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THE ORIGIN AND TECTONIC SETTING OF TOW HILL, QUEEN CHARLOTTE ISLANDS

THE ORIGIN AND TECTONIC SETTING OF TOW HILL, QUEEN CHARLOTTE ISLANDS

By

CATHERINE E. TIMMS

A Thesis

Submitted to the Department of Geology

in Partial Fulfilment of the Requirements

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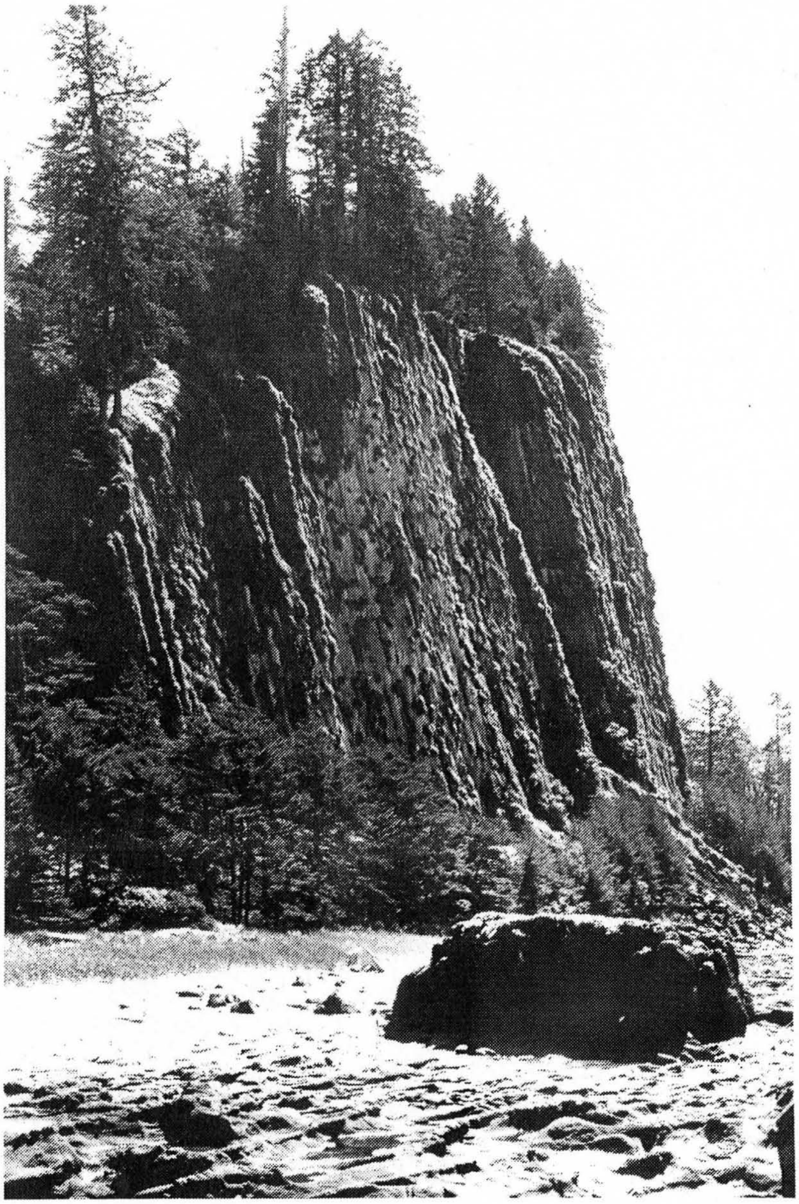

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SCOPE AND CONTENTS:

The macroscopic features of Tow Hill, Queen Charlotte Islands were studied and standard measurements, orientations, and photographs were collected. Petrographical examination of thin sections from the main basalt body as well as from the thin sills, foreign bodies, vesiculated rings and micro-sills was performed. Chemical analyses of the same samples as above were completed. These studies help to deduce the origin of Tow Hill and the tectonic setting.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. C.J. Hickson of the Geological Survey of Canada who suggested this topic and who provided ideas during the field work and to Mr. Don Olesiuk, manager of the Tow Hill Provincial Park, for enthusiastically permitting me to collect samples. The advice and encouragement offered continually by my supervisor, Dr. P.M. Clifford is greatly appreciated. Thanks are also extended to John Whorwood for his photographic work, to Len Zwicker for thin section preparation, and to Otto Mudroch for XRF chemical analyses. The fine work of Kevin Fuller in typing much of the manuscript and in the drafting of the figures is also greatly appreciated.

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ABSTRACT

Tow Hill is a 109m butte located on the north shore of Graham Island, Queen Charlotte Islands. It is composed of a massive, 105m thick layer of olivine tholeiite, underlain by thin sills of tholeiitic basalt and interbedded sediments of the Skonun Formation. The age of this basalt body has been estimated to be less than 5Ma. Three hypotheses have been proposed as to the origin of Tow Hill: 1. a sill intrusion; 2. hydroclastic material; and 3. a lava flow or flows. Macroscopic features observed on Tow Hill do not indicate an origin and each of the three hypotheses can adequately explain the features. Petrographical studies indicate that the basalt is not fragmental and thus, the second hypothesis can be rejected. Neither of the two remaining hypotheses can be strictly accepted or rejected with petrographical examination. Chemical analyses indicate that Tow Hill is made up of "within plate" basalts which are probably related to activity associated with rifting and/or transtension in a continental environment. This constrains the late Tertiary tectonic history of the Queen Charlotte Islands in that any model of the tectonics of this area must involve rifting and/or transtension.

CHAPTER 1
INTRODUCTION

Tow Hill (Figure 1.1) is located approximately 24km east of the village of Masset on the north coast of Graham Island, Queen Charlotte Islands, British Columbia. A new highway (the only highway on the Queen Charlotte Islands) allows good accessibility to the area and because Tow Hill is centered in a Provincial Park, many walking trails have been developed to permit easy access to the lower beach section of the outcrop.

Tow Hill itself is a 109m high knob of basalt. It is almost completely moss and tree covered which causes problems for examination and sample collecting of the hill itself. Although all sides of the hill are rather steep, the side that faces the ocean to the NNW is almost vertical. Below the cliff face, rock with the same make-up as the hill itself is exposed. It is highly wave polished and free of any debris, soil, and vegetation cover. Consequently, this area is the best location to study Tow Hill.

The age of Tow Hill has been determined to be less than 5 million years (Hickson, 1988; Sutherland Brown, 1968) and therefore it cannot be correlated with the older volcanics of the Masset Formation (Figure 1.2). Tow Hill was emplaced before the termination of Skonun sedimentary deposition at the close of the Upper Pliocene.

In the early 1960's, the Queen Charlotte Islands including Tow Hill were examined by Sutherland Brown (1968). Petrological studies indicated that the volcanics comprising the area are olivine basalts. Evidence such as columnar jointing, baked sediments at the contact between the Tow Hill volcanics and the underlying sediments, and the presence of correlatable olivine basalt sills in the subsurface a short distance (~5km) east of the Tow Hill outcrop (Figure 1.3) encouraged Sutherland Brown (1968) to conclude that the Tow Hill outcrop is one sill of a set which has intruded into the Skonun sediments.

It is likely that the two lowermost bodies of basaltic material are indeed sills as they are each overlain and underlain by Skonun silty shales and sandstones. However, since there is no evidence of Skonun sediments covering the main body of Tow Hill and because of the general morphology of the area, some question has arisen as to its status. Consequently, two other hypotheses have been presented concerning the nature of Tow Hill. Based upon a reconnaissance examination of the area, it has been suggested (Hickson, pers.comm.) that perhaps the development of the main body of Tow Hill was due to successive hydroclastic eruptions in which fragmental material accumulated into a thick pile. A third hypothesis proposes that Tow Hill is a basaltic lava flow (or flows).

The purpose of this project is to present and assess the evidence for and against each of the three hypotheses presented on the origin of Tow Hill: 1. a sill intrusion, 2. hydroclastic material and 3. set of lava flows. It must be stressed that any model of the origin of Tow Hill must comply with the regional tectonic setting.

The chapters that follow include descriptions of the macroscopic features of Tow Hill, petrography, and geochemistry. The macroscopic features and petrography may shed light on the origin of Tow Hill and the geochemistry will perhaps indicate a tectonic setting of this region.

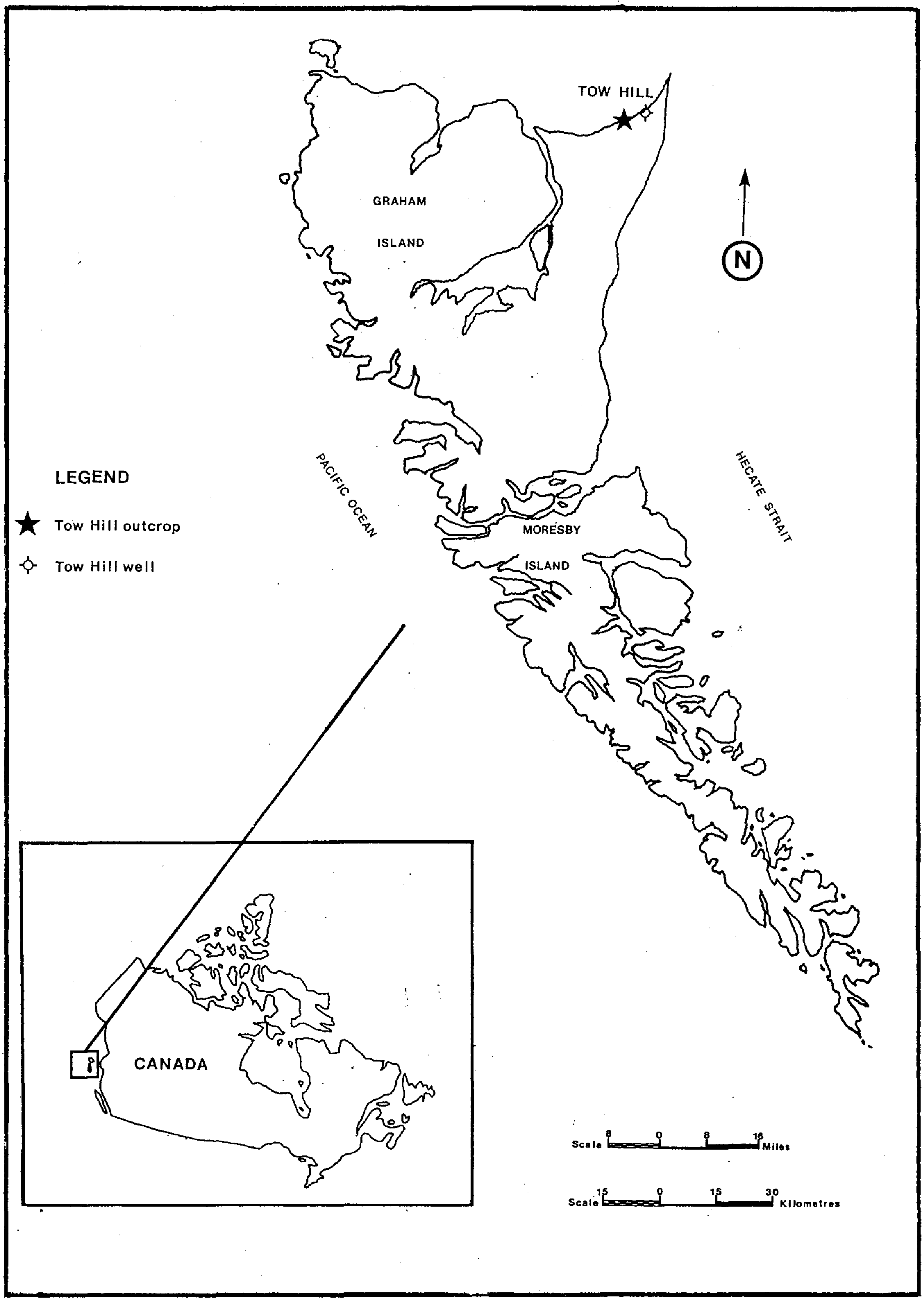


Figure 1.1. Location map of the Tow Hill outcrop and the Tow Hill well.

