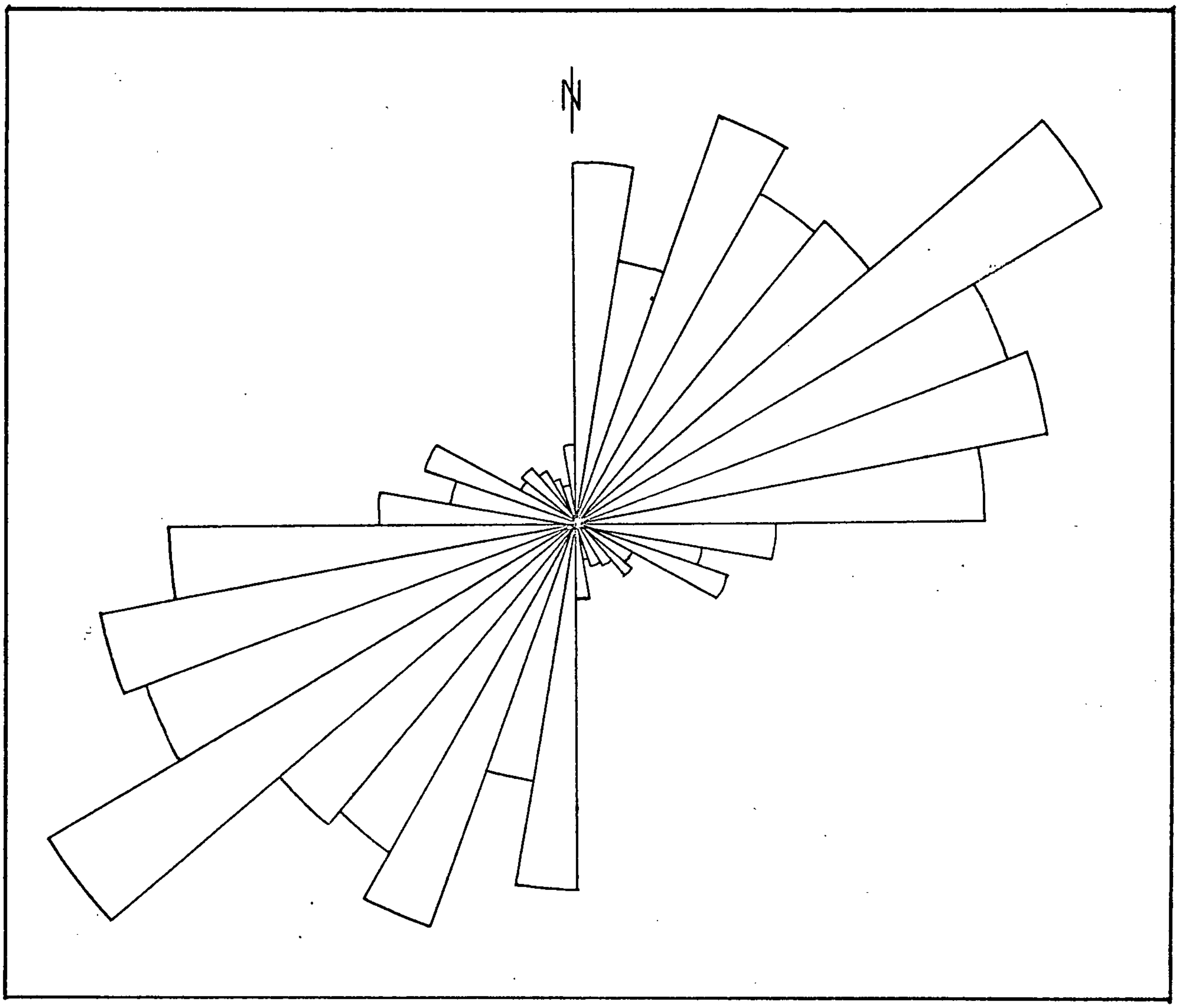


Fig. 14

Strike frequency diagram of air photograph lineaments.

(739. measurements)

- External structure.

The gabbro is in intrusive contact with the Metchosin volcanics along the north east margin of the body and at Hill Head and Pim Head on the northern coast. Small occurrences of basalt in contact with the gabbro are found at Company Point on the west coast and at Creyke Point on the east.

Many easily recognizable screens and xenoliths are found along the southwest coast facing Juan de Fuca Strait. They are also recognizable near the gabbro basalt contact in the northeastern part of the area but are difficult to trace because of heavy overburden. The preponderance of screens along the southern coast also suggests that the margin of the intrusion is just offshore. The East Sooke gabbro therefore appears to be flanked on all sides by the basalt.

The steeply dipping contact between the gabbro and Metchosin basalts to the northeast of the area is a sharp, intrusive contact with no evidence of faulting. The Metchosin basalt near the contact has, as already described, been recrystallized and the texture reconstituted. The gabbro shows no evidence of chilling and was probably intruded while the basalts were still hot.

DIFFERENTIATION

There is some evidence of differentiation in the gabbro intrusion but its effects are obscured by alteration caused by late hydrothermal or deuteric processes which are responsible for a zonal pattern of alteration towards the periphery and shear zones.

Universal stage work on calcium-rich clinopyroxenes shows that there is a change in composition which is primarily a progressive replacement of Mg by Fe^{++} (fig. 7). The crystals also show a zoning to more iron rich margins. The calcium content throughout the samples remains fairly constant between Ca_{38} and Ca_{47}. Compositional trends of augitic clinopyroxenes from the East Sooke intrusion are approximately parallel to the early part of the Skaergaard trend and augite composition trends in numerous other differentiated intrusions of basaltic composition.

Compositions of orthopyroxenes coexisting with the clinopyroxenes also exhibit a similar trend of iron enrichment (fig. 15).

If locations of clinopyroxenes whose chemical compositions are known are plotted on the map (fig. 17) it is seen that there is a tendency for the more iron-rich pyroxenes to occur near the periphery of the intrusion. The gabbros, therefore, seem to exhibit a zonal pattern of differentiation and the trend of pyroxene compositions is presumed to reflect equilibrium crystallization of pyroxene from successively more iron-rich liquids formed by fractional crystallization. This zonal pattern of differentiation is, however, different from the usual case where the border is more basic than the core.

Olivine compositions are magnesian rich and range from Fo82 to Fo67. Some of the less forsteritic olivines occur in the peripheral zone of the gabbro but the correlation of increasing iron content with the peripheral gabbros is much less obvious than even that observed among the clinopyroxenes (fig. 18). Although tie lines between co-existing olivines and pyroxenes do not show a consistent correlation (fig. 16), the range in composition of the olivines is also thought to represent the same differentiation trend whereby later fractions of the magma become progressively enriched in iron.

Plagioclase compositions within the olivine gabbro show a slight variation. In fresh rocks containing forsteritic olivine, the plagioclase is a calcic bytownite and although there are several exceptions, the more iron-rich olivines are found in rocks which contain sodic bytownite (fig. 16). The plagioclase of the unaltered olivine gabbro is only very slightly zoned, much of the individual crystal being uniform in composition with only narrow rims of slightly less calcic plagioclase at the crystal margins. These less calcic rims are caused, at least in part, by enlargement of the original plagioclase crystal by successive growth of material from the cooling magma. Differentiation of the basaltic magma which formed the olivine gabbro is therefore thought to be the cause of both the variation in composition and normal zoning of the plagioclase.

The most important mechanism of differentiation in basaltic magma is generally considered to be fractional crystallization, whereby early formed crystals are effectively removed from the magma. In the early stages of crystallization, separation of magnesian olivine and pyroxene increases the FeO/MgO ratio in the melt. The liquid also becomes

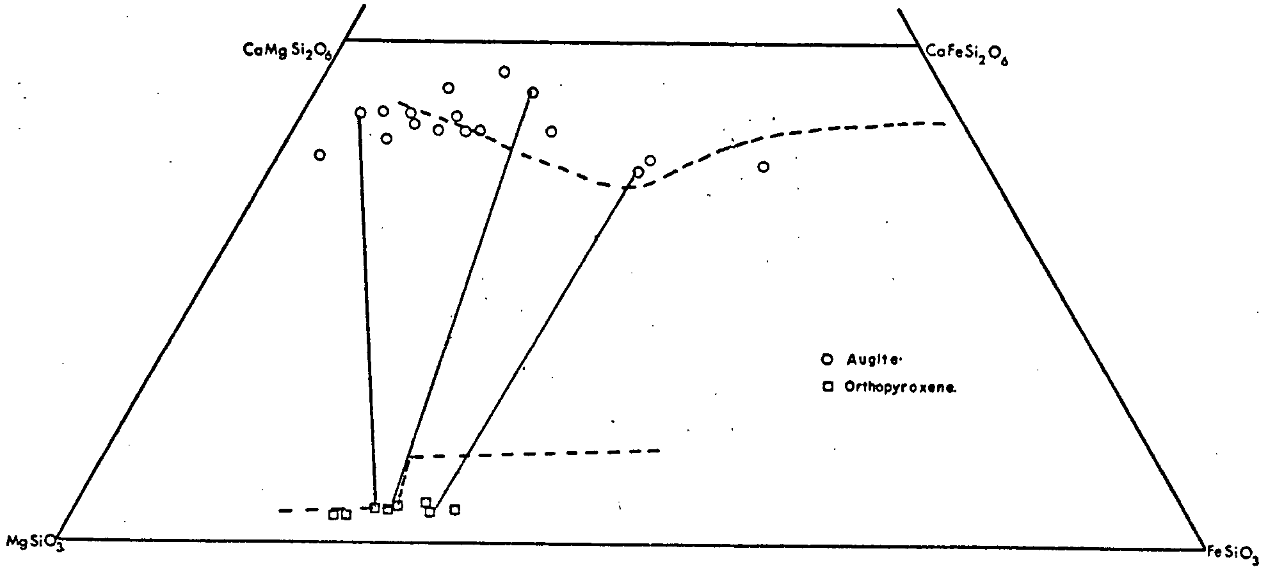


Figure 15 Coexisting pyroxenes

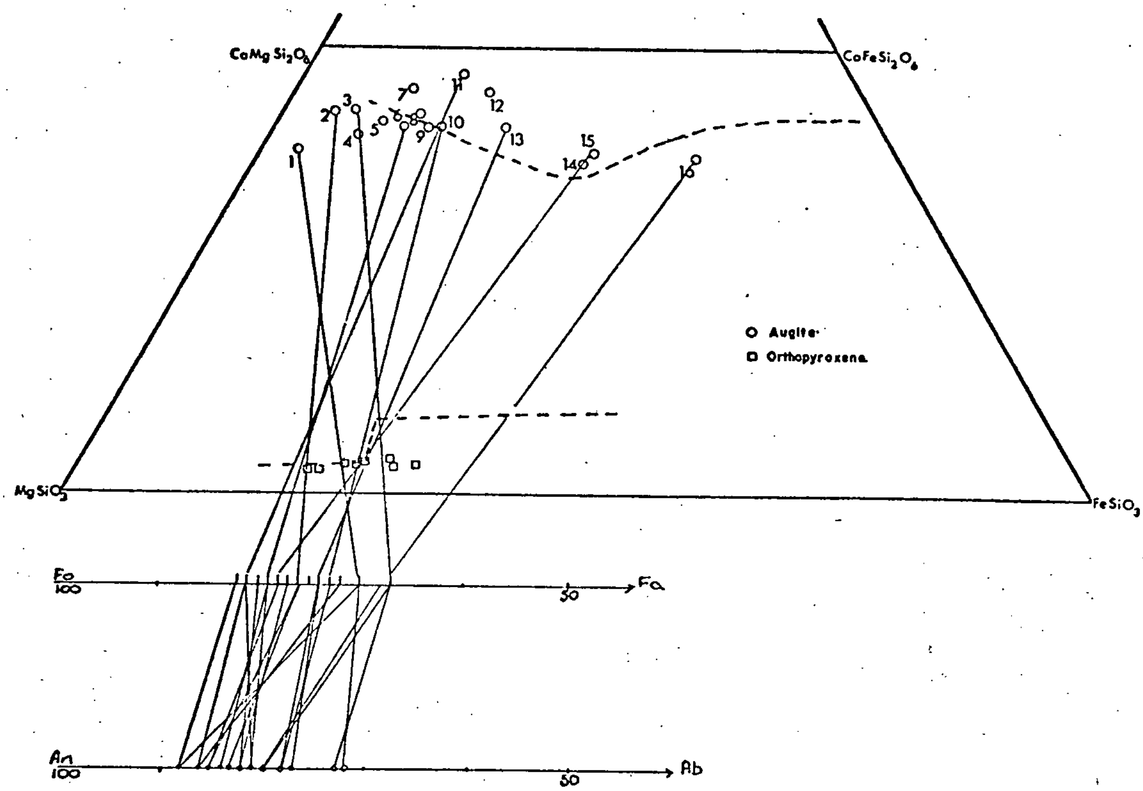


Figure 16 Coexisting clinopyroxene, olivine and plagioclase

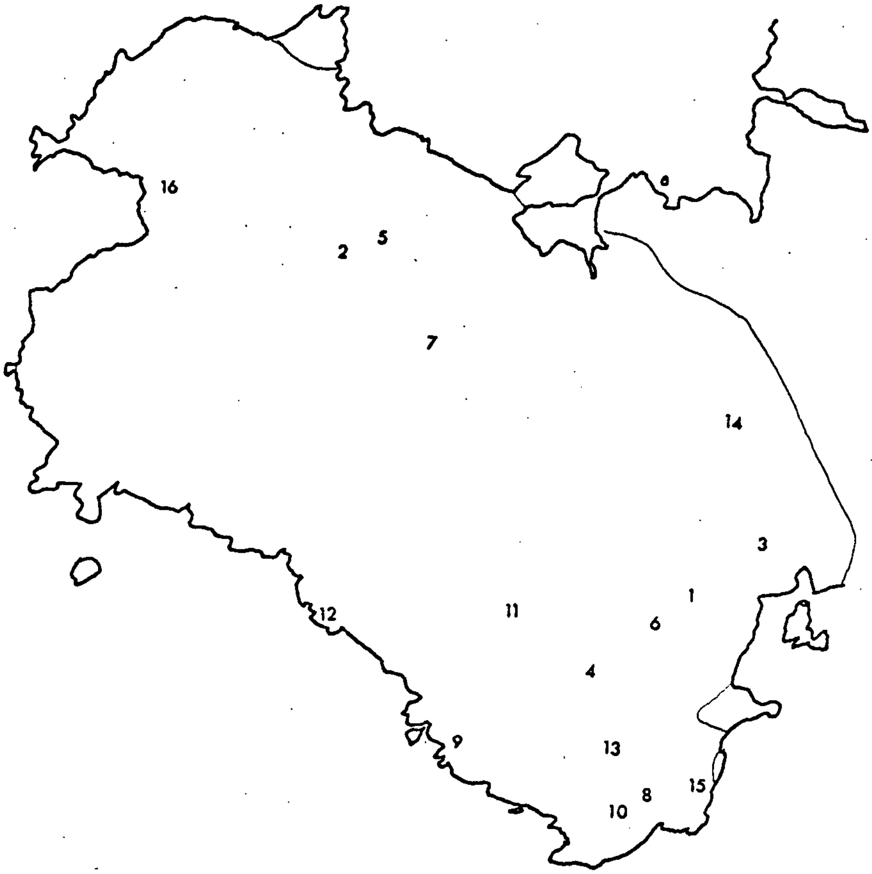


Figure 17. Distribution of analysed clinopyroxenes. cf. fig.16 for compositions.