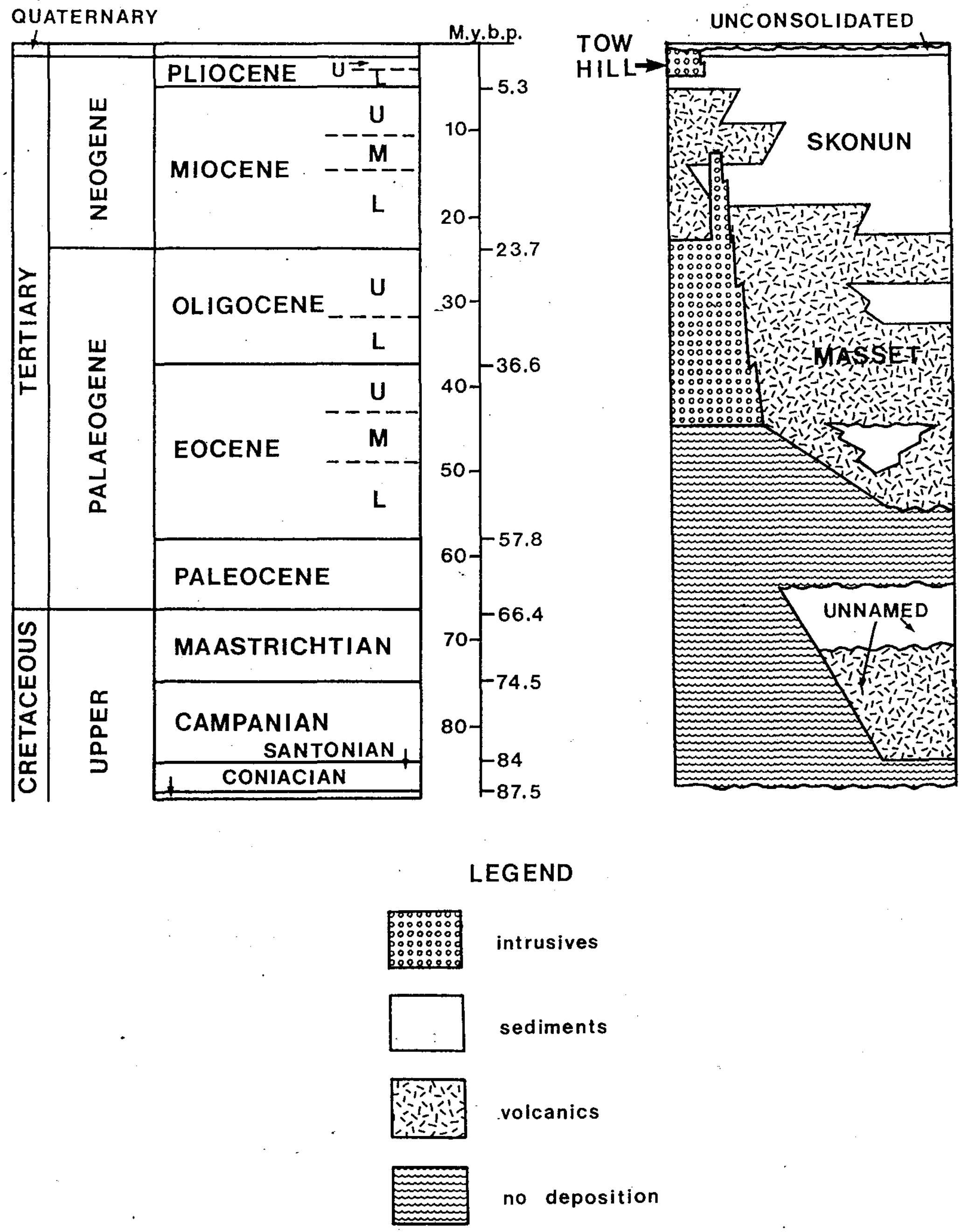


Figure 1.2. Upper Cretaceous and Tertiary stratigraphy of the Queen Charlotte Islands. Note that Tow Hill is not related to the Masset Volcanics.

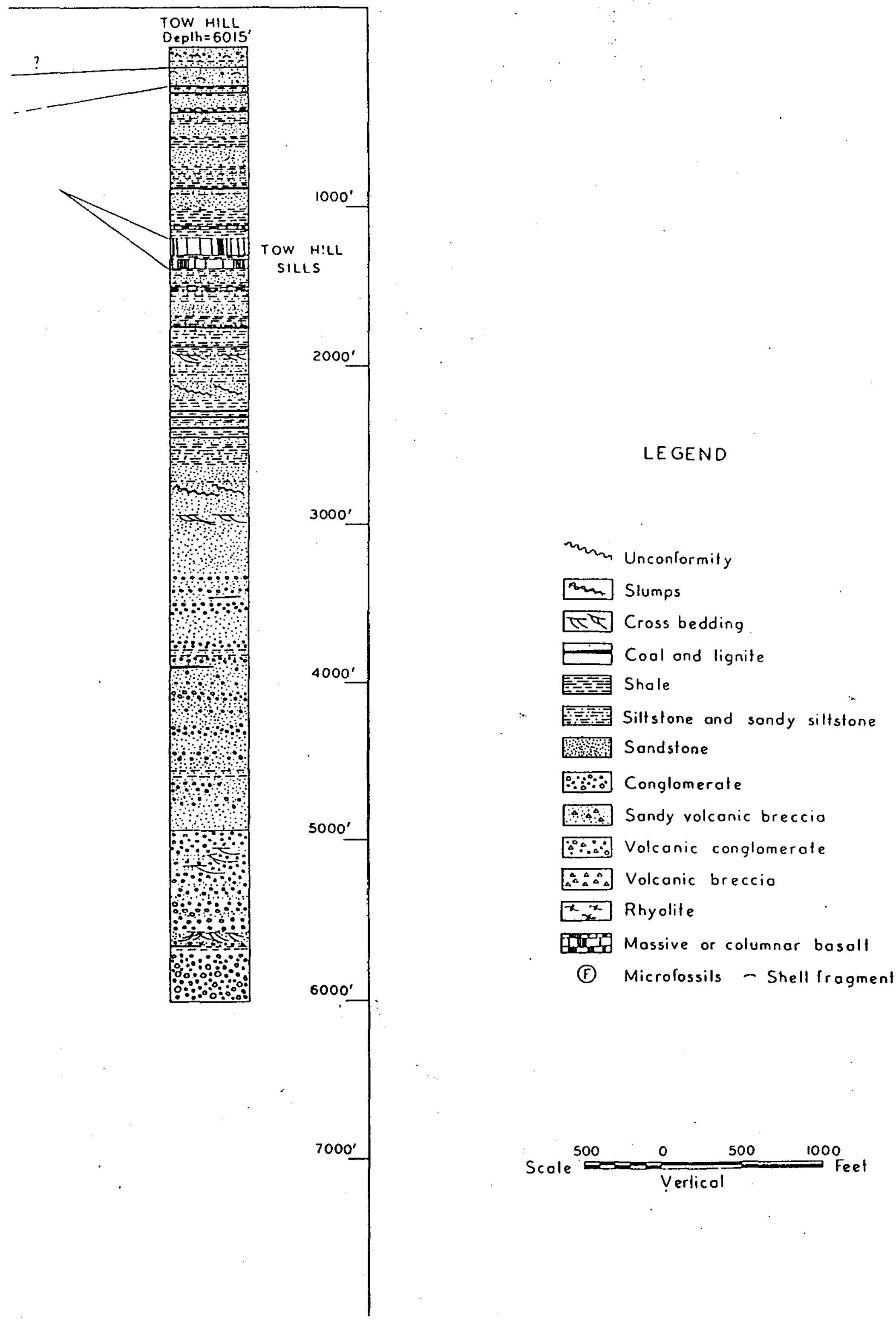


Figure 1.3. Stratigraphic section of the Tow Hill well. The Tow Hill sills are absent in all of the other wells drilled on Graham Island. (Modified from Sutherland Brown, 1968).