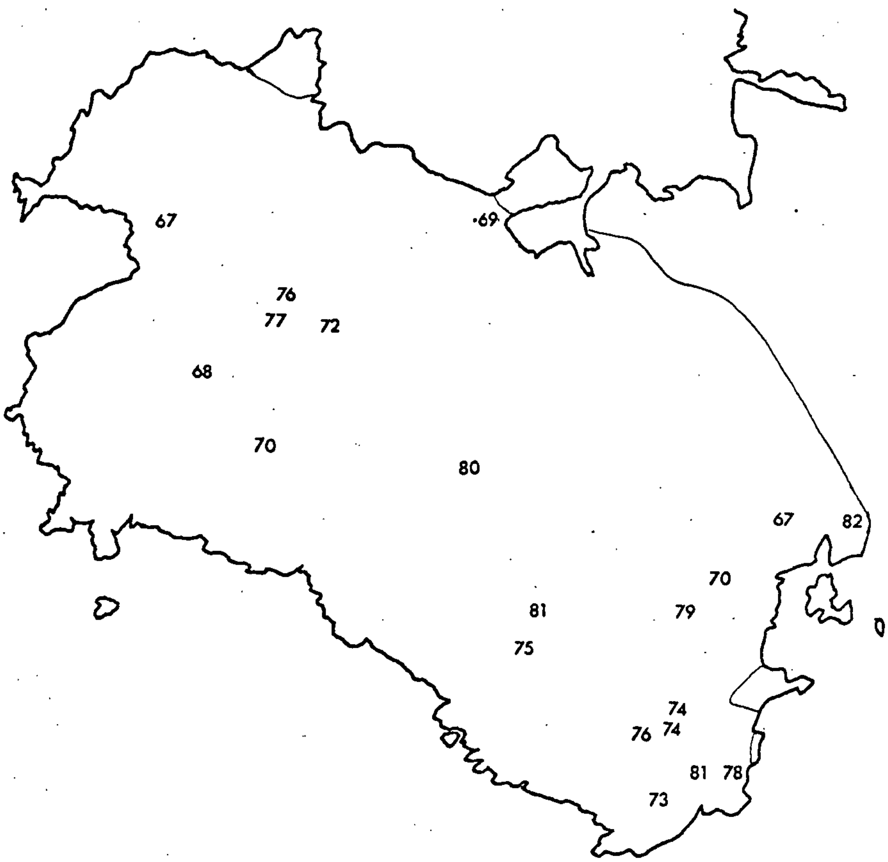


Figure 18. Distribution of analysed olivines - %Fo.

comparatively enriched in silica which may even become concentrated in excess of the amount corresponding to pyroxene-plagioclase mixtures. In the later stages of crystallization, a filter-pressed residual liquid may become greatly enriched in soda, potash and silica with corresponding impoverishment in alumina and lime.

There is ample textural evidence that olivine appeared early in the crystallization of the gabbro and was as a rule not susceptible to reaction with the magma as it was enclosed by pyroxene or plagioclase. Since the olivine is magnesian, the FeO/MgO ratio in the melt would be expected to increase.

Residual leucocratic differentiates, enriched in sodium, potassium and silica and impoverished in alumina and calcium are probably represented by the leucocratic quartz diorites. These leucocratic differentiates are probably filter-pressed residual liquids subsequently injected as dykes and pods into gabbro which had already completed crystallization.

Differentiation by fractional crystallization requires that the early formed crystals be effectively separated from the magma to prevent any possible equilibrium readjustments with the magma. Gravity settling is the most frequently invoked mechanism of removing crystals from the melt. Gravity settling aided by both intermittent and steady convection currents is the major mechanism of differentiation in the Skaergaard intrusion and there is abundant well documented evidence of gravity stratification and other 'sedimentary' features. (Wager and Brown 1967).

The gabbros of East Sooke do not exhibit any obvious large scale gravity stratification. Only locally is there any evidence that gravity settlement has occurred. Fractionation by gravity settling must therefore have played only a minor part in the differentiation of the Sooke gabbro. There is also no detectable cryptic variation in composition of any of the minerals over the height of the exposed rocks, further evidence that the mechanism of differentiation in the East Sooke gabbro intrusion was fundamentally different from that which operated in the Skaergaard intrusion.

Other processes of differentiation may have operated at East Sooke. The observed outcrop of olivine-rich rocks would seem to fit the pattern expected for flowage differentiation. Flowage differentiation is an experimentally demonstrable process capable of causing crystal and chemical fractionation in nature (Bhattacharji and Smith 1964). It is believed to be a possible mechanism for forming olivine-rich rocks in a vertical or steeply dipping position without prior concentration on a flat floor. It seems probable that this type of mechanism rather than cumulate, gravity settling formed the olivine-rich gabbros of East Sooke. If cumulate settling had occurred, it is difficult to explain why all the observed layering is almost vertical rather than horizontal or sub-horizontal as is the case in typical cumulate layered intrusions.

EMPLACEMENT OF THE GABBRO

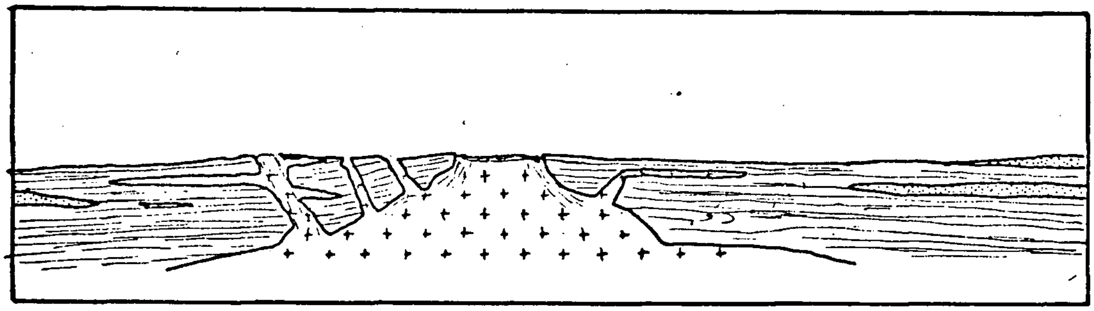
The abundant inclusions and screens of basalt within the gabbro suggest that stoping of the volcanic country rock has at least played some part in providing room for the intrusion. Some of the basalt inclusions are completely recrystallized. Basalts in contact with the intrusion have also been subject to recrystallization and have developed a linear fabric parallel to the contact. Such complex contact relations would probably exist in the lower levels of a volcanic pile, where a conduit supplying magma to the ever growing pile would eventually be expected to produce intrusive relations in the earlier formed volcanics. The observed recrystallization of volcanic rocks in contact with the gabbro may be explained by this mechanism whereby magma rising in the conduit to supply the higher level flows would probably heat and even partially remelt the earlier solidified but still hot basalt flows. The inclusions of basalt in the gabbro probably represent blocks of basaltic country rock stoped from the walls of the conduit by the rising magma, which in turn caused the recrystallization of the inclusions.

The foliation, lineation and minor layering observed in the gabbro are believed to be flow structures developed in a crystal 'mush' of magma rising up the vent. Flow foliation and layering is a widely recognized phenomenon in lavas and intrusive rocks (Balk 1937), and is believed by Thayer (1963) to be the principal kind found in alpine peridotite-gabbro complexes. The structures seen in the gabbros of East Sooke are therefore considered to be flow structures formed during the flow of a partially crystallized magma through the volcanic vent. The irregularity in flow foliation over small distances may indicate complex variations in the magmatic currents in the volcanic conduit. Successive pulses of magma surging up the vent have displaced and engulfed blocks of earlier and at least partly crystalline gabbro. These are the autolithic blocks around which the flow foliation is wrapped. The poorly defined pattern of differentiated rocks within the intrusion may also indicate that the intrusion represents a volcanic vent, periodically recharged by influxes of parental magma.

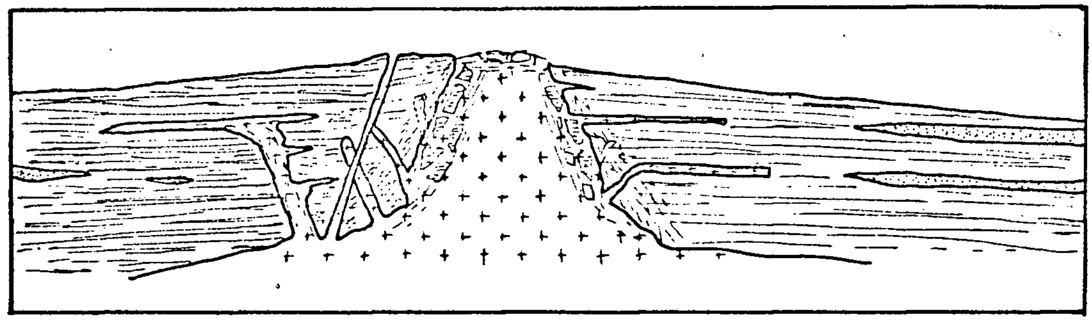
The Metchosin basalts, fed from feeders now represented by the gabbro intrusions, are thought to have built up from the ocean floor in a manner comparable to the build-up of the Hawaiian Islands. A schematic representation of this is shown in figure 19.

AGE OF THE GABBRO

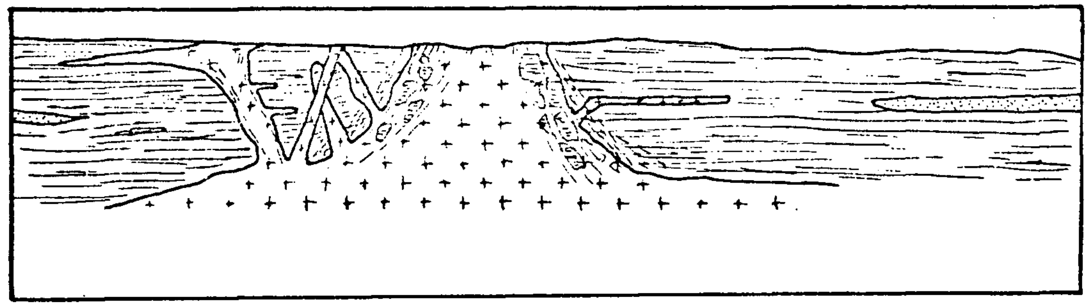
An age of thirty-nine million years from potassium-argon determinations on hornblende in the gabbro is quoted by Carson (1968). A potassium-argon age of 44±6 million years from hornblende in altered Metchosin basalts is given by Kirkham (G.S.C. 70-36). Since amphibolitization of both basalts and gabbro is believed to be related to late hydrothermal circulation caused by the gabbro, these dates are considered to approximate the late stages of magmatic activity. Much of the intrusive activity seems therefore to have taken place during the Late Eocene.



Stage 1. Extrusion of basaltic lava as a pillowed sea floor sequence.



Stage 2. Continuing build up of basaltic lava flows around fissure in a manner similar to the Hawaiian Islands. Development of flow foliation in a partially crystalline magma- xenoliths and screens - recrystallization of earlier extruded basalts during this stage.



Stage 3. Erosion to present level.

Figure 19 . Schematic representation of the build up and subsequent erosion of the volcanic pile.

ALTERATION OF THE GABBROS

Primary magmatic minerals of the gabbro and basalt are pervasively altered in certain areas. Alteration is most intense along fractures and shear zones in both gabbro and surrounding basalt. Uralitized gabbros characterize the peripheral parts of the intrusion. The alteration which generally results in the formation of hydrous phases is probably caused by hydrothermal fluids circulating along fractures and shear zones.

Prior to alteration the intrusion was probably a relatively homogeneous and only slightly differentiated olivine gabbro consisting of slightly zoned calcic bytownite, calcic augite and subordinate forsteritic olivine. It is maintained that, from this rock, variable hydrothermal action produced progressive amphibolitization towards the periphery of the intrusion. Hydrothermal fluids are also responsible for the increasing intensity of alteration towards shear zones and fractures where the gabbro is almost totally replaced by a hornblende rock containing magnetite, pyrite and chalcopyrite.

A sequence of alteration from the fresh olivine gabbro of the core region to the uralitized gabbros of the periphery and fracture zones is well seen in thin sections. Olivine which in the olivine gabbro generally appears as an unstable primary phase reacting to form orthopyroxene is very susceptible to hydrothermal alteration. At first serpentine and magnetite form in cracks or fractures within the olivine crystal. Consequent expansion in volume has produced fractures in adjacent primary magmatic minerals which are filled with a mixture of serpentine and chlorite. Iddingsite and bowlingite, common alteration products of

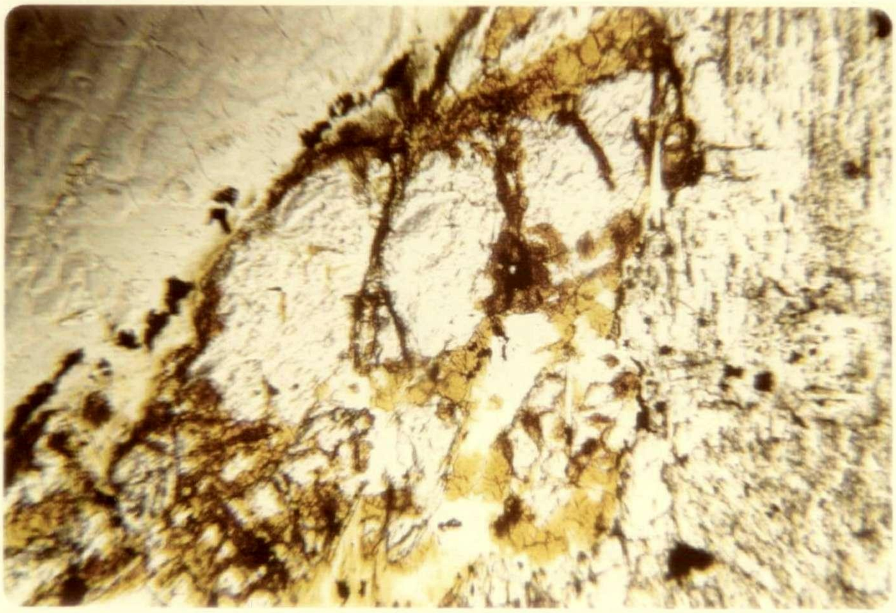


Figure 20. Incipient alteration of olivine.
Olivine- high relief mineral at centre altering to brown iddingsite and bowlingite

olivine, occur along fractures and form rims around the crystal (fig. 20). Iddingsite is reddish brown in colour and consists of haematite, goethite and an undetermined silicate. Bowlingite consists mainly of chlorite and goethite. Both of these minerals form in hydrous conditions. The formation of iddingsite from olivine is believed to be a continuous transformation in the solid state brought about by diffusion of hydrogen atoms into the structure where they become attached to oxygens and so release Mg, Fe^{2+} and Si, and allow their replacement by Fe^{3+}, Al and Ca ions. (Deer et al. 1962 Vol. 1).

The pyroxene of the olivine gabbro shows incipient alteration to a secondary brown-green hornblendic amphibole. The alteration begins at the periphery of the crystal or along cleavages and fractures and forms patchy areas of colourless pyroxene flecked with small plates of uralitic amphibole. In the least altered rocks plagioclase remains virtually unchanged, slight saussuritization being the only indication of alteration.

Further hydrothermal alteration causes increased replacement of olivine by a variety of hydrous phases. Iddingsite, chlorite, amphibole and talc are more common than serpentine as replacement products. In some specimens rims of orthopyroxene surrounding the alteration pseudomorphs provide evidence that unstable olivine within the olivine gabbro had undergone reaction to orthopyroxene before being completely replaced by the hydrous alteration products.