CHAPTER 2

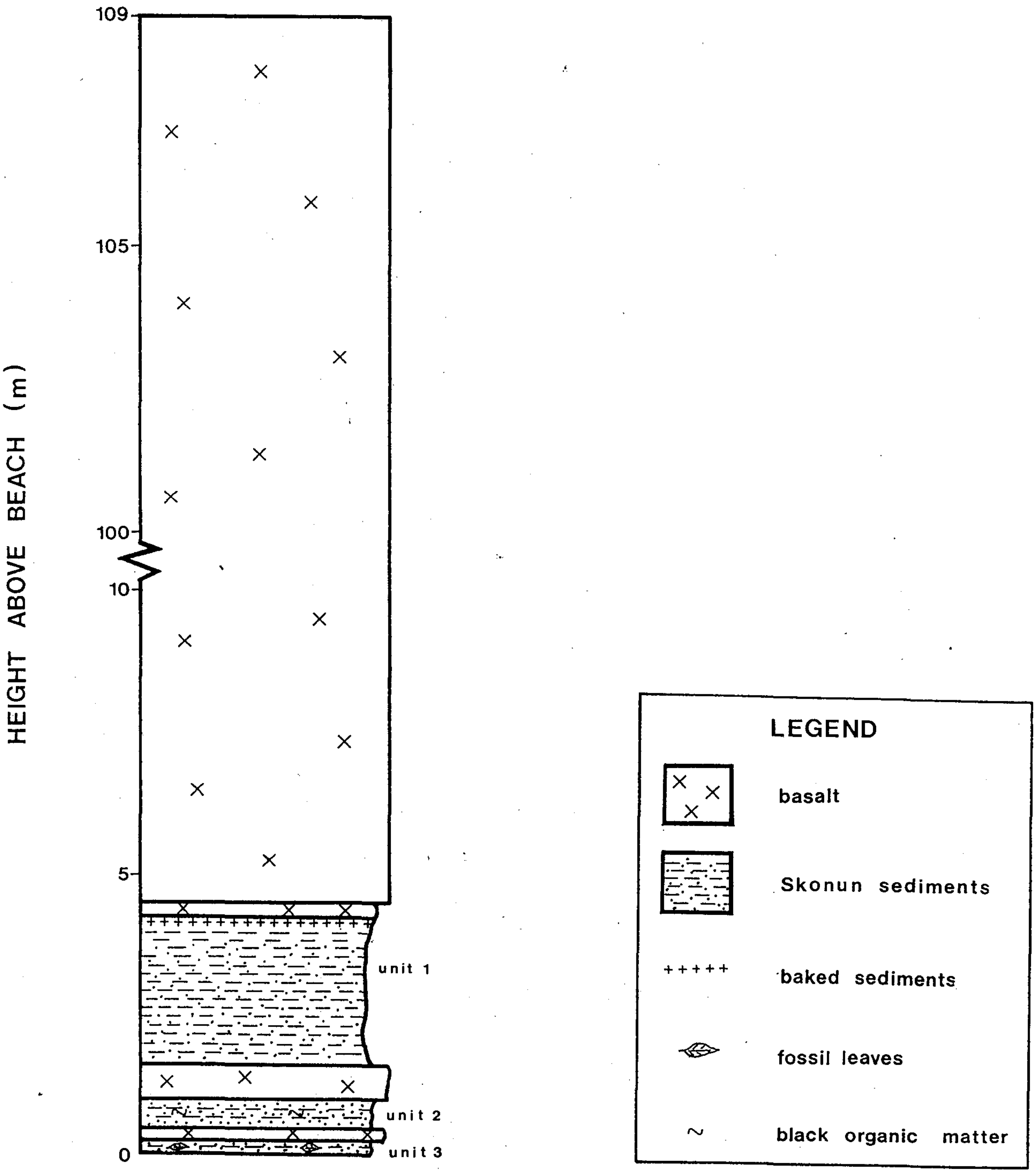
MACROSCOPIC FEATURES

As mentioned previously, the 109m high butte that makes up Tow Hill consists of basalt. This basalt layer is massive and is approximately 105m thick. Three additional basalt sills beneath this main body are much thinner and are interbedded with silty shale and sandstone of the Skonun Formation. The stratigraphy of Tow Hill is presented in Figure 2.1.

When examining the basalts of Tow Hill, the observer is struck with a complex array of numerous structures, such as columnar jointing, layering, possible fragmental material, lava tubes, and micro-sills. In addition, secondary features such as alteration, zeolitization, veining, and faulting are evident. Many of these features seem to fit the sill hypothesis, others support a more fragmental origin of the basalt body. Others give no indication either way. The sedimentary packages below the main body also may present a clue as to the origin of Tow Hill.

Figure 2.1. The three thin basalt bodies towards the bottom of the column are referred to as "thin sills". The thick basalt segment is the "main body". The height of the column marks an erosional surface so the minimum height of Tow Hill is 109m.

STRATIGRAPHY OF TOW HILL



2.1 Columnar Jointing

Columnar jointing is ubiquitous in both the main body of Tow Hill and in the underlying sills. The columns are most clearly visible on the steep cliff face of the main body and on a central knob of higher relief (Plate 2.1). Here, the joints are continuous and penetrate completely the entire cliff face, with no breaks or offset. The columns deviate slightly from a vertical orientation and do not bend. The floor of the beach exposure exhibits many polygons which mark the plan section of the columnar joints. They commonly have five or six sides and non-orthogonal intersections (Plate 2.2). Their diameters range from 80 to 120cm. However, towards the south of the beach exposure, their definition is slightly obscured perhaps as a result of weathering.

A sharp contact separates the columns of the main body from those displayed by the thin sill immediately beneath. The columns in the thin sill have the same orientation as those above but have smaller diameters of 20cm. If the other thin sills were jointed in this manner, weathering and erosion has since obliterated the evidence.

2.2 Layering

The outcrop exposed on the beach appears to be made up of gently dipping subparallel layers. Due to differential weathering, these layers form a sequence of less resistant zones separated by more resistant seams which stand out

(Plate 2.3a,b). Thickness measurements of numerous sequences at two different sites (Appendix, Table 1) reveal that the layers have an average thickness of 28cm and 32cm respectively. Furthermore, the sequences do not appear to have either a thinning or thickening trend vertically; vertical variations of the thickness are random. Similarly, the thickness along a single layer is not uniform. In fact, some layers obviously pinch and swell. Thickness measurements of an individual layer at regular 2m intervals yield an average thickness of 38cm (+7/-4cm). No matter how thick the entire sequence is, the more resistant seam retains a constant thickness of 6 to 7cm.

Most layers are laterally continuous over the extent of the outcrop (approximately 75m). However, in some instances, layers were observed to pinch out completely and others were notably discontinuous with some offset (Plate 2.4). The latter examples do not exhibit any evidence such as vertical fractures or breaks in the rock which would indicate that faulting has occurred.

In hand samples, there appears to be no chemical or mineral phase differentiation throughout a single layer and in addition, no variation of crystal size. The adjacent cliff face does not display evidence of layering. Thus, the presence of the layers does indeed seem to be dependent on the more intense erosion offered by the wave action.

2.3 Foreign Bodies

Not uncommon in the beach outcrop, are oddities which resemble foreign bodies imbedded in the rock. Their shapes are variable and include subrounded, angular, and string-like varieties (Plate 2.5a,b,c,d). Although they are present throughout the outcrop, in one area 20m north of the southern edge of the outcrop, subrounded and angular examples with diameters of 10-50cm are extremely abundant and form a group.

The bodies contrast with the surrounding basalt because they usually contain a higher percentage of zeolites and they weather less effectively and so have positive relief. In other cases, their colour is not consistent with the surrounding rock. Excepting these differences in hand sample, their mineralogy appears similar to the host rock. The more string-like varieties have a patchy distribution and are markedly zeolitized. Some contain zeolites up to 1.5cm in diameter.

2.4 Concentric Vesiculated Rings

Less commonly, the basalt on the floor of the beach exposure is marked by circular or oblate rings 13-30cm in diameter (Plate 2.6). The rings are more richly zeolitized than either the center of the rings or the surrounding basalt.

2.5 Micro-sills

Thin layers which resemble veins or "micro" sills are common in the southern section of the beach exposure. They are unusual in that they appear to have texture and mineralogy similar to the foreign bodies or vesiculated rings. They are 2-5cm thick, (thus the name micro-sill) and very resistant to weathering. Most are subparallel to the layered sequences previously described although some curve obliquely and cross through the layers (Figure 2.2). All micro-sills observed are laterally continuous for the extent of the outcrop. In one area, "fingers" of the material protrude perpendicularly from the micro-sill (Plate 2.7). They contain nodules of quartz.

2.6 Secondary Features: Alteration, Zeolitization, Veins, and Faults

Most, if not all of the exposed rock has been altered. The basalt is dark brown/gray and is mottled in hand sample. The basalt comprising the thin sills below the main body of Tow Hill are also altered but not so extensively. This could possibly be an illusion derived from the more finely grained nature of these basalts.

Zeolitization is ubiquitous in the Tow Hill basalts in the main body as well as those in the thin sills below. The diameters of the fibrous zeolite infillings are most commonly 1-2mm but a maximum of 3mm is occasionally observed. As mentioned previously, zeolites are more abundant in the

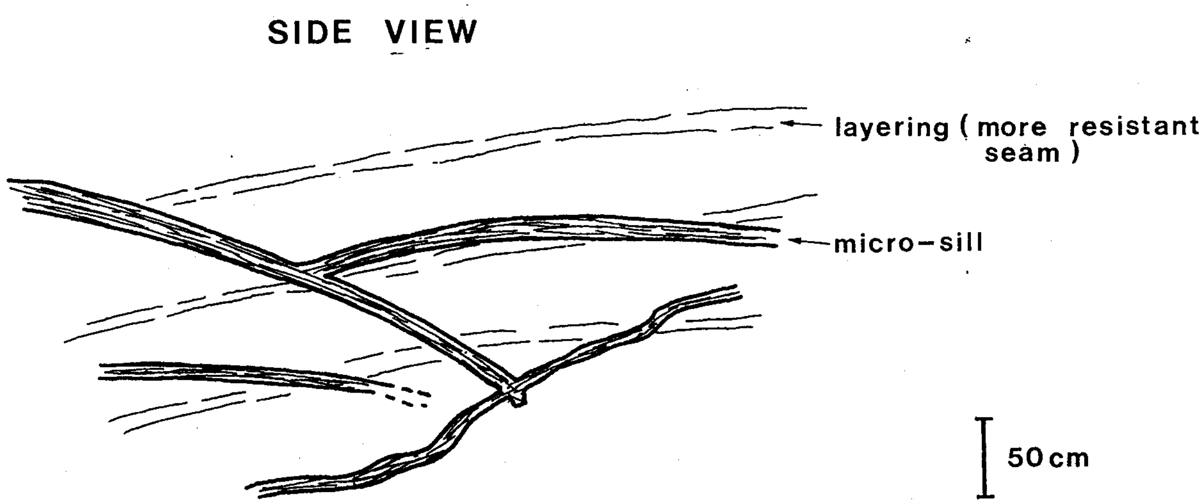


Figure 2.2. The micro-sills cross obliquely through the layering. Note also that the micro-sills amalgamate with adjacent micro-sills.

possible foreign blocks and rings. In these entities, they can reach up to 2cm in diameter although more commonly they exhibit diameters of 3-4mm.

Thin (1/2 cm thick) calcite and silica veins are present in the Tow Hill basalts. Although most of the veins are subparallel to the layers, they are not restricted to this orientation. Some run obliquely through the sequence of layers. Others outline the polygons which mark the columns (Plate 2.2). Little deformation has occurred in the immediate area of Tow Hill; however, two sets of faults trending approximately 15 and 120 degrees cut through the beach exposure. No offset or displacement is evident.

2.7 Sedimentary Units

Beneath the main basalt body are three packages of sedimentary rock of the Skonun Formation, each separated by thin basaltic sills. Sedimentary unit #1 (Refer to Figure 2.1) for the most part does not appear generally baked from the emplacement of the overlying basalt. However, some isolated areas exist immediately adjacent to the basalt above, where baking does seem to have occurred. These areas are 6cm thick, are more resistant, and have a distinct blue colour compared to their unbaked counterparts. These areas are only exposed where the shales appear to have been recently dug away so it is likely that this baking is only evident on the fresh surface. The contact of the shales with the basalts is very sharp. Undulations in the contact do not exceed amplitudes greater than 5cm.

In contrast, neither sedimentary unit #2 or #3 appear to have undergone baking from the emplacement of the sills that separate them. Curious irregularities have formed from the interfingering nature of the contact between sedimentary package #2 and the overlying basalts (Figure 2.3). The interfingering occurs in a number of three dimensional views in the outcrop and is not confined to mere two dimensional views. Both sedimentary unit #2 and #3 are more coarsely grained than the sedimentary unit above. Much organic material is present as discontinuous layers in sedimentary package #2 and in sedimentary package #3, fossil leaves are present.

2.8 Interpretation and Discussion

It is the existence of the continuous columns on the steep cliff face that indicates that the main body of Tow Hill is a single unit. Although a break in the columns would not necessarily indicate an hiatus in the accumulation of the unit, if an hiatus was present it most surely would show up as a discontinuity in the columns. Thus, this body is interpreted as a single cooling unit. It is well known that columnar jointing is not confined to extrusive lava lakes but commonly form when there is a thermal gradient in sills, dykes, and plugs. Thus, neither the sill or lava flow

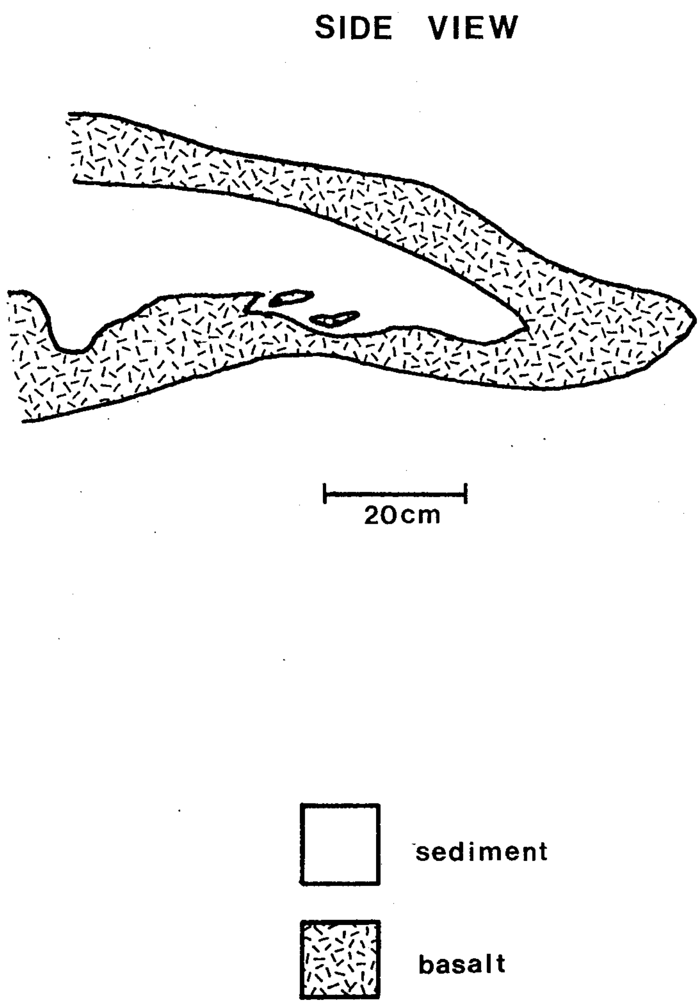


Figure 2.3. Irregular or "brecciated" contact of the thin basalt sill with the Skonun sediments. Although this is a two-dimensional side view, similar surfaces are displayed on the top and the other adjacent faces.

hypothesis can be rejected by this evidence. Furthermore, columnar joints can also form in many sedimentary materials (DeGraff and Aydin, 1987) just as long as contraction due to cooling is possible. Therefore, thermally induced joints could concievably form in a fragmental volcanic pile if the pile was rapidly emplaced and the heat retained. Therefore, the hydroclastic fragmental pile hypothesis cannot be rejected either on the basis of the presence of columns. However, one constraint is now placed upon it. If Tow Hill is made up of hydroclastic material, the material was emplaced rapidly and if not in one episode, a few events in quick succession. No reworking of the fragments by water is likely to have occurred because this would have acted to dissipate the required heat for thermal contraction.

The process(es) which formed the layering in the Tow Hill basalts is(are) not well understood. Therefore, the relevance of the layering in interpreting the origin of Tow Hill is not strong. Thus, various proposals concerning their mode of development are highly speculative. Layering sometimes develops parallel to the sill/host rock interface as a result of differentiation. The layers in the Tow Hill basalts are indeed parallel to the contact with the underlying sediments, however, no colour or mineralogic variation is evident in the layers. Thus, differentiation does not seem to be a suitable mechanism for the formation of the layers.

The layers may mark individual events of explosive hydromagmatic activity (which occurred in quick succession), with each pair of non-resistant and resistant zones representing a fining upward sequence. Since the layers would thus be a sedimentary phenomenon, the few layers which appear to be pinched out could be due merely to the absence of deposition in that area during the emplacement of the layer. Nonetheless, the weathering is not adequately explained; and there is no evidence of a fining upward sequence in the layers.

A third and most likely possibility as to the mechanism of layer formation is that they are a result of the incremental growth of columnar joints. It is now evident that columns produced by contraction grow incrementally as a result of cycles of tensile stress build-up and release during cooling (DeGraff and Aydin, 1987). Each period of growth is represented by a band oriented normal to the columns. A stereographic projection shown in Figure 2.4 illustrates that the layers are indeed, normal to the column orientations. Although the examples of horizontal bands that DeGraff and Aydin (1987) describe are discontinuous across the vertical joint sets, in all other respects, the Tow Hill layers are very similar. These authors include photos in their paper of bands pinching out (Figure 8, Figure 9, 1987) which they attribute to the overlap of noncoplanar cracks. They greatly resemble the few

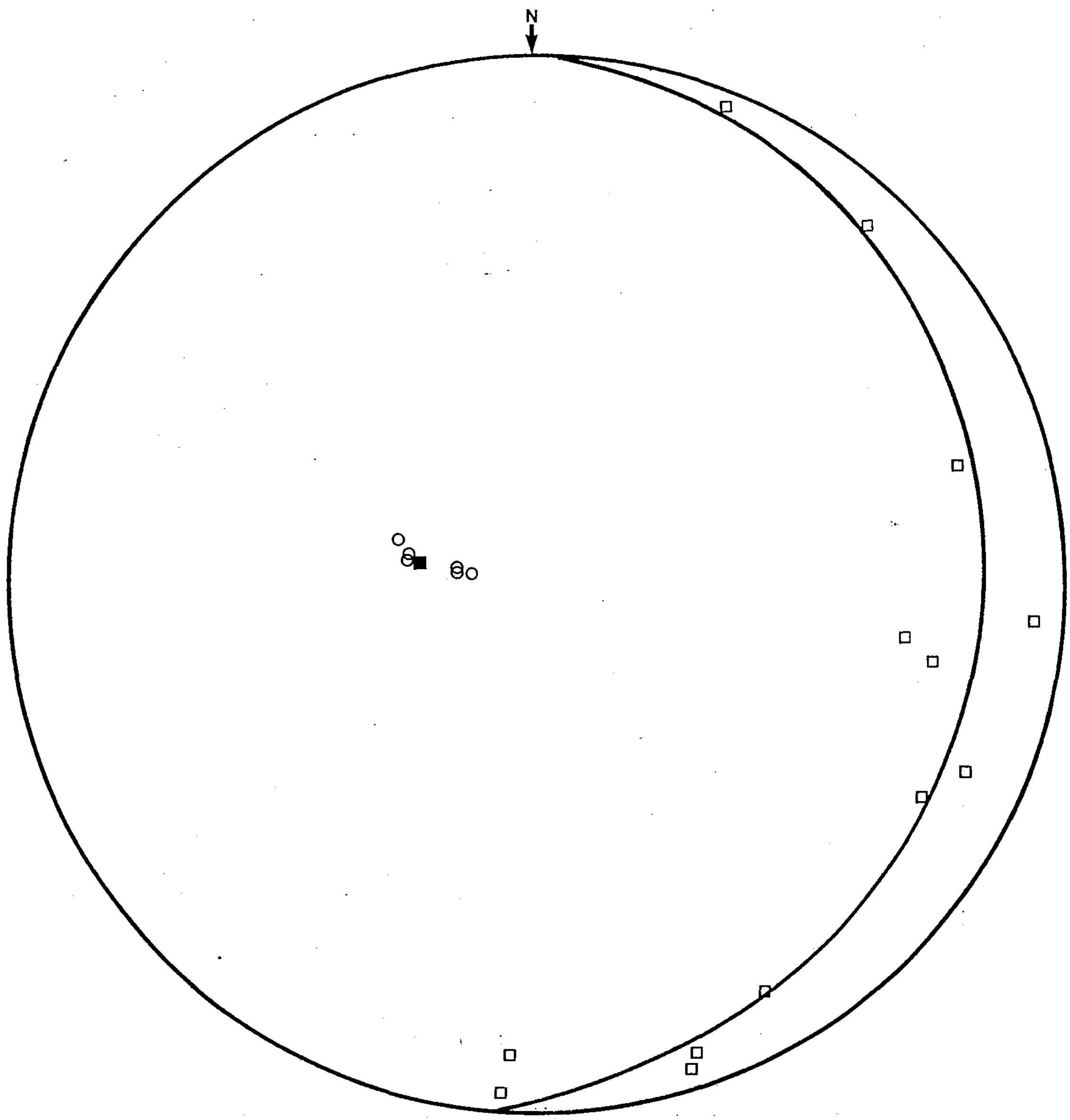


Figure 2.4. Stereographic projection illustrating the perpendicular orientation of the layers to the columns. Open circles are poles to the layers. Open squares are poles to the column faces and are joined by a best-fit great circle. Closed square is the mean longitudinal axis of the columns.

examples of band pinch-out at Tow Hill (Plate 2.4). In addition, every photo displayed in their paper exhibits differential relief in the bands, similar to those observed at Tow Hill. It is difficult to say with certainty that the layers are due to cross joint processes because the plumose structures on each band on the column face which indicate that such a process was prevalent (DeGraff and Aydin, 1987) have since been weathered away at Tow Hill, if they were once present. One other problem is the fact that the steep column face is not marked by similar horizontal layers. They should be evident if this process occurred. Perhaps, though, the original bands were less distinctive over Tow Hill and subsequent minor differences in deuteric alteration on the jointing surfaces on the beach exposure has caused their differential relief. Nonetheless, if this cross-jointing process associated with columnar jointing was responsible for the development of the horizontal layers, neither the lava flow, sill, or hydroclastic pile hypotheses can be rejected since it has already been concluded above that columnar jointing could possibly have been produced in all three cases.

The "foreign" bodies could also have several possible origins. Unfortunately, it is difficult to give them a name that does not also have genetic connotations. Thus, it must be stressed that the name "foreign body" does not necessarily mean that these entities are secondary additions to the original basalt body, but that they only look as if they are.

If Tow Hill is the result of a hydroclastic deposit or lava flow, the foreign bodies and concentric vesiculated rings could simply be bombs or blocks that were included in the deposit. These could be derived from the walls of the subvolcanic basement or from other local flows; in the latter case, the mineralogy of the block would be very like the host flow. However, in the case of a hydroclastic deposit, one would expect an explosive eruption to produce some lithic blocks derived from the underlying strata, the Skonun sediments. None were observed. All "foreign bodies" and rings examined appear to have the same mineralogy as the host rock and as described below, they are similar in thin-section and chemistry to the surrounding rock. In the case of a basaltic lava flow, the probability of lithic blocks derived from the surrounding sediments and being carried by the flow is not as great. Bombs have variable shapes and the many varieties of the foreign bodies and rings at Tow Hill could be attributed to this. For example, the string-like bodies could be ribbon bombs, and the more angular ones could have been almost solidified when erupted (Williams and McBirney, 1979). If so, the string-like varieties indicate that the vent is proximal to and probably within 1km of Tow Hill.