At this stage of the alteration sequence the pyroxene is progressively replaced by amphibole and the rock, now devoid of fresh olivine, has the mineralogy of the uralitized gabbro of the peripheral

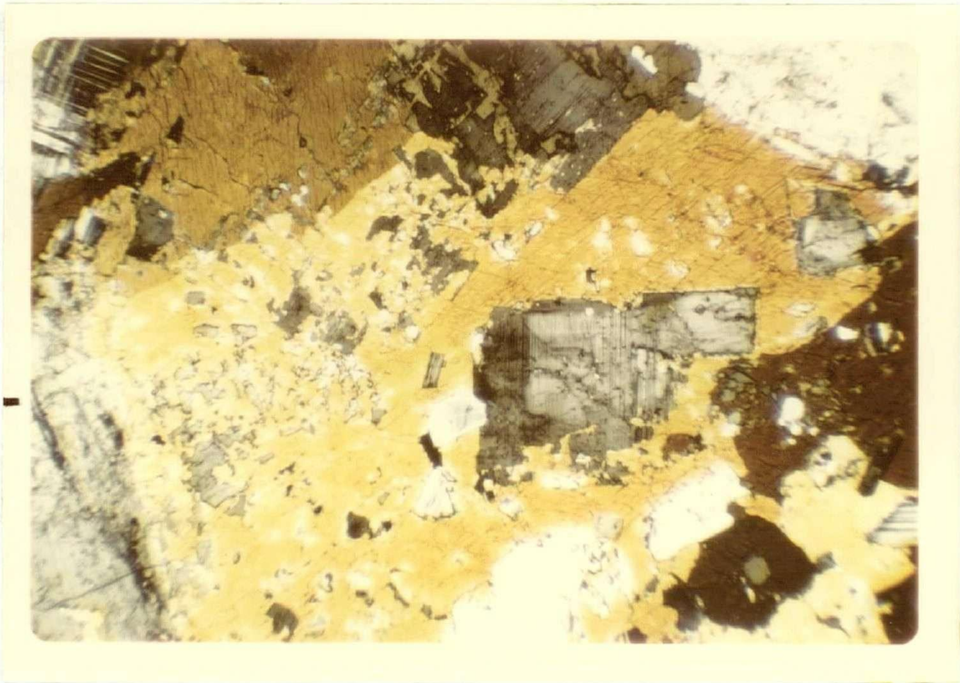


Figure 21. Replacement of plagioclase by amphibole.

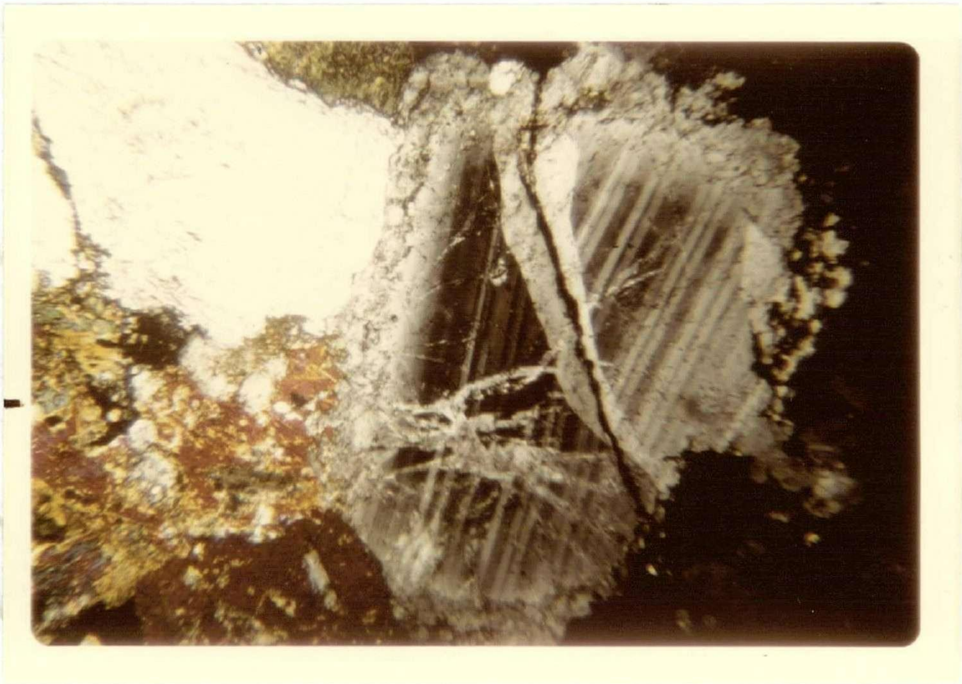


Figure 22, Plagioclase crystal - albitized along margins and fractures.

region. The plagioclase of the uralitized gabbro also shows evidence of increased alteration. Epidote is a common alteration product resulting from the breakdown of the basic plagioclase which in some of the more altered rocks is almost completely saussuritized. In highly altered rocks containing no olivine and in which the pyroxene has completely altered to amphibole, plagioclase is directly replaced by green amphibole (fig. 21).

The range of compositional zoning within the plagioclase increases in the more altered rocks. The variation of anorthite content between the cores and margins of plagioclase becomes greater with increasing intensity of alteration. In extreme cases, plagioclase with labradorite cores are zoned progressively to albiteoligoclase margins. The observed progressive zonation from cores to margins in the plagioclase of the altered rocks is not considered to be only a primary magmatic feature. Since the range in composition of the zoning in the plagioclase corresponds directly with the intensity of alteration, much of the zoning is believed to be caused by the hydrothermal activity which produced the alteration.

The anorthite content of the cores of the plagioclases in the altered rocks is significantly less than that of the plagioclases in the unaltered olivine gabbro (Table I). Although it is uncertain whether this difference is caused by primary magmatic differentiation or whether it is caused by secondary alteration processes it is significant that, even in the olivine gabbro of the core area, as intensity of alteration increases towards fractures, the anorthite content of the plagioclase decreases. This relationship is demonstrated graphically in figure 23. It seems possible, therefore, that hydrothermal alteration may have had an effect on the anorthite content of the plagioclase cores.

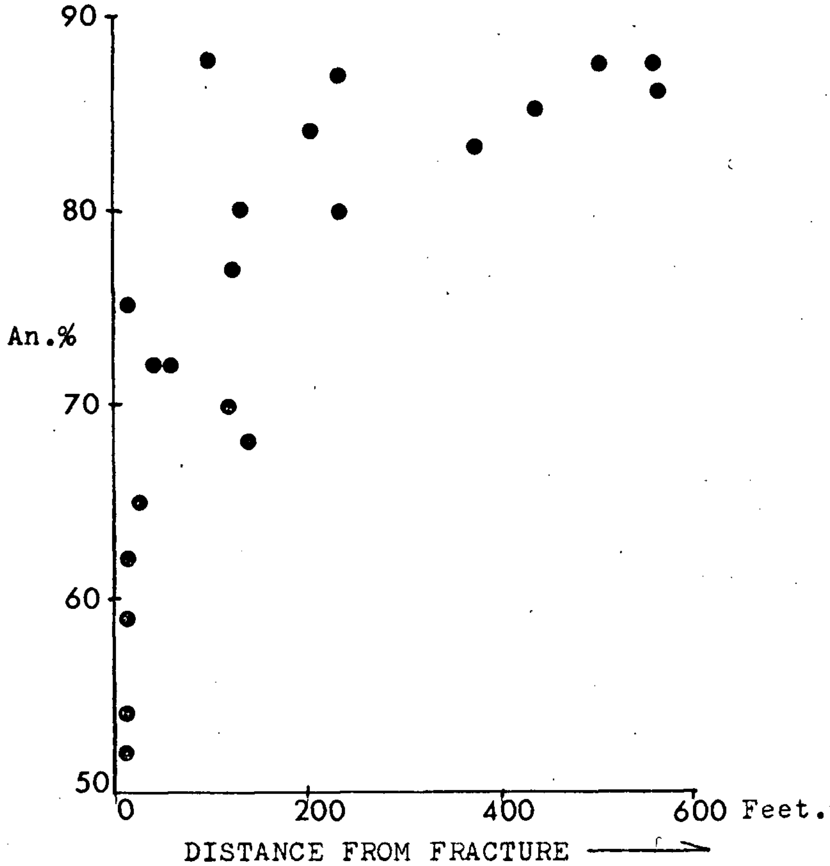


Figure 23 Relationship between anorthite content of plagioclase and major fractures.

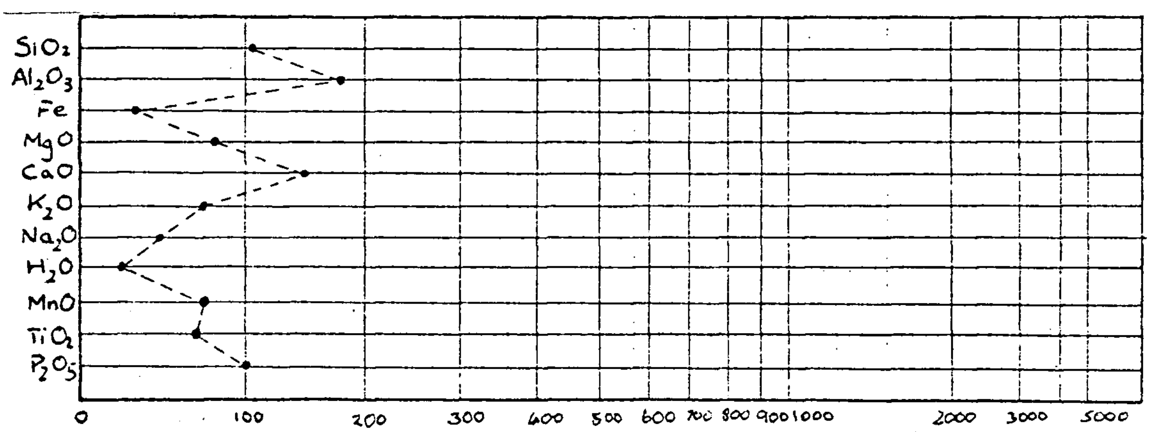


Fig.24 Diagram illustrating hornblendic alteration (Cooke 1919)

The albitization of fractured plagioclase in the altered rocks also provides evidence that hydrothermal fluids could have produced the observed compositional zoning of the plagioclase. The albitized crystals show a strong zonation towards margins of low relief plagioclase. Low relief albitic plagioclase is also seen to border fractures cutting across the crystal (fig. 22). Some crystals exhibit a zonation towards the fractures while in others there is no zoning towards the albitic plagioclase bordering the fractures. Albitic plagioclase does not seem to have been added to margins of fractures in plagioclase crystals, rather the part of the plagioclase crystal adjacent to the fractures appears to have been depleted of the anorthite component by fluids passing through fractures. These fluids are believed to be the same hydrothermal solutions which caused the alteration of the gabbros.

The albitization and possibly the strong zoning of the plagioclase is apparently caused by a progressive cation exchange mechanism since the plagioclase series is the prime example of solid solution involving a coupled substitution, Ca Al $\rightleftharpoons$ Na Si to preserve charge balance. Experimental work (Orville 1972) on plagioclase cation exchange equilibria with aqueous chloride solutions demonstrates that albitic plagioclase can be produced from anorthite-rich plagioclases by addition of silica and sodium while calcium and aluminium are removed. The probable hydrothermal or deuteric reaction cited by Orville is:

$$2NaAlSi_3O_8 + CaCl_2 \rightleftharpoons CaAl_2Si_2O_8 + 2NaCl_2 + 6SiO_2.$$

Reaction in the left hand silica-consuming direction produces an albitic feldspar product whose volume is larger than the original feldspar and therefore no opportunity exists for opening up channels in the structure by pseudomorphic replacement. In other words, once albitic feldspar has formed at the margins of crystals, it seems that no further reaction can take place and the reaction ceases. Although reaction of this type could have produced albitic zones at the margins and along fractures in plagioclase crystals it is doubtful whether it caused the zoning of the crystals before the reaction was terminated by the formation of the albitic margins.

Adams (1968) cites a mechanism of differential solution of plagioclase in supercritical water whereby plagioclase held in water at $500^{o}C$ to $800^{o}C$ at 2kb. loses albite components in solution while the anorthite components remain as a relatively insoluble residue. According to Adams, solution works inward from the surfaces of grains, producing a "reverse" compositional zoning in the plagioclase. He also noted that the anorthite component could be removed preferentially by acidic solutions. This mechanism could possibly produce the normal zoning in plagioclase by removal of anorthite in a manner similar to that which produced the reverse zoning by removal of albite.

Anomalous structural states of many of the albitized feldspars indicate that the structure has been disturbed by the alteration. The cores of the crystals consist of ordered labradoritic plagioclase in low structural state but the less calcic margins frequently show a departure from low structural state to a slightly more disordered intermediate structure (Table I). In general, plagioclase, in which the margins show partially disordered structures of intermediate states, is common within the zone of uralitized gabbro.

Most intense alteration of the gabbros and basalts occurs along or within shear, or fracture, zones. Pyroxene has been completely replaced by pleochroic green amphibole and the plagioclase is strongly saussuritized or, in more extreme cases, is replaced directly by amphibole (fig. 21). The final product of the alteration process is a hornblendite consisting of a felted mass of long bladed crystals of dark green common hornblende. Only minute interstitial grains of albitic feldspar and scapolite remain. Epidote occurs in veins and more commonly as segregation blebs and pockets. Apatite also occurs as isolated blebs surrounded by clusters of bladed hornblende.

An analysis of the hornblendite is given in column 2 of Table V. In comparison to the analysis of the olivine gabbro (column 1) the hornblendite is relatively deplete in silica, calcium and alumina but is enriched in sodium, iron, water and to a lesser extent in magnesium and potassium. This is in accord with the conclusions of Cooke (1919) who utilized a straight line diagram (fig. 24) as a convenient means of expressing graphically the character of the changes that have taken place during a rock alteration of any kind. The following description of the alteration of the gabbros and the utilization of the straight line diagram is taken from Cooke's report of 1919:

"The (straight line) diagram is made up of a number of horizontal lines, which are subdivided by vertical lines according to any convenient method. The diagram figured, which has been contrived by Mead, is so divided that a finite line represents any quantity up to infinity. One of the horizontal lines is allotted to each of the component oxides of the rock. The position of the point on each line, which represents the change of that oxide during alteration, is obtained by dividing the percentage of that component in the chemical analysis of the fresh rock by its percentage in the altered rock, and multiplying the result by 100. The points so obtained on the various horizontals may then be connected by lines. The result shows at a glance the relative gains and losses during alteration, or the absolute gains or losses if any factor is known to have remained constant. Thus, if any constituent has remained constant, then all of the constituents whose points fall to the right of the known point have decreased in absolute amount, and the constituents whose points fall to the left have increased. If weight has remained constant, i.e., if 100 grams fresh has yielded 100 grams of altered rock, then all constituents whose points lie to the right of the vertical 100-line have decreased in absolute amount, those whose points lie to the left of this line have increased. If an absolute change in weight can be determined, i.e., if 100 grams of fresh are known to have yielded 90 grams of altered rock, then the vertical line 90 is the zero line, and points to the right or left of this represent absolute losses or gains respectively. When lack of information renders it impossible to fix any point as constant, the relative gains or losses of the different constituents are all that can be determined.

In the present case no one constituent can be assumed to have remained constant, as all were probably very soluble in the hot solutions. If alumina, the most insoluble oxide, were supposed constant throughout, the curves show that a large increase both in weight and volume must have taken place, of which there is no field evidence . . . . . the hornblendite is about ten to fifteen per cent heavier, volume for volume, than the gabbro. If therefore the weight had remained constant throughout the alteration, it must have been accompanied . . . . . by decrease of volume. There is no evidence observed in the field that either have occurred. The most probable assumption appears to be that volume remained constant or nearly so. If so, the zero point for the hornblendite curve would lie between the vertical lines 110-115. . . . .

Under this assumption, leaving out of consideration the minor components of the solutions, such as K_2O, MnO, TiO_2, P_2O_5, which altogether make up less than one per cent of any of the rocks, it is seen that the hornblendite alteration resulted in slight increase of silica, large increase of iron, magnesium, soda and water, with loss of lime and alumina . . . . . It may also be seen from Figure 24, that in the main these conclusions are correct, whether the hypothesis of constancy of volume be accepted or not, as most points are so far to the right or left of the assumed vertical zero that, in order to alter their significance materially, quite inadmissable assumptions as to weight and volume changes would have to be made."

Late metalliferous solutions have caused significant mineralization in some of the hornblende bearing rocks. Pyrite, pyrrhotite, marcasite, chalcopyrite and minor magnetite are interstitial to bladed hornblende. Shear zones containing hornblende rocks are of variable width up to approximately one hundred feet wide. Since the intensity of alteration of the olivine gabbro decreases away from the shear zones at a rate generally proportionate to fracture density, it appears that the alteration pattern is a consequence of the decreasing activity of hydrous fluids away from the main shear zones.

Any explanation of the observed alteration pattern must take into account the peripheral zone of amphibolitized augite gabbros. Rocks of the peripheral zone demonstrate the same characteristics as the less intensely altered rocks found near shear zones and are believed to have formed similarly by aqueous fluids moving through the rock. Convective circulation (Norton 1972) of the fluids is believed to be caused by the hot intrusive mass. Fractures in the Metchosin country rock and gabbro intrusive appear to have considerably aided the flow of fluids and as a consequence the most intense alteration of both volcanic country rock and gabbro is found in the vicinity of fractures and shear zones.

THE MINERAL DEPOSITS OF THE EAST SOOKE PENINSULA

Copper mineralization at East Sooke was discovered in 1863 and since then various deposits have received sporadic attention. Detailed descriptions of the deposits and their history are found in the Report of the Minister of Mines, B.C. (Fyles 1963). The properties on which the mineralized zones occur are shown in figure 25. Five of the zones of copper mineralization have been explored by adits, shafts or open cuts and ore has been extracted from two of them. A zone of magnetite mineralization at Iron Mine Hill has also been subject to some underground development.

Copper deposits of the type found in the Cooke, Heustis, Griffith and Merryth zones are the most common and most important of the area. These deposits are structurally controlled by shear or fracture zones and all occur in the highly altered gabbros. The best mineralization is found in hornblende rocks at the intersection of major north and northeasterly trending shears with east-west trending shear or fracture zones.

Chalcopyrite, the common copper bearing mineral of the East Sooke copper deposits, is disseminated throughout the altered rock as an interstitial mineral between bladed hornblende (fig. 26). Many of the hairline fractures and veins in the hornblende rocks are filled with chalcopyrite. Other sulphides present are pyrrhotite, pyrite marcasite, and cubanite. The sulphides are almost totally confined to the altered gabbros and are virtually absent from the unaltered olivine gabbro. Although textures indicate that most sulphide deposition occurred

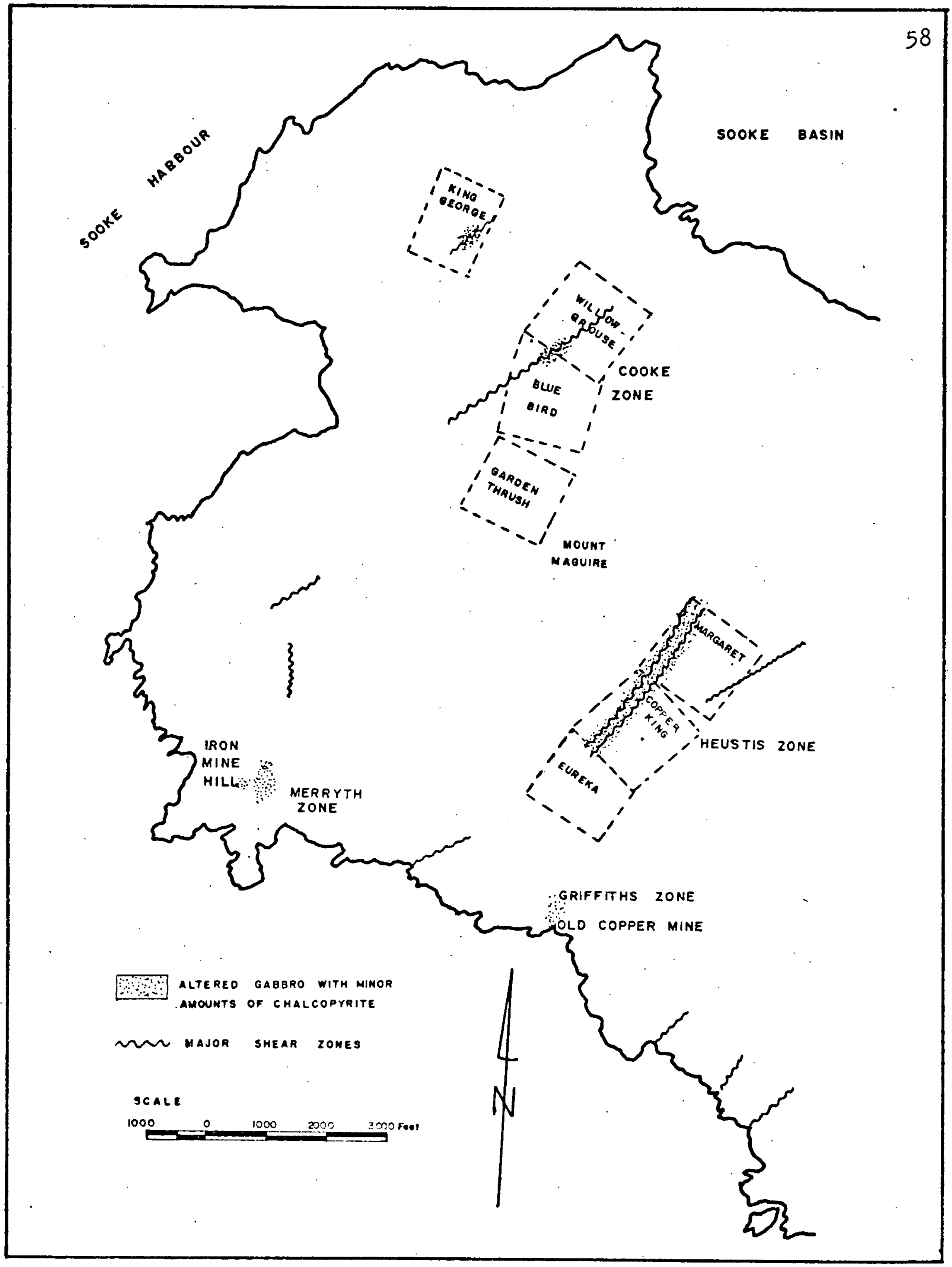


Fig. 25 Location of Mineralized Zones - East Sooke.

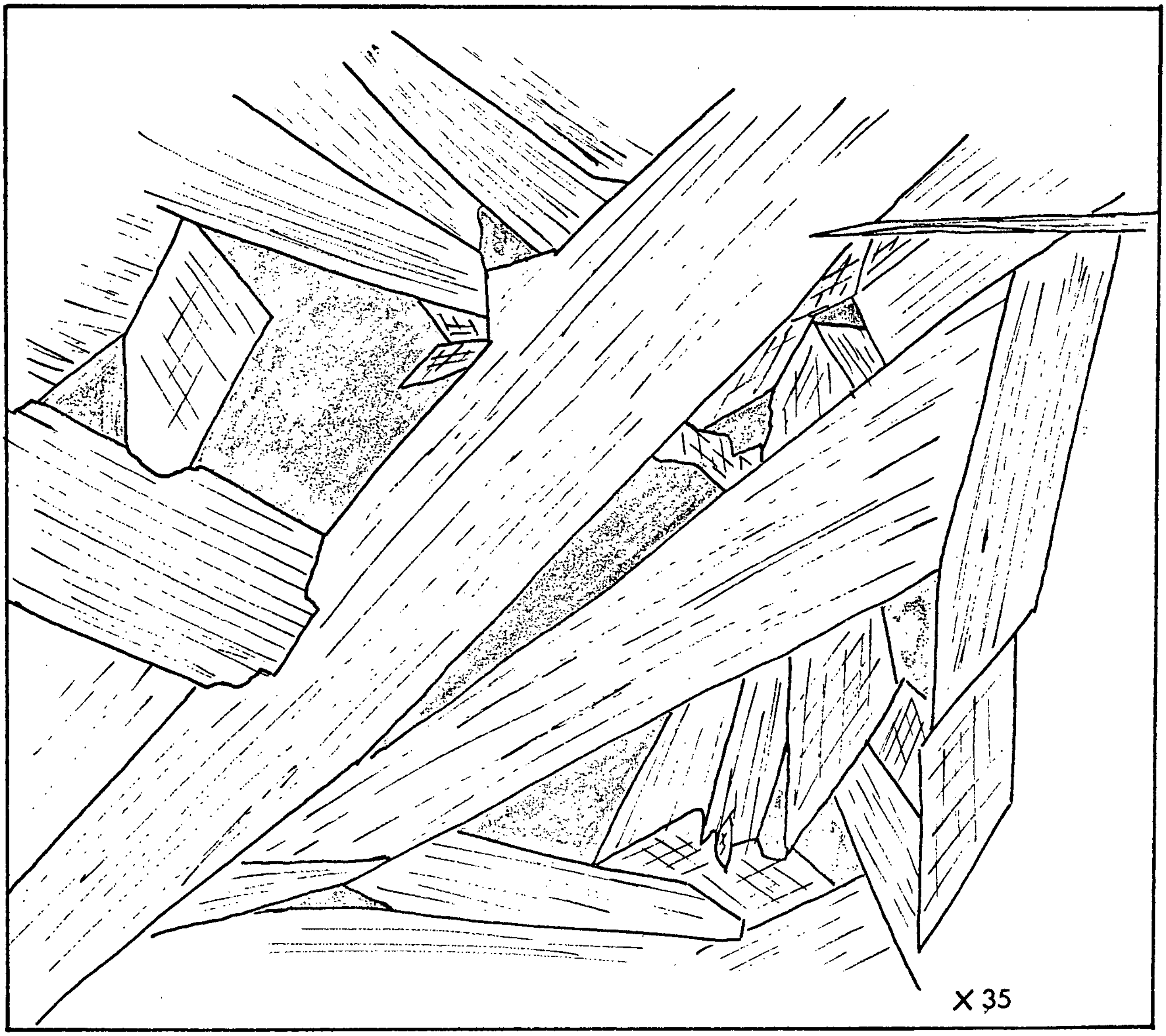


Figure 26. Chalcopyrite interstitial to blades of hornblende.

after the formation of the hornblendites, their origin is also hydrothermal. It appears that hot aqueous fluids circulating in both the gabbro and the Metchosin country rock produced, in the later stages of hydrothermal activity, concentrations of sulphides. The circulation of fluids, as previously described, is possibly caused by convective flow around the hot intrusive. Fractures have acted as passage-ways for the hydrothermal fluids and zones of extensively broken rock between cross cutting fractures or faults have allowed the passage of the late sulphide rich solutions. These areas, therefore, are the sites of the most extensive copper mineralization. Since the faults are generally steeply dipping or vertical, the ore bodies, although irregular, are contained in steeply plunging ore shoots which lie along fracture intersections.

Magnetite mineralization occurs in veins and is also disseminated through the altered gabbro and in some places through inclusions of country rock. Magnetite at Iron Mine Hill is concentrated in fractures within and close to xenoliths and screens of basalt enclosed within the gabbro. At this locality magnetite is abundant and in places forms veins up to six inches wide. Microscopic examination of partially recrystallized basalt inclusions from the Iron Mine Hill area indicate that magnetite was highly mobile during the recrystallization process. Abundant magnetite is disseminated through the rock but is also concentrated into veins and stringers which cross-cut the recrystallized rock. Since many specimens of the Metchosin basalt examined are extremely rich in magnetite, it is possible that the magnetite in the basalts close to the intrusion was mobilized and locally concentrated by the hot but cooling magma of the intrusion.

GEOPHYSICAL DATA

A positive Bouguer anomaly, the Sooke High, which reaches a maximum in the vicinity of Sooke is shown in the Bouguer Anomaly Map of Southwestern British Columbia (Walcott 1967). Over the basalts and gabbros of the Sooke area the Bouguer anomaly is around +60 milligals. This anomaly decreases towards the south and reaches a minimum of -95 milligals over the Olympic Peninsula (figs. 27 and 28). Over the Metchosin basalts of the Olympic Peninsula the anomaly is around -20 milligals.

The Sooke High also decreases northwards across the Leech River Fault. The change from the denser rocks south of the fault to the less dense metasediments of the Leech River Formation to the north is believed to cause the rapid decrease in gradient of the gravity anomaly (fig. 29). If the Leech River Fault has any effect upon the Bouguer anomaly, the observed change in gravity over the fault is inconsistent with a northward dipping fault (Walcott 1967). This evidence may indicate that, although the fault dips northwards on the surface, it may, at depth, dip to the south and be a reverse or thrust type fault.

The Olympic Low is attributed in part to the thick greywacke and argillite sequence (Walcott 1967) and though the Sooke High can be partly accounted for by the dense gabbros and basalts of the area, the rocks are not of sufficient density to produce the strong positive anomaly. The anomaly is thought to be caused by an underlying layer of dense peridotitic rocks. Similar, though more intense, Bouguer gravity anomalies exist in New Caledonia and Papua (fig. 30) where obduction of

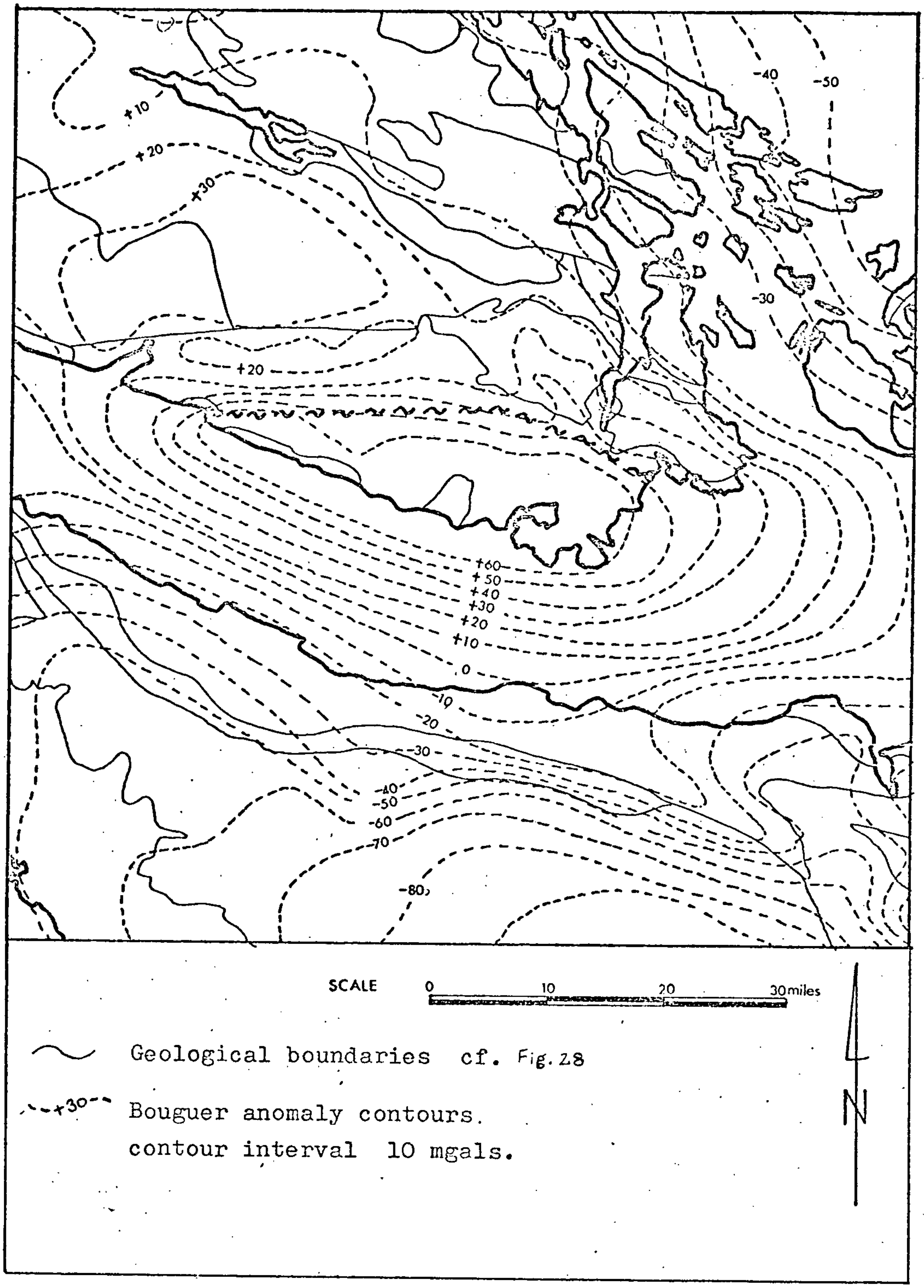


Figure 27. Bouguer anomaly map of South Vancouver Island (after Walcott 1967)