Extensive vesiculation is common in bombs and they tend to be spheroidal except in the case of ribbon bombs where they are usually tubular. In ellipsoidal bombs they are generally arranged in a concentric pattern marking the outline of the bomb (Williams and McBirney, 1979). The rings which exhibit a concentric arrangement of the zeolites (which mark the vesicles) may be derived from this type of bomb. An additional proposal as to the origin of the zeolite-rich rings postulates that they mark the quenched skin of lava tubes. They do resemble examples of those observed in the flows of Mt. Etna (Clifford, pers.comm.). If Tow Hill is the result of emplacement of a basaltic sill, the foreign bodies observed could be xenoliths torn from the walls of the magma chamber. They are probably not brecciated fragments from the chilled margin of the sill which have been carried into its interior because there is no evidence of a chilled margin, nor of brecciation or fragmentation at the Tow Hill basalt-thin basalt sill contact. It is plausible that the vesiculated rings could be inhomogeneities within the basalt intrusion although a question arises as to the nature of the inhomogeneity. Usually, areas of greater vesiculation in sills occur as long thin strings of vesicles which occur close to and parallel to the contact with the underlying and overlying strata. Again, none of the three presented hypotheses regarding the origin of Tow Hill can be rejected or accepted. Each model can at least adequately explain the presence of the foreign blocks and vesiculated rings.

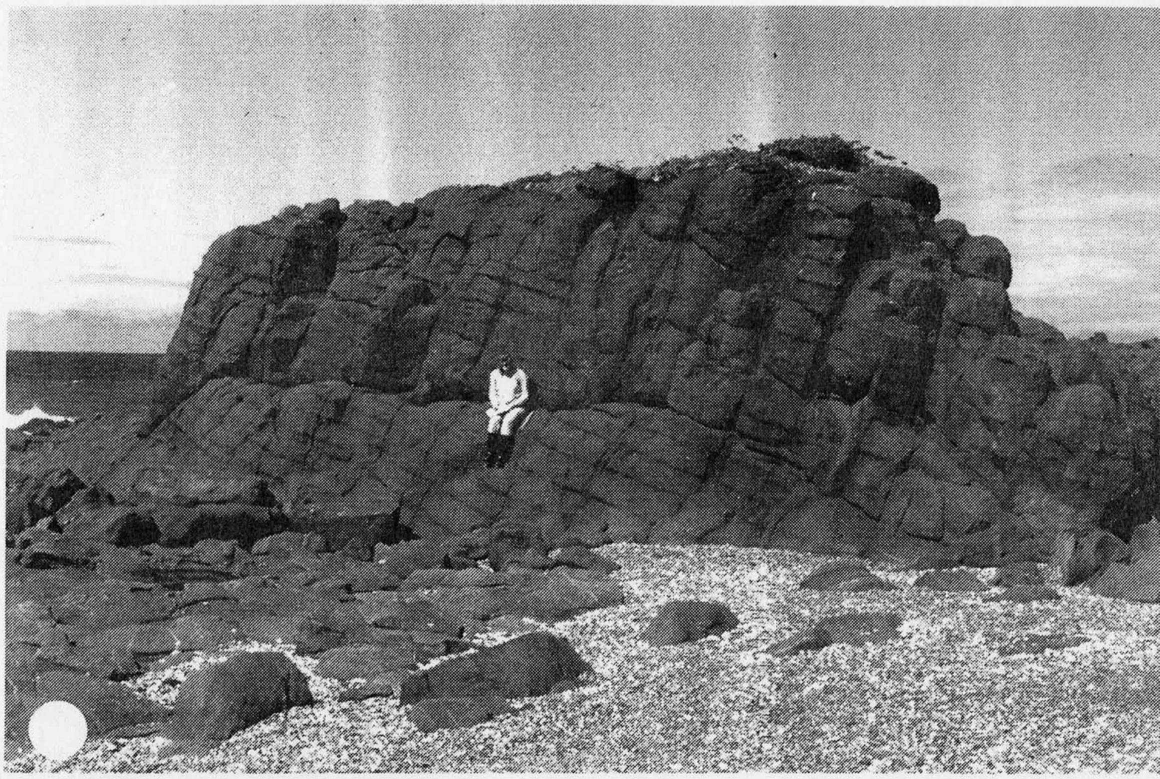
The name "micro-sill" is interpretive and it is stressed that these forms only <u>resemble</u> micro-sills and their identity is not to be inferred from the name. Micro-sills could either be an early or late feature of Tow Hill. If early, they could represent several chilled tops of overlapping lava flows. They certainly have the correct near-horizontal orientation. However, these micro-sills put a constraint on the lava flow hypothesis. If a series of flows make up Tow Hill, they must have been extruded in quick succession in order to cool as one entire unit. One problem with this is that in some cases, the micro-sills cross obliquely through the horizontal layering, indicating that the layers were formed before the micro-sills. If the layers are the result of cross jointing during the growth of the columns as seems likely, then they would have formed after the micro-sills. Furthermore, if the layers are formed due to tensile stress, the layers should be affected in the immediate vicinity of the micro-sills because the tensile stress field would have been altered. No such evidence is present. Therefore, quenched flow tops do not seem to be a probable origin of the micro-sills. Most likely, they represent later sill intrusions which occurred after the main body of Tow Hill was emplaced and cooled. In hand sample, and in thin section a 5-7mm chilled (not glassy) margin with a parallel vesicle train is evident on the top of one such micro-sill. Unfortunately, the bottom of the micro-sill was not sampled and it could not be deduced if there was a corresponding chilled margin and vesicle train on the bottom of the micro-sill. The thin chilled margin also implies that these features are not flow tops because a glassy or aphanitic texture would be evident. This is not the case. Nonetheless, the micro-sills do not shed light on the origin of Tow Hill since their emplacement probably succeeded the formation of the basalt that makes up this body.

The secondary features described in section 2.6 do not disclose the origin of Tow Hill, although they are important in understanding some of the changes or processes that have taken place since the formation of this body such as alteration. Alteration of olivine crystals to serpentine and chlorite has occurred extensively but not completely throughout the outcrop. As will be noted in the next chapter, the least weathered samples show fresh well-developed olivine crystals with a lack of serpentinized or chloritized rims. However, in hand sample, they all have the same appearance. Therefore, alteration was probably extensive and thus, due to interactions with hot fluids.

In summary, the macroscopic features described do not immediately define an origin for the basalts of Tow Hill. Nonetheless some valuable points can be concluded. Firstly, the main body cooled as a single unit, thus producing continuous, uninterrupted columns. The horizontal layering, given its perpendicular orientation to the columns and its morphology, is likely representative of the cross joints related to columnar jointing. Secondly, fragmental evidence is limited to the foreign bodies and concentric vesicle-rich rings; fragmental texture throughout the basalt itself is absent. Furthermore, these features can just as easily be explained in terms of the lava flow and sill hypotheses. Thirdly, the micro-sills are probably later injections of magma/lava which succeeded the emplacement of Tow Hill.

Plate 2.1. Columnar jointing on a knob of higher relief. The joints are continuous and no breaks or offset is present.

Plate 2.2. Calcitic veinlets fill the cracks which mark the polygonal outlines of the columns. Plan view.



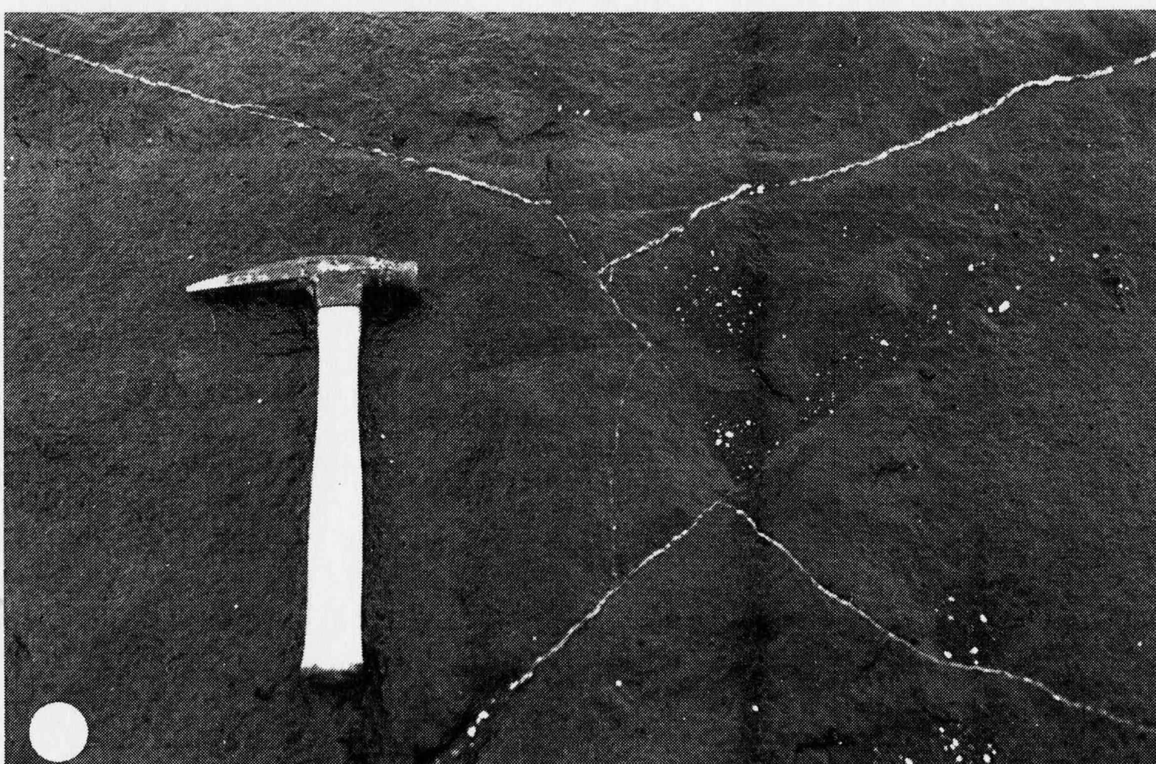


Plate 2.3a. The more resistant seams are thin (6 to 7cm) and are located at the hammer head. The less resistant zone makes up most of the layer sequence and is located at the handle of the hammer.

Plate 2.3b. Another view of the layering. The shadow cast by the hammer illustrates the relief exhibited by the more resistant seams.

Plate 2.4. Arrow A marks layers which pinch out. Arrow B marks a discontinuous set of layers with offset.