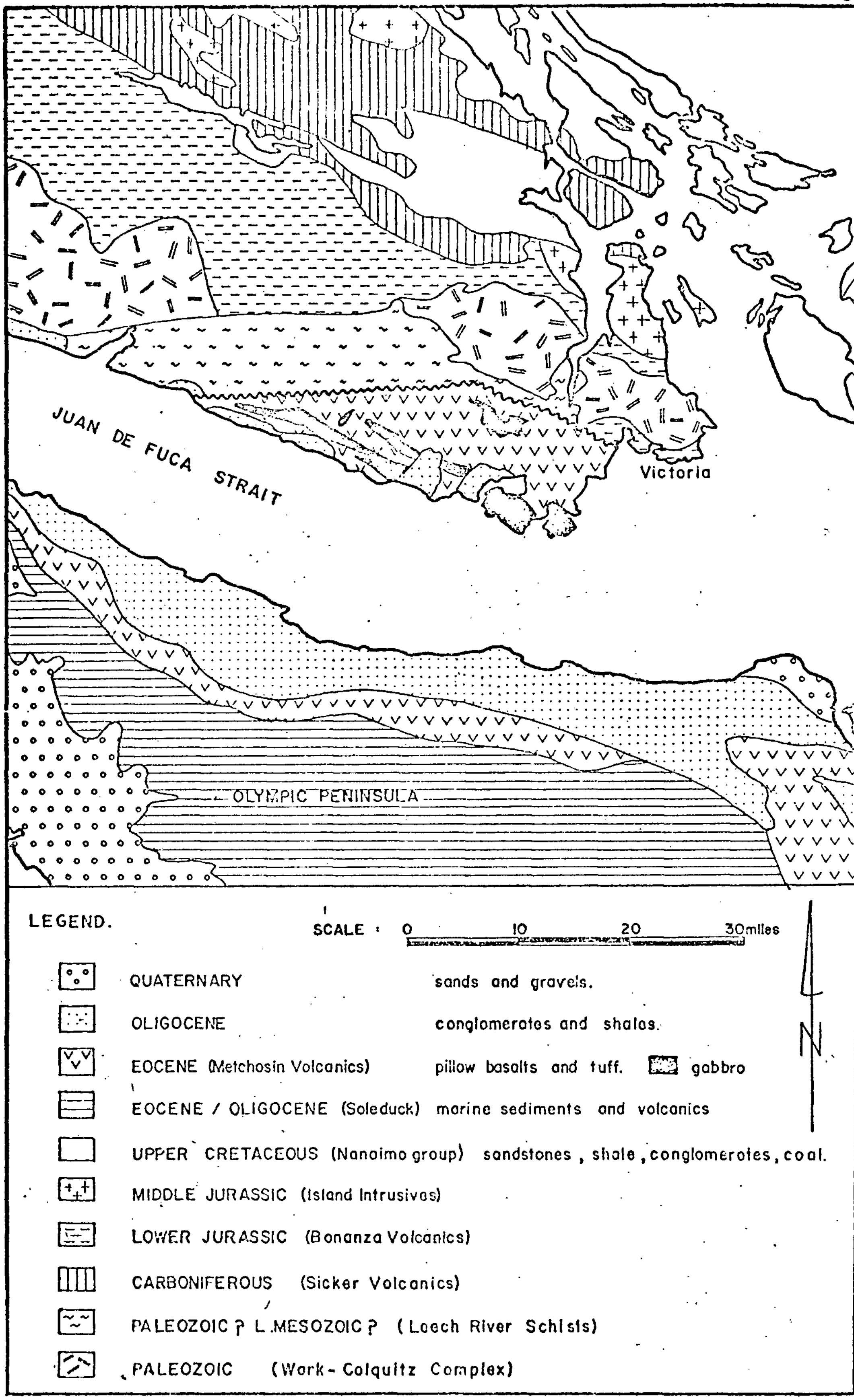


Figure 28 Compiled geologic map of South Vancouver Island and part of the Olympic Peninsula.

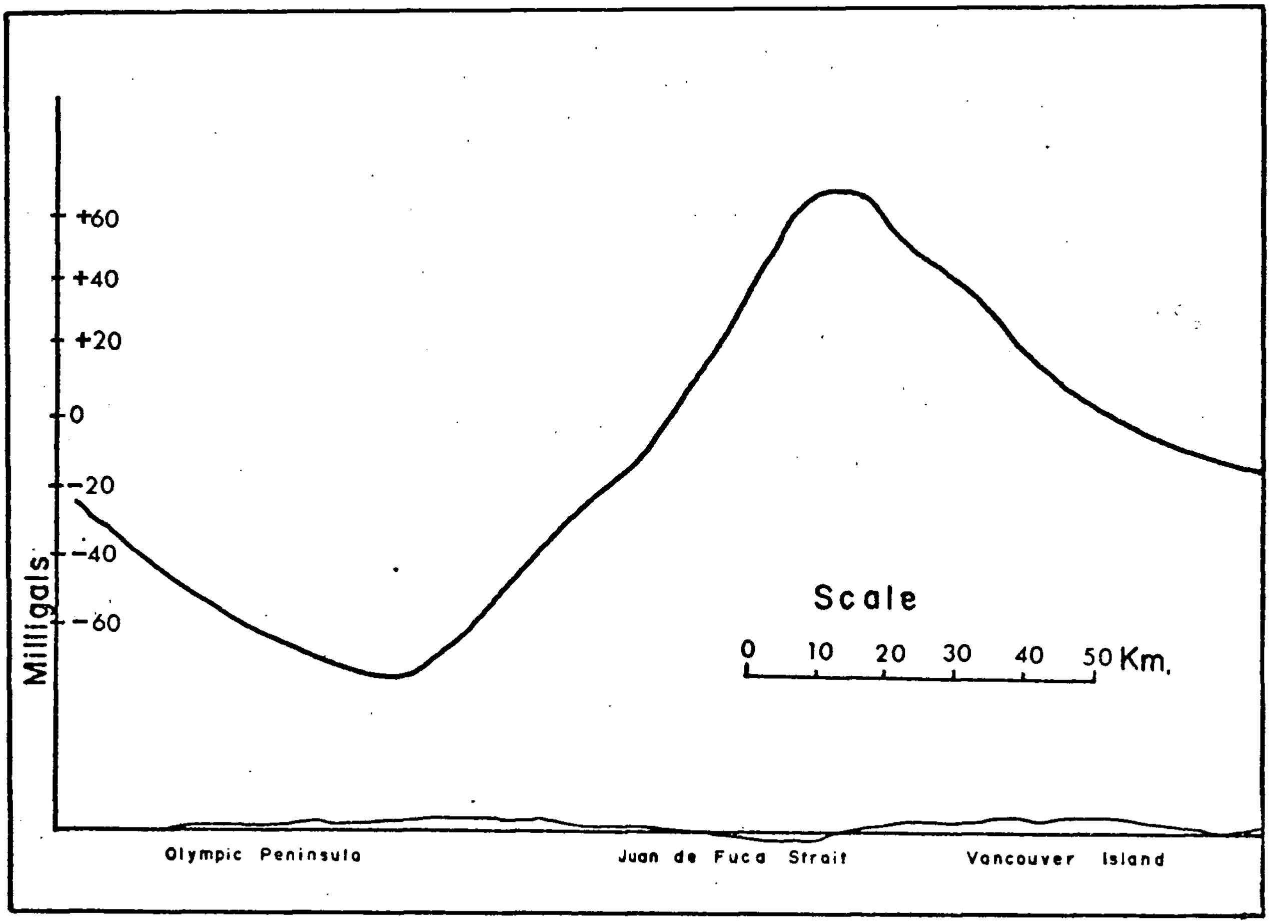


Fig. 29
Coastal Bouguer Anomaly Profile across the Olympic Peninsula and Vancouver Island.

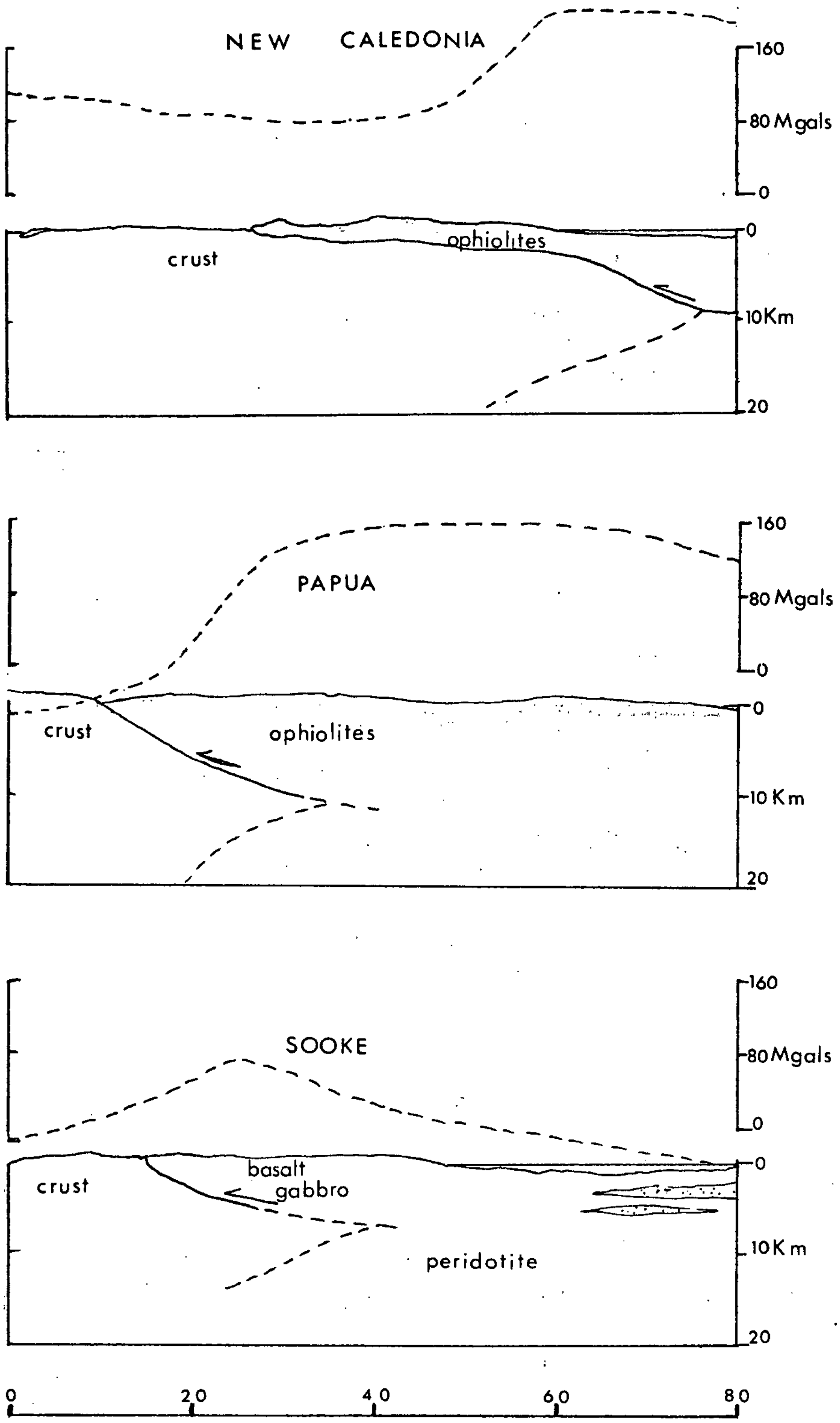


Figure 30. Bouguer gravity anomalies of New Caledonia, Papua and East Sooke.

oceanic crust and mantle on to continental margins is reported to have taken place (Coleman 1971).

Seismic data includes a profile crossing the Leech River Fault (Milne and White 1960). The seismic profile lies east of the gravity maximum and was carried out by exploding a number of charges in Juan de Fuca Strait and recording at Albert Head, the Dominion Astrophysical Observatory and the Pacific Naval laboratory.

The travel-time curves obtained are shown in figure 31. Milne and White consider the Albert Head and D.A.O. records as two separate groups and ignore the P.N.L. readings. Thus they consider the travel-time curve to indicate two different velocities. Using a least squares method, the closer station at Albert Head yields a velocity of 5.41 Km/s with an intercept time of 0.12 s whereas the D.A.O. records fit a travel-time curve of velocity 8.7 Km/s. Milne and White discount the 8.7 Km/s velocity as being obviously incorrect since they believe the area to be underlain by granitic basement. They interpret the 8.7 Km/s velocity as being a high apparent velocity obtained because of a dipping top bed and propose that the Metchosin basalts overlie a granite basement and dip north at 20 degrees resulting in a depth of 14,000 feet of basalts at the Leech River Fault (fig. 32). Granitic rocks are, however, not seen south of the Leech River Fault and geological evidence indicates that gabbroic rather than granitic rocks underlie the basalts.

An alternative interpretation, though grossly oversimplified, does provide some interesting results. A travel-time curve of velocity 7.1 Km/s with an intercept time of 0.48 s can be drawn through the P.N.L. readings which were omitted by Milne and White in their interpretation.

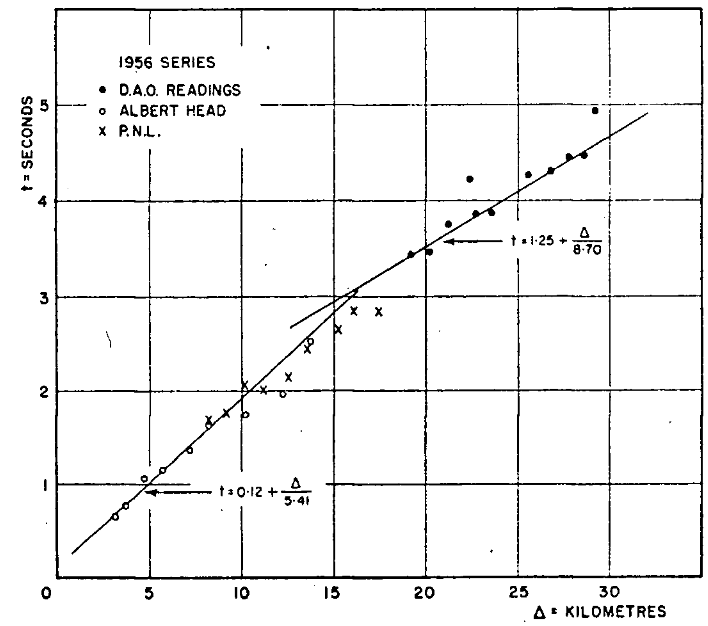


Figure 31 Travel-time curve, 1956 series Milne and White.