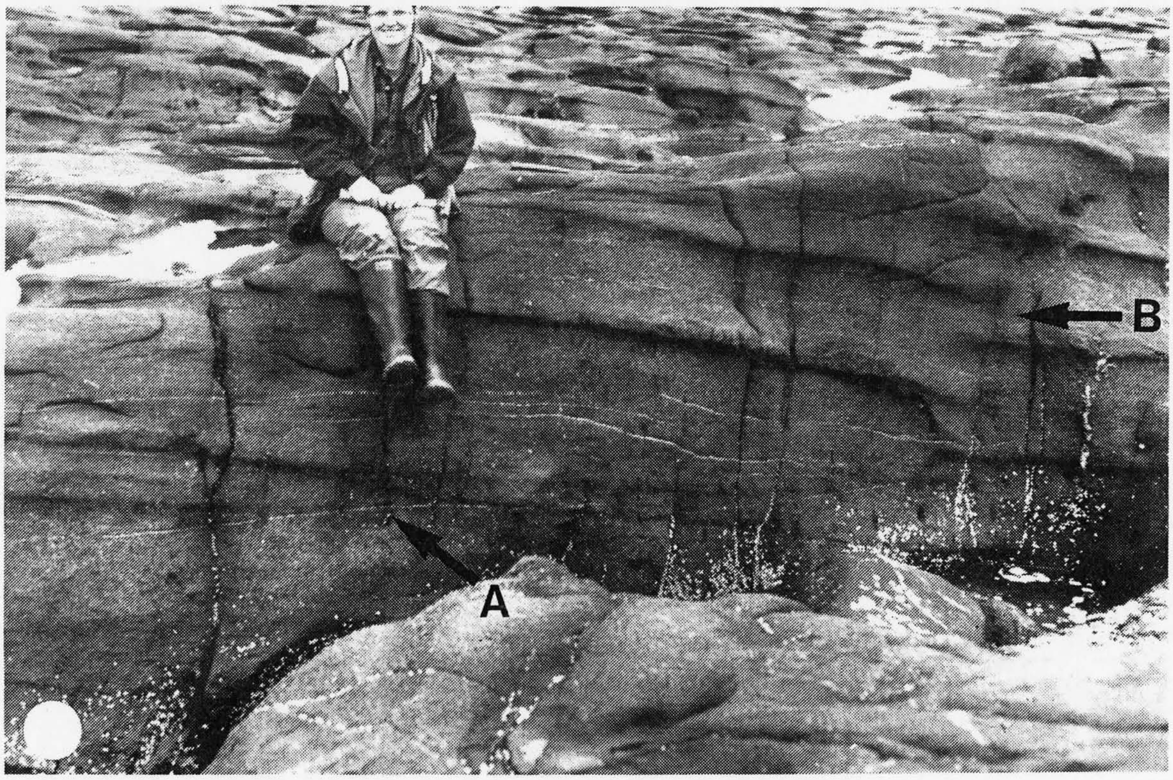

B
A

Plate 2.5a. Solitary subrounded foreign body. It exhibits higher relief and more extensive zeolitization than the surrounding host rock.

Plate 2.5b. String-like variety of foreign body. Note the large zeolite aggregates which have filled the vesicles.

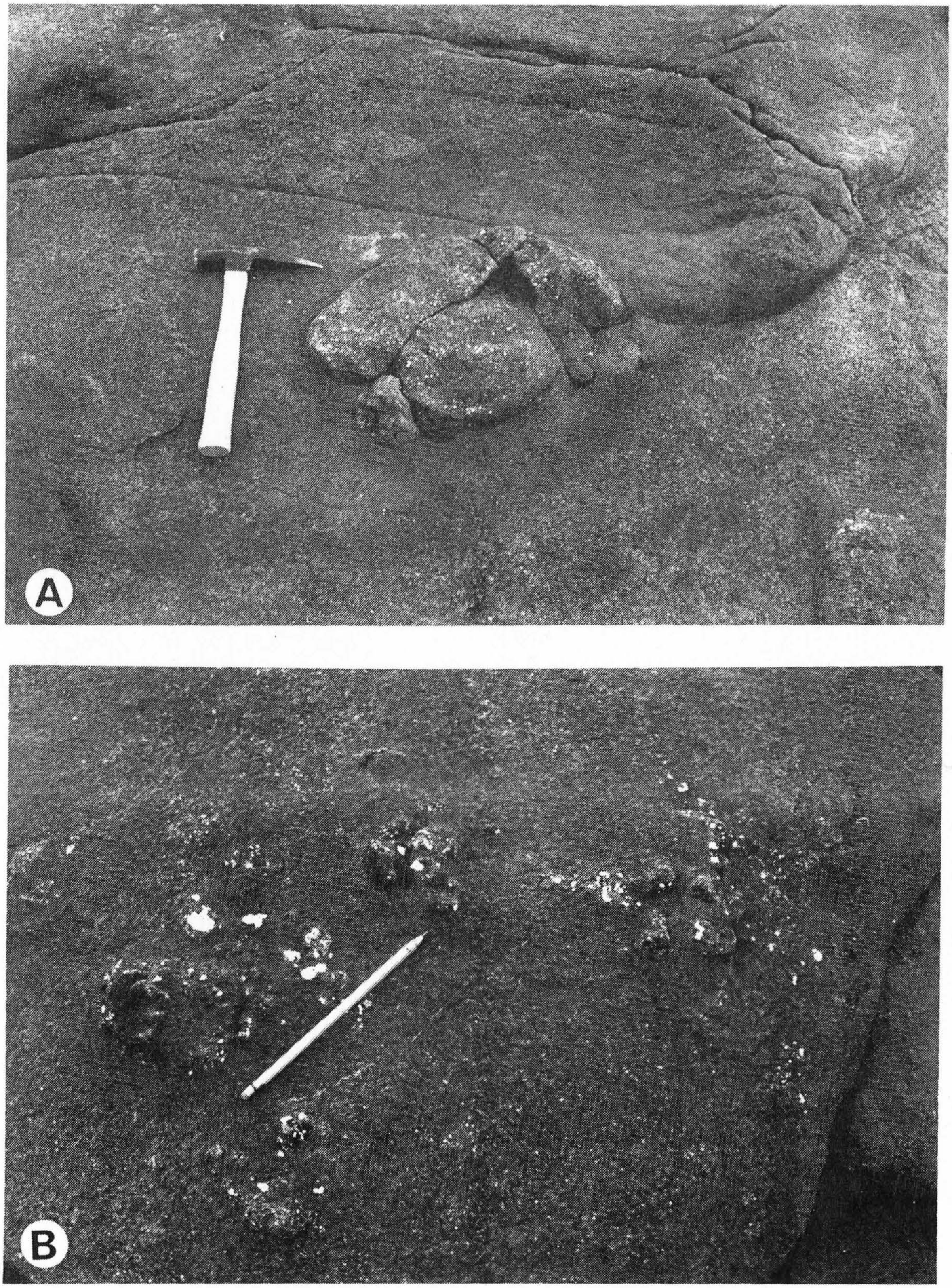
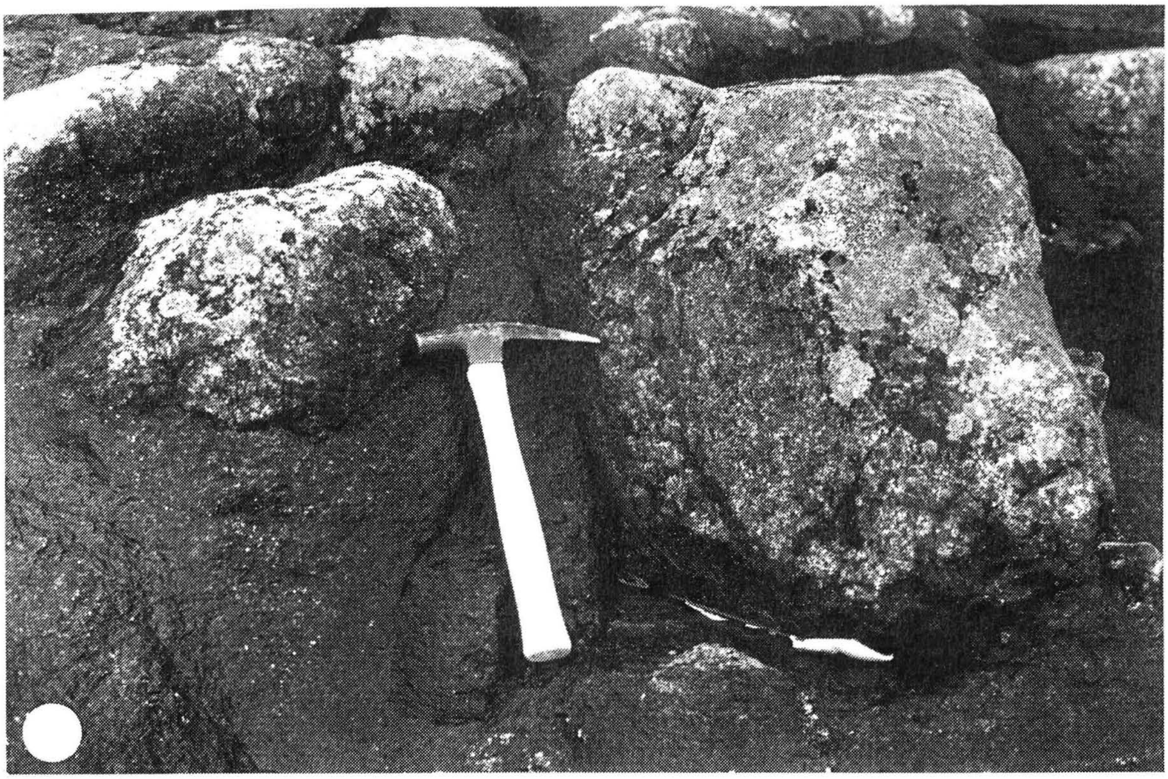

A
B

Plate 2.5c,d. A group of subrounded foreign bodies which were found 20m north of the southern edge of the outcrop. They are more resistant than the surrounding rock so have higher relief. (c): a close-up view showing the "squeezed" appearance of the host rock. (d): a larger field of view displaying the clustering nature of the bodies. The pogo stick is 1.5m long.