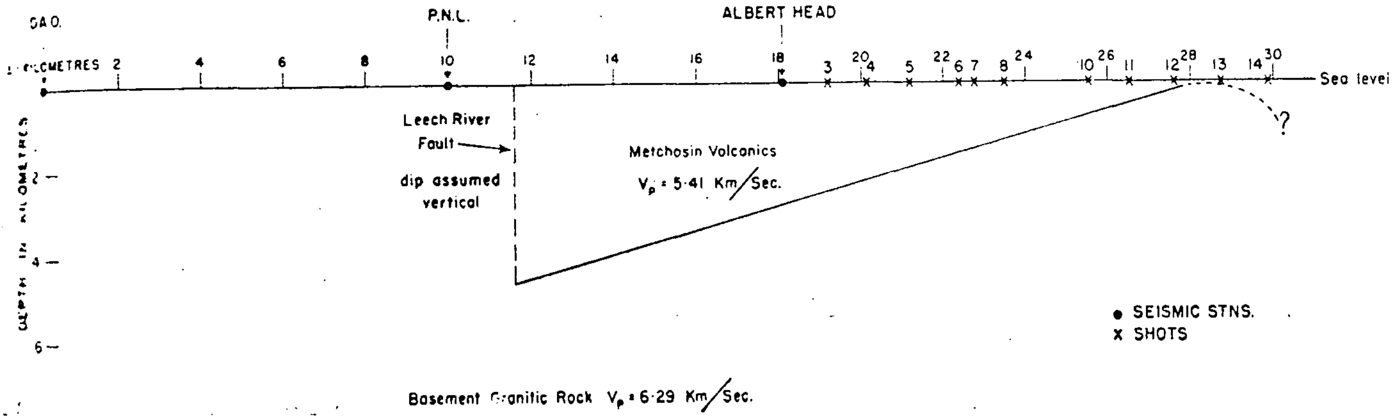


Figure 32 Profile along 1956 series (plane-layer interpretation Milne and White)

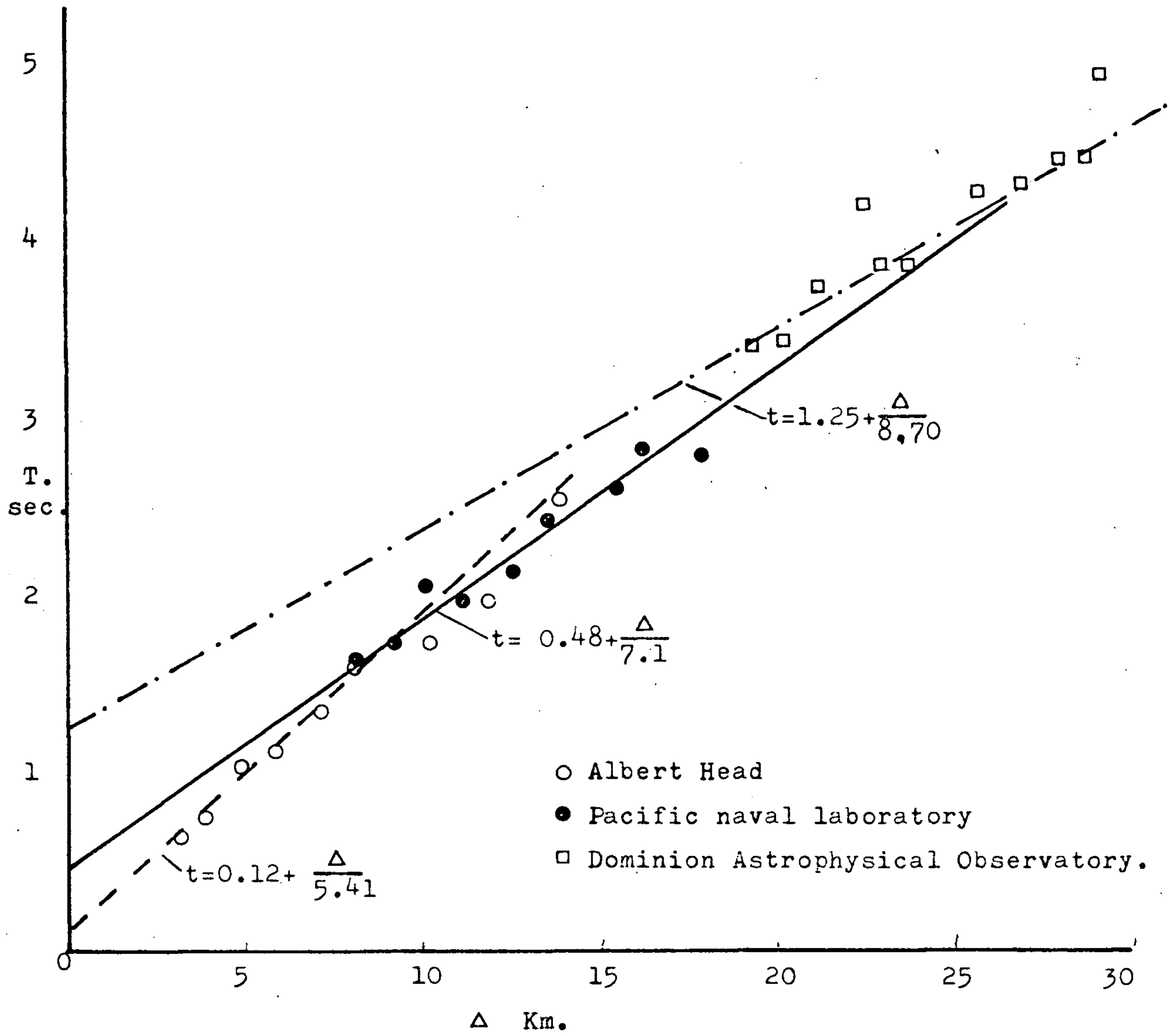


Figure 33 Travel-time curves - three layer interpretation.

The three travel-time curves (fig. 33) if interpreted on the basis of a three layer model indicate that a layer of velocity 5.41 Km/s overlies a layer of velocity 7.1 Km/s which in turn overlies a high velocity layer of velocity 8.7 Km/s. The upper layer comprises the basalts with a seismic velocity of 5.41 Km/s. The seismic velocities from the second and third layers, though slightly high, are about equivalent to velocities obtained from gabbroic and mantle rocks respectively. The apparent high velocities even for gabbroic and mantle rocks possibly indicate that the lower interface dips north but at a shallower angle than in Milne and White's interpretation.

According to this model the thickness of the layer of basalts is approximately 1.6 Km. and the thickness of the underlying gabbroic layer is of the order of 6 Km. In other words the depth to the surface of the high velocity layer is between 7 and 8 Km., which is equivalent to the thickness of oceanic crust. The high velocity layer may therefore represent the upper mantle.

Though this model is obviously oversimplified in that planar layers probably do not exist as the gabbro intrudes the basaltic layer, it does fit the strong positive Bouguer gravity anomaly and in general fits a hypothesis that the gabbros and basalts represent a slice of oceanic crust.

GEOLOGICAL HISTORY OF THE AREA

The Sooke gabbro intrusion is the largest of a number of elongate gabbroic intrusions which occur within the Metchosin Formation on the south-west coast of Vancouver Island (fig. 4). Significantly, no intrusions of Sooke gabbro are found north of the Leech River Fault which separates the Tertiary basalts of the Metchosin Formation on the south from the Mesozoic metasediments on the north (fig. 28). The Metchosin basalts and gabbros on Vancouver Island therefore comprise part of a geological province distinct from the Cordilleran Insular Belt. The fundamental difference is that the basalts and gabbros are part of a "eugeosynclinal" assemblage stretching southwards through the Olympic Peninsula in north west Washington (Snavely and Wagner 1963), whereas the rocks of the Insular Belt are mainly much older and of quite different types.

Extensive melting of a suitable parent rock must have taken place to produce the vast volume of up to 100,000 cubic miles of Eocene basalt. If the assumption that the mantle is composed largely of dense silicates rich in iron and magnesium is correct, then the basaltic magma could be derived from mantle material by differential fusion. McKee (1972) states that, "The lava probably came from the mantle; chemical analyses of the basalt strongly resemble those from recent basaltic eruptions in oceanic areas where a subcrustal origin is certain".

The basalts and gabbros which are closely related in time are probably genetically related. The gabbro is thought to have been intruded during the late Eocene and since much of the volcanic activity also took place during the late Eocene, the basalts and gabbros are considered contemporary. Contemporaneous origin is reasonable in the light of the hypothesis that the gabbro represents intermediate levels of what was presumably a volcanic feeder vent, now exposed by erosion of part of the volcanic pile. Feeder vents and surrounding basalts appear to have grown into volcanic islands as the nature and distribution of sediments interbedded with the lava suggests that they were deposited on or near volcanic islands (McKee 1972).

McKee suggests that the extensive Eocene volcanicity originated in a manner comparable to the Hawaiian eruptions and that the Eocene pillow lavas built up from the ocean floor until the pile eventually built above sea level. This seems a reasonable suggestion since there is evidence that some of the later Eocene lavas were erupted subareally because old soil zones formed by weathering can be seen between the flows (Waters 1955). If the Eocene lava was erupted to form oceanic islands, the gabbro and pillow basalts of the Metchosin Formation must be considered to represent an ocean floor sequence.

Geophysical information on the Sooke area substantiates this hypothesis that the gabbro and basalts are part of an oceanic sequence. The Bouguer gravity anomaly over the Sooke area is one of the most pronounced in North America and though less intense is similar to gravity anomalies in areas such as New Caledonia and Papua where there is obduction of ocean crust on to continental edges (Coleman 1971).

An alternative interpretation of the seismic results of Milne and White (1960) indicates that 1.6 Km. of basalts are underlain by approximately 6 Km. of gabbroic rocks. Beneath these layers is a high velocity layer situated at a depth which corresponds to the depth

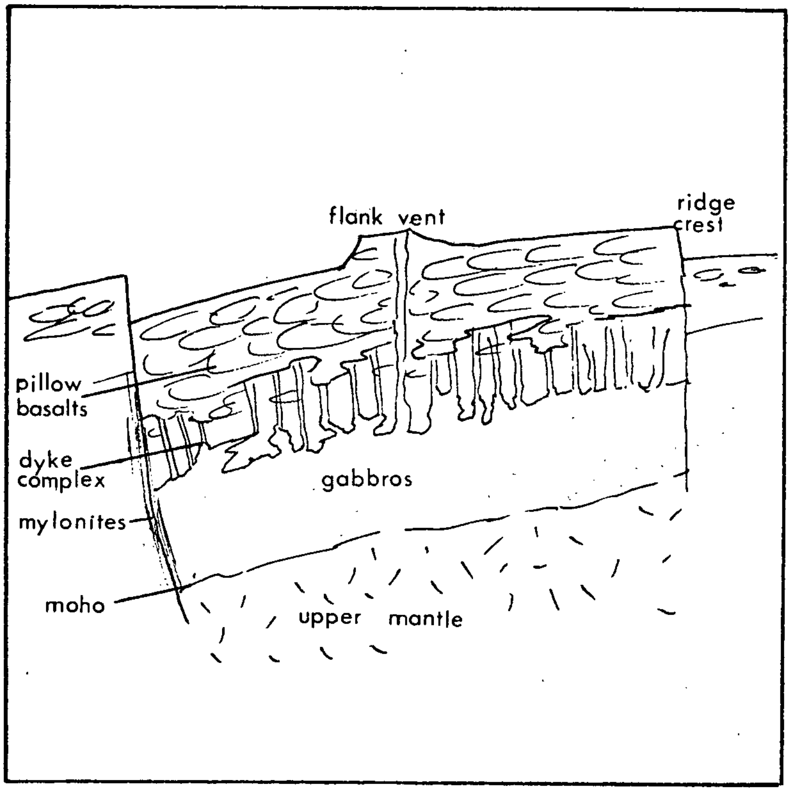


Figure 34 MODEL FOR THE OCEANIC CRUST
After Dewey and Bird 1970.

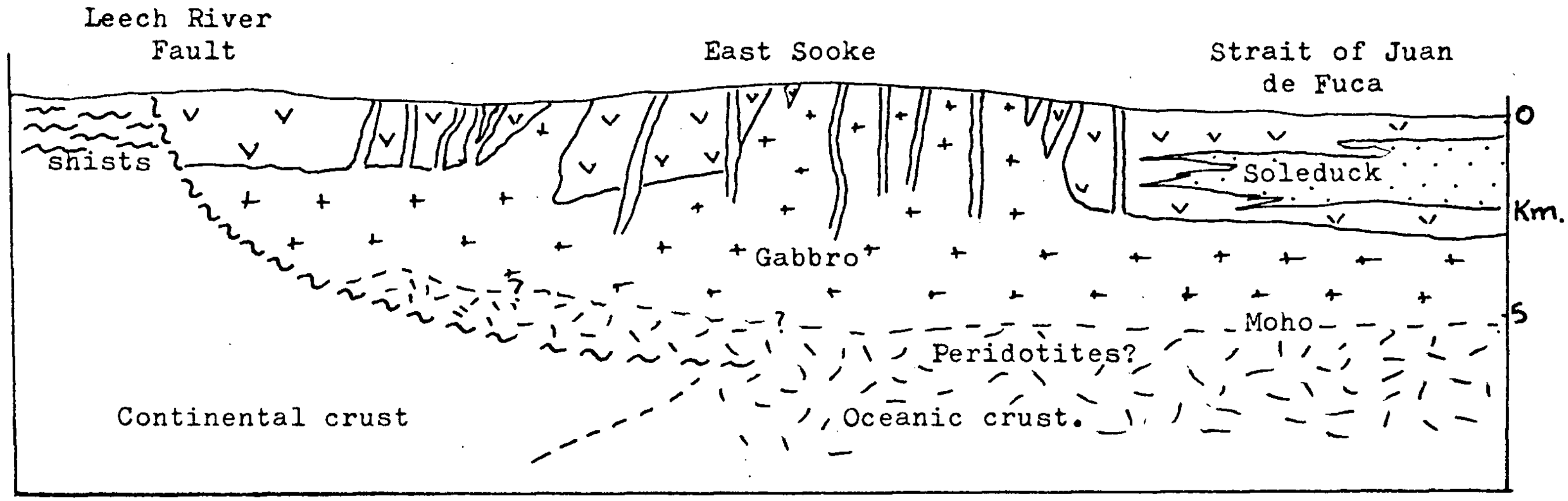


Figure 35. Schematic model for obduction of oceanic crust on to continental crust - South Vancouver Island.

of oceanic crust. The high velocity layer is therefore thought to represent peridotite rocks of the upper mantle. If this seismic model is reasonable then the sequence of rocks in the Sooke area is similar to that proposed by Dewey and Bird (1970) in their model for ocean crust (fig. 34).

The Leech River Fault is believed to mark the interface between oceanic crust and continental crust, as does the Queen Charlotte Fault. Although the Leech River Fault dips to the north at the surface, there is evidence from the gravity interpretation that the dip may be reversed at depth. Since the fault which marks the interface between oceanic crust and continental crust appears to be a reverse or thrust type fault, it is proposed that the oceanic assemblage was obducted on to Vancouver Island (fig. 35).

Obduction of the large slice of oceanic material on to southern Vancouver Island must have involved large scale tectonic forces which only the mechanism of ocean floor spreading could provide and probably resulted from the relative motion of the Juan de Fuca and North American plates.

CONCLUSIONS AND SUMMARY

The Sooke gabbro intrusion is an elliptical body of slightly differentiated olivine gabbro which is composed of calcic plagioclase and clinopyroxene with minor olivine and orthopyroxene. The gabbro does not exhibit any obvious cryptic or cumulate layering of the type which characterizes many other layered basic igneous rocks. Instead steeply dipping structures such as weak layering, foliation and lineation are believed to be flow structures of the type described by Balk 1937.

Uralitization of the gabbro is a hydrothermal or deuteric alteration, the intensity of which is everywhere spatially related to fractures or to the margin of the intrusion. Fractures in both gabbro and surrounding basalt appear to have acted as channelways for the migrating solutions which, in the later stages, deposited copper sulphides in structurally favourable areas. The hot intrusion is believed to have acted as a "heat pump" causing a convective flow of hydrothermal or late stage deuteric solutions around the peripheral regions of the intrusion and along fractures.