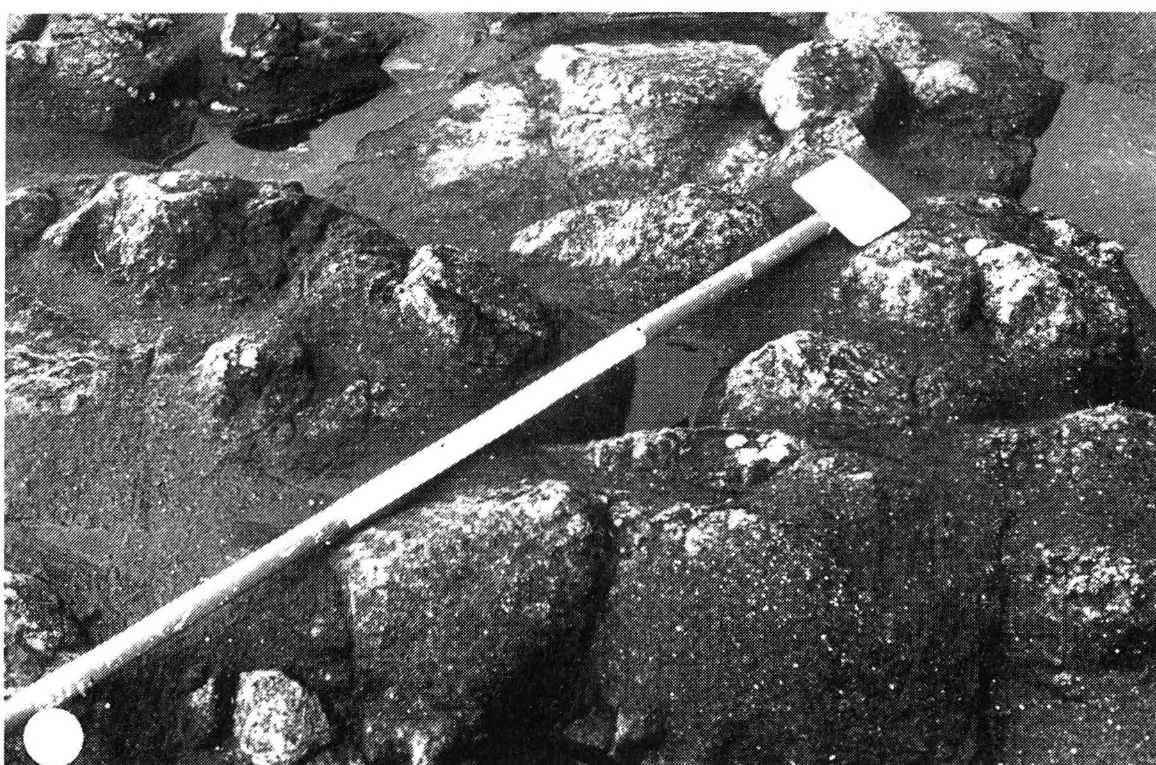
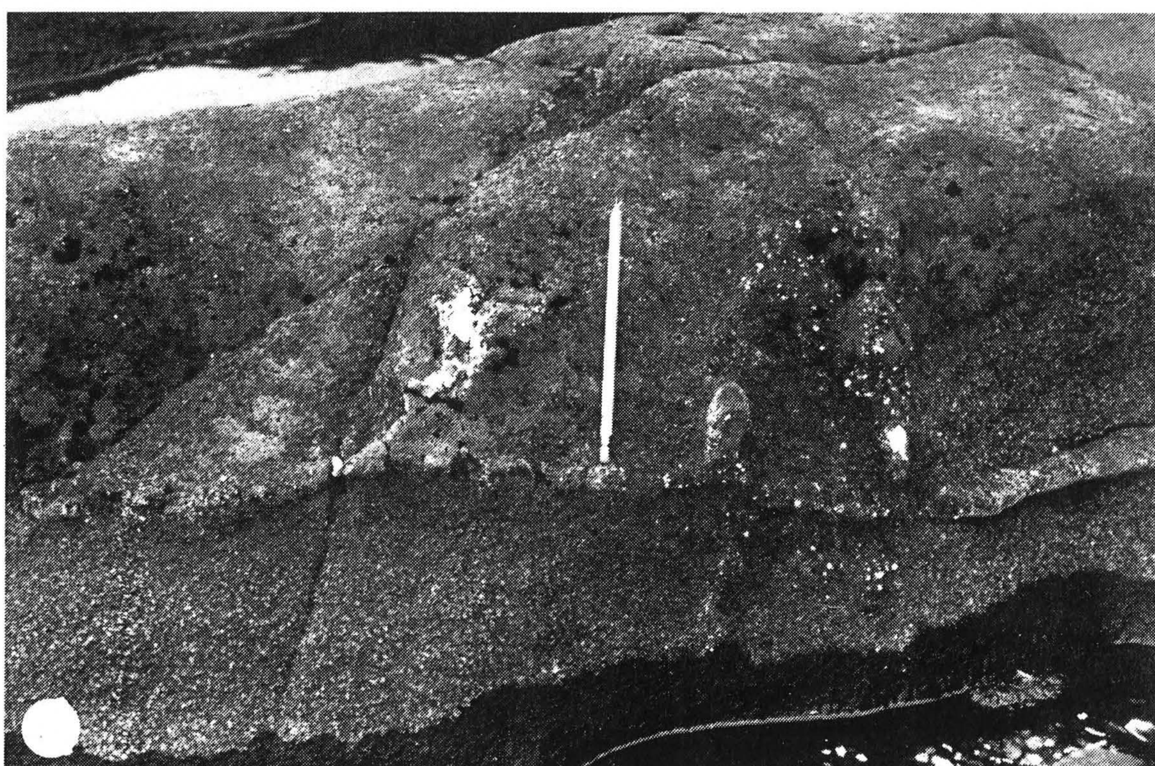


Plate 2.6. Concentric vesiculated ring. Note the enrichment of the zeolites which mark the high vesiculation of the ring compared to the host rock. The material which infills the ring is similar to the host rock.

Plate 2.7. Micro-sill displaying "fingers" which protrude from the otherwise near horizontal orientation of the micro-sill.



CHAPTER 3

PETROGRAPHY

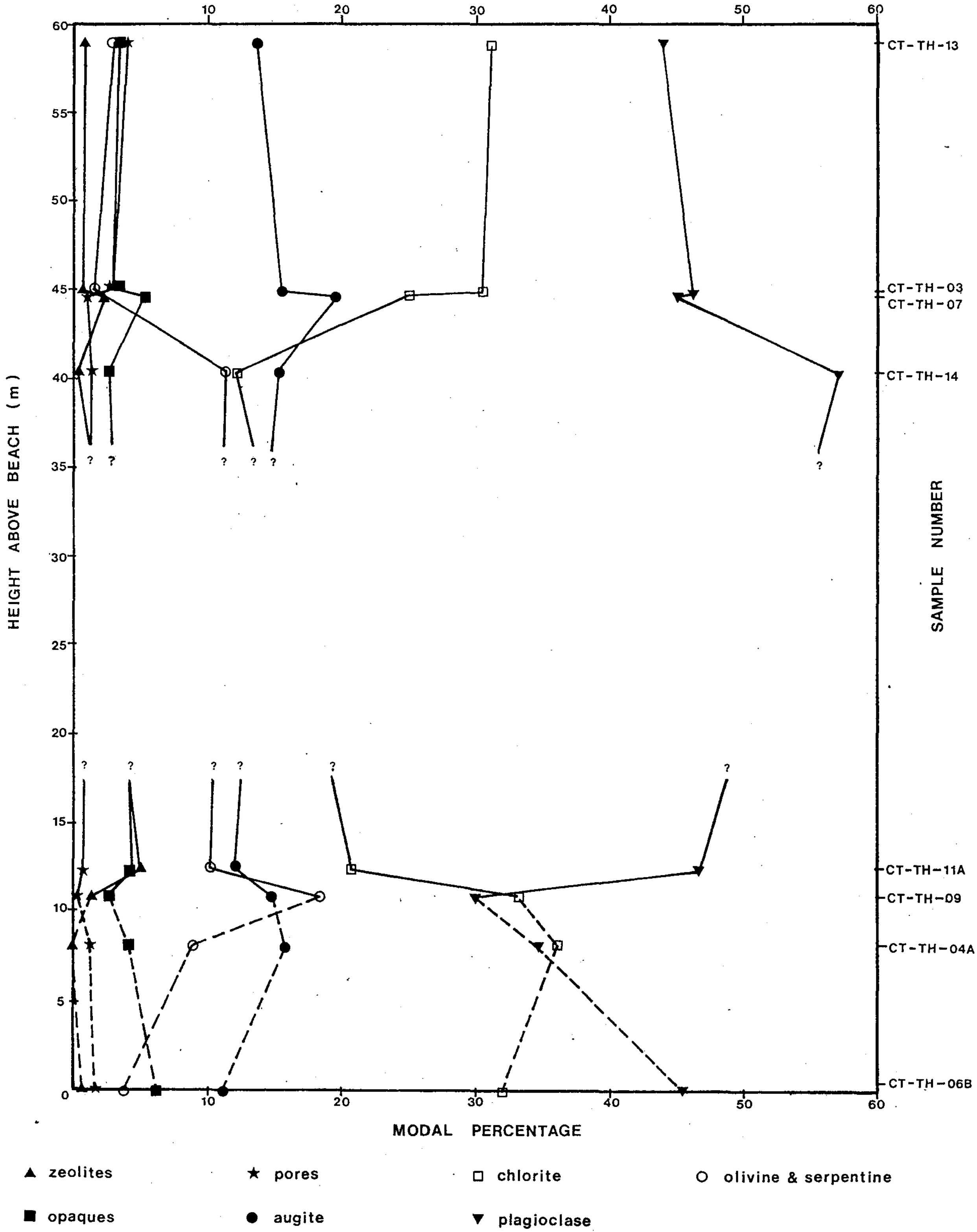
Thin sections of the main body basalts, the thin sills beneath, the foreign bodies, and the micro-sills were examined in order to determine the mineralogy and textural relations of the minerals. In addition, thin sections of the sedimentary units including the baked margin were studied. In all cases, a modal analysis was performed using a minimum count of 2000 points. The data are recorded in the Appendix, Table 2 and the modal percentage of the minerals is plotted against height in Figure 3.1.

3.1 Basalts of the Main Body

These basalts have plagioclase, clinopyroxene, and olivine (often serpentinized) as their main constituents. Opaques are present as accessory minerals and chlorite and serpentine are alteration products of olivine and possibly of glass given its interstitial character. In addition, zeolites and less often, calcite form infillings of vesicles.

Plagioclase is the most abundant mineral, making up about 45% of the rock in most of the samples. However, there are extreme values depending on the severity of the alteration. Sample CT-TH-09, which exhibits the most alteration of the samples examined, is more depleted in plagioclase compared

Figure 3.1. Variation of the modal percentage of each mineral with height. The greatest variations with height occur with plagioclase, chlorite, and olivine + serpentine. Refer to text. The section of the column from approximately 12m to 40m was not sufficiently sampled to allow a continuous line to be drawn to join samples CT-TH-11A and CT-TH-14. The dashed lines represent the trend through the thin basalt sills.


10
20
30
40
50
60
HEIGHT ABOVE BEACH (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
CT-TH-13
CT-TH-03
CT-TH-07
CT-TH-14
CT-TH-11A
CT-TH-09
CT-TH-04A
CT-TH-06B
SAMPLE NUMBER
MODAL PERCENTAGE
▲ zeolites
★ pores
□ chlorite
○ olivine & serpentine
■ opaques
● augite
▼ plagioclase

with the norm as it only contains about 30%. Conversely, sample CT-TH-14 is much fresher than the norm and contains 57% plagioclase. The composition of the plagioclase in all of the main body basalts is An_{46-57} (determined from Michel-Levy tests). The subhedral to euhedral laths have a variable size with a maximum length of 3mm. Although plagioclase is distributed uniformly throughout the samples, the smallest crystals are intimately associated with clinopyroxene. Despite the alteration of other mineral phases, plagioclase does not appear altered in the least.