The gabbro is bounded on all sides by upper Eocene Metchosin basalts which are believed to be comagmatic with the gabbro. Though the gabbro causes some recrystallization of the basalts near the contact and though it is generally intrusive into the basalts, it is believed to represent a lower level of a volcanic neck or feeder now exposed by erosion of a thick sequence of basalts.

The Metchosin pillowed basalts which are locally interbedded with tuffaceous marine sediments (Snavely and Wagner 1963) are clearly submarine in origin. The nature and distribution of the sediments interbedded with the lava suggests that they were deposited on or near volcanic islands (McKee 1972). There is evidence that some of the lava flows highest in the volcanic pile were erupted subaerally as old soil zones formed by weathering can be seen between flows (Waters 1955). The build-up of the Eocene basaltic pile can be compared to the Hawaiian chain which grew from the ocean floor by the successive build-up of basaltic lava flows until finally the pile built above sea level.

An hypothesis of oceanic origin for the basalt and gabbro sequence is further complemented by the geophysical information on the area. The high Bouguer gravity anomaly is compared to similar anomalies in areas where obduction of oceanic crust on to continental crust is considered to have taken place. An alternative interpretation of the seismic results of Milne and White yields a three layer model with seismic velocities of each layer corresponding to those of basaltic, gabbroic and mantle rocks. The nature of these layers and their relative thicknesses corresponds well with other models proposed for oceanic crust.

If Eocene lava was indeed erupted to form oceanic islands, then subsequent spreading of the sea floor seems to have rafted them against the edge of the continent. The oceanic suite has been obducted on to the southern end of Vancouver Island by the large scale tectonic forces resulting from the relative motion of the Juan de Fuca and North American plates.

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APPENDIX

DETERMINATIVE METHODS FOR MINERAL COMPOSITIONS

A.) Plagioclase.

Plagioclase compositions were determined on a four axis universal stage. Optical and crystallographic elements in twinned plagioclase were measured in order to determine the twinning law, anorthite percentage and the structural state. The procedure used in the measurement of these elements is described by Slemmons (1962) and is essentially a revision of the Turner method. Optical curves for both volcanic and plutonic plagioclases are used to determine the structural state of the plagioclase. Slemmons also gives various tests and procedures for eliminating any ambiguous results.

The composition of different zones in zoned plagioclase were determined by the same method using optical and crystallographic data from each zone.

Compositions of plagioclase derived using Slemmon's method seem to be accurate and results are normally reproductable to within two per cent anorthite.

B.) Pyroxenes.

Compositions of the orthopyroxenes were determined using 2V. The percentage of calcium in the orthopyroxenes cannot be determined by this means and an average value of three weight per cent calcium was assumed when plotting compositions.

Clinopyroxene compositions were determined using a combination of 2V, $Z \hat{} C$ and $A \hat{} C$ angles and plotting the values on the appropriate determination chart given by Ruegg (1964). This method was found to be of low accuracy because of a number of factors. Slight errors in the measurement of optical data can lead to significant errors in composition. Also, exsolution lamellae and the patchy development of uralitic amphibole within many pyroxene crystals influence the optical data to such an extent that any compositions so derived are subject to high error. To minimise this source of error fresh pyroxene was used where possible for optical measurements. The refractive index $n\beta$ was determined in some cases to narrow the margin of error.

C.) Amphiboles.

2V and $Z \hat{} C$ vslues determined on the universal stage were useful only in determining that common hornblende is the usual alteration amphibole present in the gabbros.

D.) Olivine.

Compositions of fresh olivines were determined using X-ray methods. A slow scan speed on the diffractometer was used to determine the 130 spacing. Potassium Bromide was used as a standard. The 130 spacing can be used to determine the composition of the olivine by plotting values on the olivine X-ray determination curve given by Yoder and Sahama (1957).

E.) Other Minerals.

The presence of scapolite in veins was verified by X-ray diffraction. Various opaques in the ore zones were determined using a reflecting microscope.

MODAL ANALYSES

Several modal analyses of gabbros were made. One thousand points were counted for each specimen in order to achieve an accuracy of about one per cent.

CHEMICAL ANALYSES AND AGE DATES

All chemical analyses were obtained from previous works. Similarly, the K/Ar age dates were obtained from Carson (1968) and Kirkham (1972).

TABLE I.

Spec. No.	An.% Core	An.% margin	Structural state	Rock Type
M6	87		L	Olivine gabbro.
M7	50		L	Uralitized gabbro.
M9	86		L	Olivine gabbro.
M11	82		L-I	Olivine gabbro.
M15	83		L	Olivine gabbro.
M16	80		L	Olivine gabbro.
M18	88		L	Olivine gabbro.
M20	70		I-H	Uralitized olivine gabbro.
M21	59		L-I	Uralitized gabbro.
M23a	65	53	I	Uralitized olivine gabbro.
M23d	58		?	Uralitized gabbro.
M26	72	66	L	Olivine gabbro.
M28	60	20	I	Uralitized gabbro.
M30	84		L	Olivine gabbro.
M33	72		I	Uralitized gabbro.
M33a	80	67	L	Olivine gabbro.
M34	84	77	L	Olivine gabbro.
M36	75		I	Uralitized olivine gabbro.
M37b	80		I	Gabbro/dyke contact.
M38a	77		L-I	Olivine gabbro.
M39	78		L	Olivine gabbro.
M40b	85		L	Olivine gabbro.

Structural states : L= Low, I = Intermediate, H = High.

TABLE I. (cont.)

Spec. No.	An.% core	An.% margin	Structural state	Rock Type
M44	53		I	Basalt inclusion.
M47	51	26	I	Gabbro-xenolith contact.
M51a	87		L	Olivine gabbro.
M52	86		L	Olivine gabbro
M53	77		L	Olivine gabbro.
M54	81		L	Olivine gabbro.
M55	78		L	Olivine gabbro.
M58b	58		I	Basalt inclusion.
M60	83		L	Olivine gabbro.
M63	85		L	Olivine gabbro.
M64	76		L-I	Olivine gabbro.
M66	68	79 64	L-I	Recrystallized basalt.
M69	68	60	L-I	Uralitized gabbro.
M70a	54		L-I	Uralitized gabbro.
M72	53		I	Porphyritic basalt xenolith.
M74	65	49	I-H	Bsaalt inclusion.
M75	61		L-I	Olivine gabbro
M76	73		L	Olivine gabbro.
M84	66	70	L	Basalt inclusion.
M84b	28	9	?	Leucocratic vein
M85	75	65	L	Basalt inclusion.
M87a	75		L	Basalt inclusion
M90	61		I	Bsaalt inclusion.
M92	52		L	Uralitized gabbro.
M93	51		L-I	Basalt inclusion.

TABLE I. (cont.)

Spec. No.	An.% core	An.% margin	Structural state	Rock Type
M94	80		L	Olivine gabbro.
M95	85	72	L	Olivine gabbro.
M96	85	70	L	Olivine gabbro.
M98	82		L	Olivine gabbro.
M100	80	74	L	Olivine gabbro.
M102	78		L	Uralitized olivine gabbro.
M104	63	52	I	Basalt inclusion.
M106	75	49	L	Norite.
M109	75		L	Olivine gabbro.
M111	62		L	Uralitized olivine gabbro.
M112	88	65	L-I	Basalt inclusion.
M113	52	59	L-I	Basalt inclusion.
M117	81		L	Olivine gabbro.
M118	63		?	Olivine gabbro.
M120	81		L	Olivine gabbro.
M121	80	71	L	Uralitized olivine gabbro.
M122	85	69	L	Olivine gabbro.
M123	86		L	Olivine gabbro.
M124	64		I	Uralitized gabbro.
M128	91		L	Olivine gabbro.
M130	60		L-I	Uralitized gabbro
M130a	54		I	Basalt inclusion.
M131	80		L	Olivine gabbro.

TABLE I. (cont.)

Spec. No.	An.% core	An.% margin	Structural state	Rock Type
M132	88		L	Olivine-rich gabbro.
M135	86	63	L-I	Basalt inclusion.
M139	81		L	Olivine gabbro.
M140	56		L-I	Uralitized gabbro.
M142	76	68	L-I	Uralitized gabbro.
M142a	64		L	Uralitized gabbro.
M153	82		L	Olivine gabbro.
M155	84		L	Olivine gabbro.
M156	79		L	Olivine gabbro.
M86	22	10	I	Leucocratic vein.
M86a	68	54	I	Basalt inclusion.

TABLE II

Spec. No.	An.% of early formed plagioclase, poikilitically enclosed in laterminerals.	An. % of phenocrysts in basalt.
M33a	81	
M39	83	
M87a		89
M85		75
M9	88	
M11	87	
M51a	90	
M139	87	

TABLE III. OLIVINE COMPOSITIONS.

Spec. No.	%Fo.	Spec. No.	%Fo.
M9	72	M63	78
M11	77	M76	67
M16	76	M94	68
M26	70	M100	67
M30	79	M112	70
M38a	74	M118	75
M39	74	M120	81
M40b	76	M132	82
M52	81	M139	79
M55	73	M153	80

TABLE IV. Modal analyses.

Spec.	Pl.	Cpx.	Opx.	Ol.	Hb.	Ep.	Chl.	Serp.	Acc.
M7	62·1	-	-	-	34.8	-	2.6		0.5
M34	58.4	29.7	2.0	8.9	tr				1.0
M38a	40.7	38.4		11.6	7.4	tr			1.6(mag.)
M53	58.7	23.5		tr	16.2	tr			1.6(Qtz.)
M63	40.4	35.5	8.6	9.9	4.8		tr		0.8
M64	60.53	35.46		2.06				1.4	0.53
M69	47.2	28.1			24.5				0.2
M76	46	39.5		12.3	1.4	0.5			0.3(cpy.)
M100	64.9	19.3		12.4	0.5	0.7		1.5	0.7
M147	56.5	31.3			10.1	1.3	0.5		0.3(cpy.)

M7 Uralitized plagioclase-rich gabbro

M34 Olivine gabbro

M38a Olivine gabbro

M53 Olivine gabbro slightly uralitized.

M63 Olivine gabbro

M64 Plagioclase-rich olivine gabbro

M69 Uralitized gabbro.

M76 Olivine gabbro.

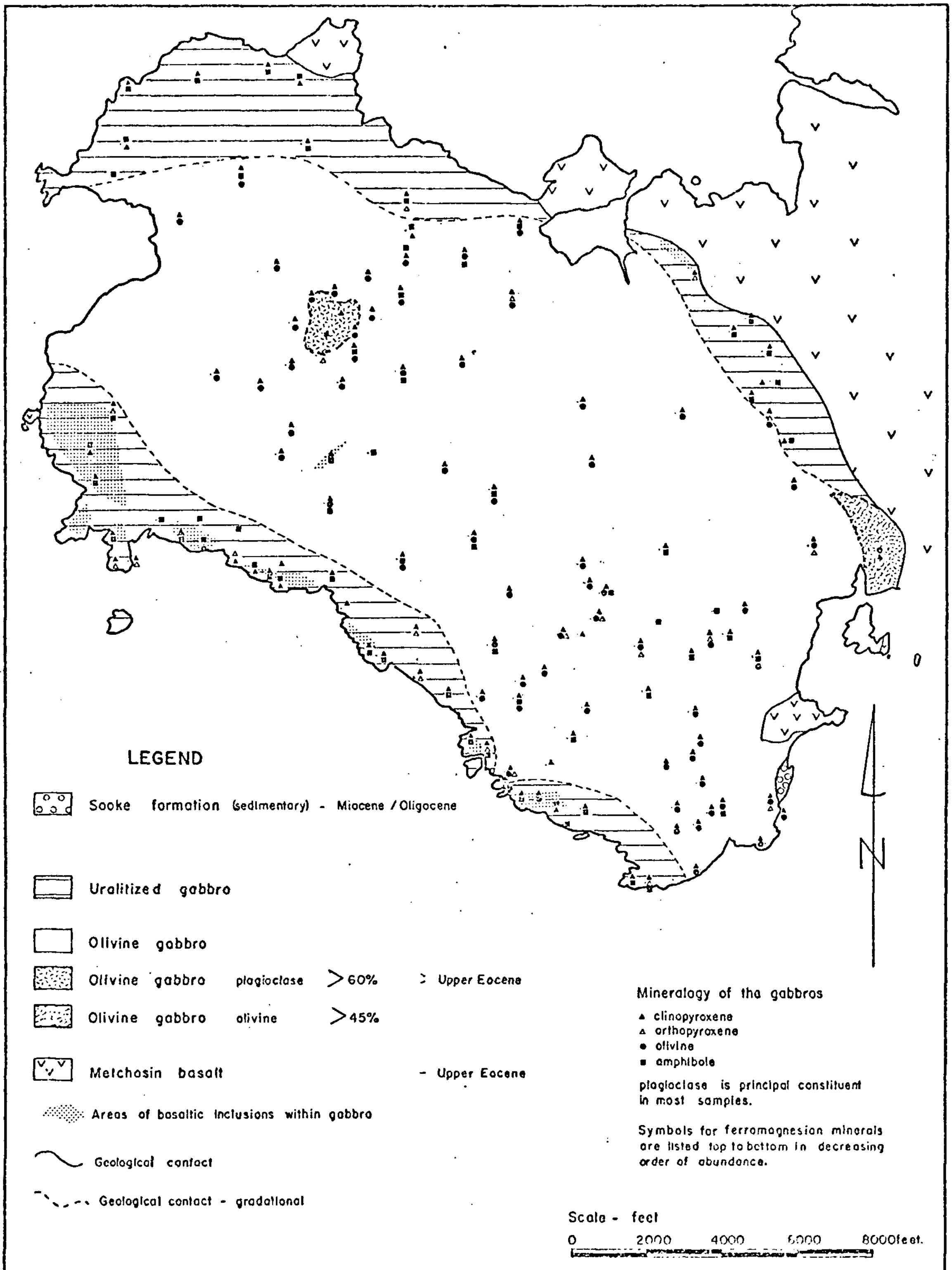
M100 Plagioclase rich olivine gabbro.

M147 Gabbro - partly uralitized.

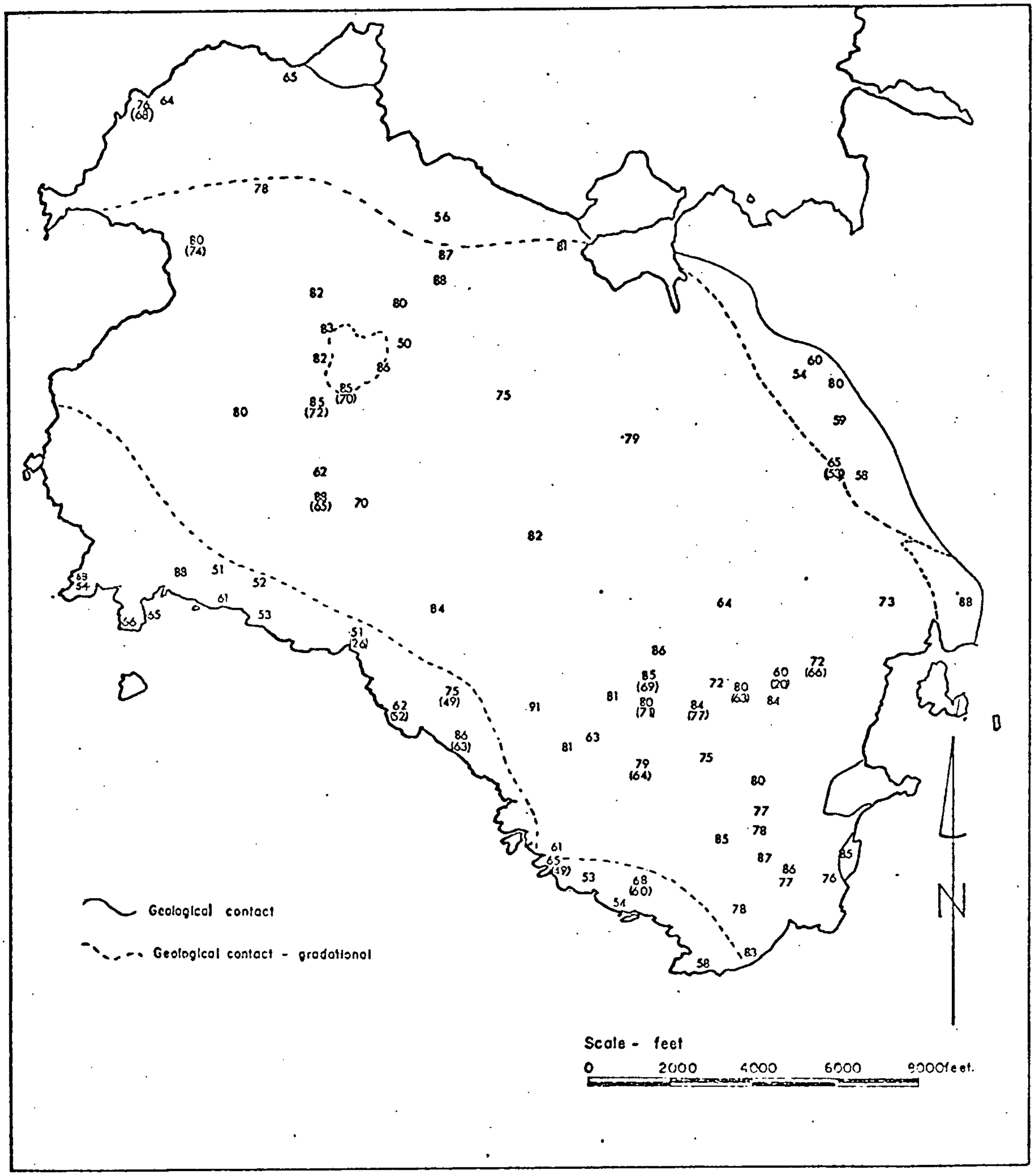
TABLE V. Chemical analyses.

	1	2	3	4	5	6	7	8
SiO_2	47.58	45.42	77.89	67.50	45.70	51.24	50.45	49.61
TiO_2	0.20	0.30	0.25	0.55	0.33	2.01	2.33	1.43
Al_2O_3	18.03	10.64	11.96	13.20	14.90	13.12	14.94	16.01
Fe_2O_3	1.01	3.03	0.21	2.20	1.80	4.33	3.38	11.49
FeO	3.34	10.22	0.32	4.10	5.80	9.15	7.55	
MnO	0.06	0.08	0.02	0.07	0.15	0.21	0.08	0.18
MgO	10.88	13.82	0.29	1.40	8.70	4.26	7.69	7.84
CaO	16.92	11.84	1.92	3.00	13.40	8.61	9.17	11.32
Na_2O	1.04	2.17	5.67	5.70	2.30	2.40	2.84	2.76
K_2O	0.32	0.45	0.31	0.30	0.16	1.01	0.35	0.22
P_2O_5	0.01	0.01	0.04	0.13	0.06	0.61	0.27	0.14
H_2O	-	-	-	0.90	2.50	2.66	0.96	-
CO_2	-	0.03	-	0.10	0.1	-	-	-
	100.08	100.21	99.65	99.10	95.90	99.61	100.04	

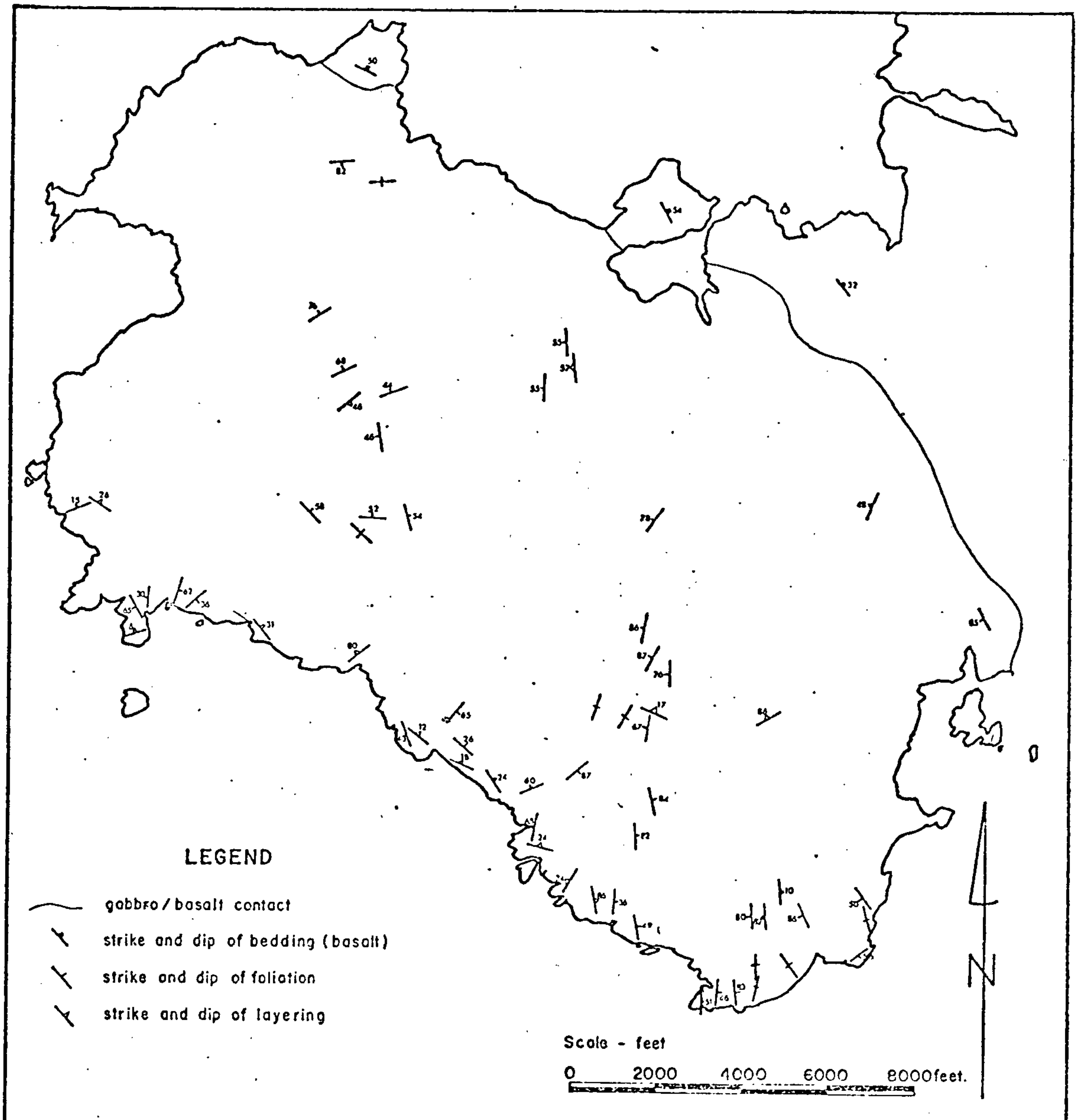
1. Fresh rather fine grained olivine gabbro with approximately 5 per cent olivine,(Cooke 1919).
2. Hornblendite, (Cooke 1919).
3. Aplite, (Cooke 1919).
4. Quartz diorite, (Carson 1968).
5. Altered gabbro, (Carson 1968).
6. Average of four analyses for Eocene Olympic basalts, (Waters 1955).
7. Average of ten basalts, Koolau basalt series, Hawaii. (Wentworth and Winchell 1947).
8. Mean of 96 oceanic basalts (tholeiites), (Cann 1971).



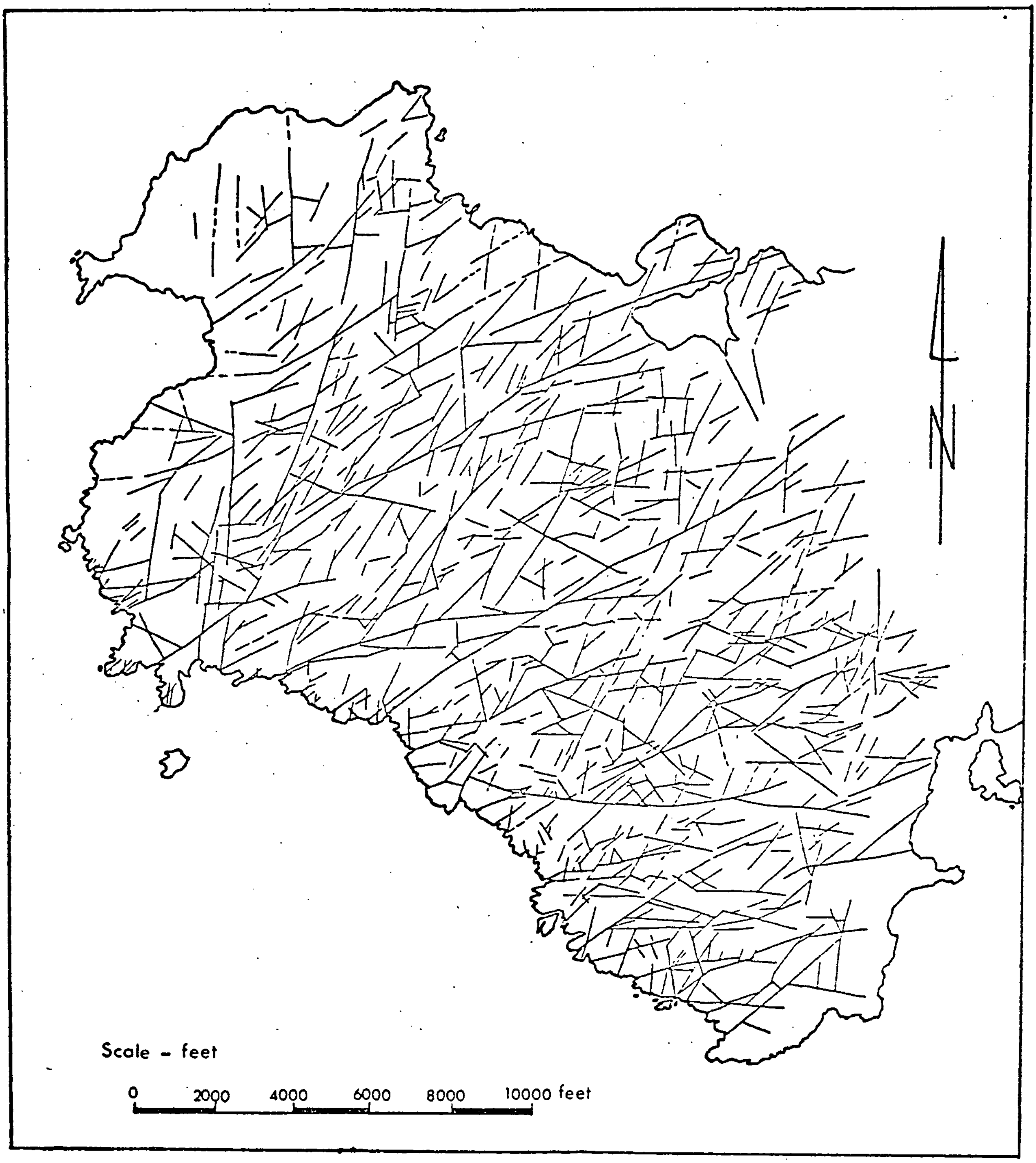
MAP A. GEOLOGIC MAP — EAST SOOKE PENINSULA.



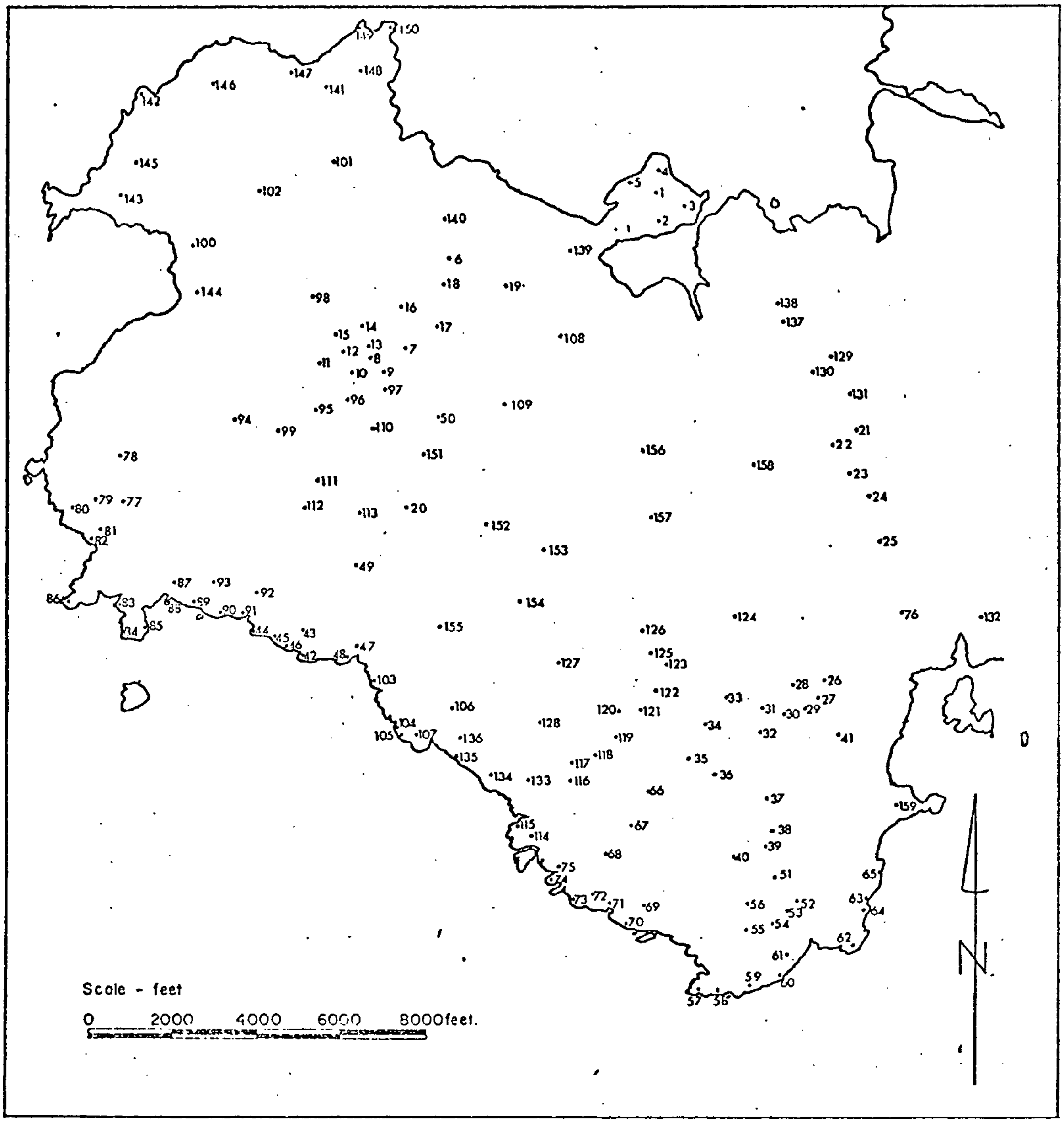
MAP. B. Anorthite percentage of plagioclases.
Figures in brackets are anorthite percentages of crystal margins



MAP C. STRUCTURE MAP - EAST SOOKE GABBRO.



Map D. Topographic lineaments. Map prepared from air photos.



MAP E. Sample Location Map