Clinopyroxene, which is probably augitic in composition, forms large (up to 5mm), tabular, subhedral phenocrysts. These are very fresh.

Olivine is a diagnostic mineral of the Tow Hill basalts and its presence was one of the governing factors which prompted the exclusion of Tow Hill as part of the Masset Volcanics as the Masset rocks contain no olivine (Sutherland Brown,1968). Commonly, euhedral serpentinized pseudomorphs after olivine are the only clue to this mineral's presence in the Tow Hill basalts. Many of the pseudomorphs are now hollow. In other, fresher samples, olivine is unaltered except for a thin rim of serpentine and chlorite around the perimeter. Olivine crystals are usually clustered in large groups of up to approximately ten small crystals, although they are not confined to this arrangement.

Opaques are the only primary accessory mineral present and occur as small anhedral to subhedral grains. They are evenly distributed throughout the sample and do not appear to be specifically associated with other minerals.

Chlorite is ubiquitous in all of the samples. It is an alteration product of olivine and possibly also of glass. It forms brown amorphous material in the interstices of the other minerals and is especially common proximal to the glomerocrysts of olivine. Chlorite and serpentine are very difficult to differentiate because of their close association and similar optical properties.

Texturally, the basalts are holocrystalline and medium to fine grained glomeroporphyritic. The continuous size range of plagioclase give the rock a seriate texture as well. Plagioclase laths are often partially or wholly embedded in the clinopyroxene, thus exhibiting a subophitic texture in the augite phenocrysts. Plate 3.1a,b is a typical sample of the basalt from this area.

3.2 Basalts of the Thin Sills

The composition of the thin sills is identical with the main basalt body above and the abundance of each mineral phase is also very similar in each area. Texturally, however, differences are distinctive. Plagioclase is again the most abundant constituent of the sample, making up about 40% of the total. Two populations of plagioclase crystals are present, one of which forms subhedral to euhedral phenocrysts up to 1.5mm in length and commonly forms clusters. The second group are very fine grained and make up a portion of the aphanitic ground mass.

Clinopyroxene is not present as phenocrysts and is only present in the ground mass. Due to its microcrystalline nature, it is difficult to assess the pyroxene's composition; however, it is probably augite.

Olivine phenocrysts have been fully altered to serpentine and chlorite and their original euhedral habit is now marked by hollowed out serpentinized pseudomorphs. Both single crystals and glomerocrysts are evident.

All other constituents of these basalts, such as opaques, are confined to the ground mass. The texture of the thin sill basalts is holocrystalline porphyritic. Glomerocrysts of both plagioclase and olivine as well as single crystals of these mineral species make up the phenocrysts (Plate 3.2a,b). Vesicles and zeolites are extremely rare.

3.3 Basalts of the Foreign Bodies

The mineralogy of the foreign bodies is almost identical to the basalts of the main body and the thin sills. Plagioclase is the most abundant constituent only in the larger blocky bodies. In the more string-like bodies, a mere 13% of the sample is plagioclase. In both types of bodies however, plagioclase is subhedral to euhdral and has a more restricted size range. Crystals do not exceed 2.5mm in length and laths less than 1mm long are absent. Phenocrysts of anhedral tabular clinopyroxene (probably augite) are the largest crystals in the samples.

Olivine only exists in the blocky bodies and its absence in the string-like bodies is the only remarkable difference of mineralogy between these entities and the rest of the basalts. The olivine in the blocky bodies is remarkably fresh; any alteration is restricted to very thin rims on the perimeter of a few crystals. The amount of chlorite, an alteration product, is considerably less in these samples as compared to the other basalts (Appendix, Table 2). The crystals of olivine are euhedral and most commonly form glomerocrysts although they are not restricted to this arrangement.

The crystal shape and habit of the opaques also differ in the two types of foreign bodies. In the blocky examples, they are minute, anhedral specks which are evenly distributed throughout the sample. In contrast, the opaques in the string-like varieties are skeletal or acicular and form needles up to 8mm in length and have no preferred orientation. Some stubby, anhedral forms are also present. Both types are distributed evenly throughout the sample.

Chlorite and serpentine are abundant in the string-like bodies. Perhaps olivine was present but severe alteration has obliterated the olivine to yield serpentine pseudomorphs. Zeolitization has been extensive in these same samples; the zeolites have a variolitic texture in the circular vesicles.

The textures of each type of foreign body are dissimilar. The texture of the blocky bodies is holocrystalline equigranular with glomerocrysts. The string-like varieties have a holocrystalline inequigranular texture with phenocrysts of clinopyroxene. Both types show a subophitic relationship between the pyroxene and plagioclase.

3.4 Basalts of the Micro-sills

Plagioclase has a more restricted size range similar to that exhibited in the foreign bodies. Crystals smaller than 1mm in length are rare and those that are present are embedded in the clinopyroxene, forming an ophitic texture. Augite is the probable composition of the clinopyroxene and it forms large subhedral tabular crystals.

Olivine is very fresh with alteration to serpentine and chlorite limited to a thin border around the euhedral crystals. A few crystals are completely altered to serpentine pseudomorphs. The olivine commonly forms glomerocrysts, similar to most of the basalts of Tow Hill.

The opaques show various crystal shapes including stubby, acicular, and curious skeletal forms. Texturally, these basalts are holocrystalline equigranular but have a marked variation in crystal size, spatially. The top of the micro-sill is finely crystalline whereas the interior is characterized by medium sized crystals. Due to the unavailability of the bottom portion of the micro-sill sample, the crystal variation in this region cannot be ascertained.

3.5 Sedimentary Units

Sedimentary unit #2 in between the two lowermost thin sills (sample CT-TH-05A) is a medium grained poorly sorted silty sandstone made up of a large variety of mineral species. Angular quartz and plagioclase are most abundant. Biotite, closely associated with opaques and organic material, forms horizontal stringers across some areas of the sample. Less common minerals include hornblende, olivine, bent crystals of muscovite, clinopyroxene, and garnet. Calcite cement and in some areas, mud, surrounds most of the grains entirely and very few grains are in contact with one another. Thus, these clastic sediments are matrix supported where the matrix is cement and/or mud. Porosity is low due to the poorly sorted nature of the sediment. Metamorphic recrystallization of the sandstone is absent even though the sample was taken less than 10cm from the contact with thin sill basalts.

The sediments (unit #1) from just below the contact of the uppermost thin sill (sample CT-TH-04B) is very fine grained in thin section (Plate 3.3a,b). A few small particles including quartz and plagioclase are embedded in a felted ground mass in which at least chlorite is present. Other minerals cannot be discerned with the optical microscope. Organic remains form very thin stringers parallel to the bedding.

3.6 Interpretation and Discussion

It is immediately evident when examining thin sections of the basalts of the main body that a hydroclastic origin of Tow Hill is unlikely. Each sample is completely crystalline, exhibiting only textures which result from a cooling magma without interruption. Furthermore, evidence of fragmental material such as broken fragments or shards is lacking.

Plate 3.4a,b illustrates the "most fragmental-looking" example studied. Even so, plagioclase and augite display subophitic texture which pervades the rock. It is possible that such obviously intergranular textured areas are large fragments made up of crystalline material; however, no examples of broken crystals, a binding cement, or evidence of recrystallization around the perimeter of these areas is present in any of the thin-sections studied. Thus, based upon petrographical evidence, it does not seem probable that the origin of the Tow Hill basalts was from a hydroclastic eruption. Instead, the basalts were derived from uninterrupted cooling of a magma or lava.

Some information about the cooling history of the magma/lava can be gained by the examination of the textures of these basalts. Euhedral olivine was probably the first mineral to crystallize on the grounds of its shape and much of its development probably occurred before the final emplacement of Tow Hill. The olivine crystals are not larger than the other crystals of plagioclase and augite. Thus, crystallization of these phases were probably in close succession to the olivine. Or, perhaps the growth rate of the latter minerals was faster. The glomeroporphyritic nature of some of the olivine indicates that perhaps flotation of plagioclase and sinking of olivine and pyroxene occurred prior to the arrival of the magma/lava in the sill or flow which resulted in this texture. Nonetheless, simultaneous crystallization of augite and plagioclase occurred to develop the subophitic texture. Flow fabric is absent and the random arrangement of all the mineral phases and the circular vesicles indicates that the basalts cooled in a quiet environment perhaps either as a shallow intrusion or as a lava lake.

The porphyritic texture of the thin sills indicate that possibly two "stages" of crystallization occurred. The first stage involved a slower cooling rate, probably at a depth where the phenocrysts of olivine and plagioclase could develop around sparse nuclei. The second stage of crystallization was instigated by a rapid injection of the magma into cold wall rocks or by an eruption at the surface. These conditions would lead to a higher nucleation rate and nucleation density in the remaining magma/lava so forming the fine-grained ground mass which surrounds the phenocrysts.

Correspondingly, there are two plagioclase "types" in the main body of Tow Hill. The plagioclase phenocrysts, devoid of intergrown clinopyroxene, are type I and presumably are equivalent to the phenocrysts of the thin sills. Type II plagioclase is generally smaller, and occurs in subophitic intergrowth with augite. These are interpreted, as for the thin sills, as early, low nucleation density plagioclase, crystallizing in the absence of augite; and late, high nucleation density plagioclase, crystallizing simultaneously with augite. The later plagioclase in the main body is not very different in size from the early plagioclase and is not always easy to distinguish by size. Presumably, this is because the main body is much thicker than the thin sills, and so suffers less drastic undercooling than the thin sills. This would yield generally lower nucleation densities and growth rates.

The textures of the foreign bodies are somewhat different from the basalts desribed above. They are no finer grained than the basalts of the main body, indicating that cooling did not occur at a faster rate. If these bodies are bombs or lithic blocks, they must have been almost completely solidified before their flight through the air. Another possibility is that their flight time was short (seconds only in most cases) which helped to prevent rapid internal cooling. The string-like varieties exhibit much more intense vesiculation compared to any other basalt studied. This indicates that these bodies solidified from magmas saturated with a gas phase.

An alternative hypothesis suggests that the blocky type of foreign bodies are perhaps blocks or clots of magma partially crystallized before being swept up by the main flow material. Support for this contention is provided by the fact that large amounts of fresh olivine crystals are present which possibly implies a cumulate texture. If so, the source of such clots would be from deep within the main magma body where heavier olivine crystals would have accumulated. As this olivine cumulate was carried away from this source, plagioclase and pyroxene crystallized simultaneously, filling in the interstices between the glomerocrysts of olivine.

The acicular and skeletal form of the opaques in the string-like bodies may indicate a high degree of supercooling even though the grain sizes of the other minerals are not fine-grained. Lofgren (1980) has documented cases whereby progressive supercooling of plagioclase, olivine, and pyroxene result in various growth forms of crystals, including acicular and skeletal forms. Furthermore, he generalizes these cooling effects to all mineral phases, suggesting that quench textures contain skeletal crystals (among others). Perhaps the opaques crystallized first when there was substantial supercooling of the magma/lava and the other minerals crystallized afterwards, as the degree of supercooling lessened.

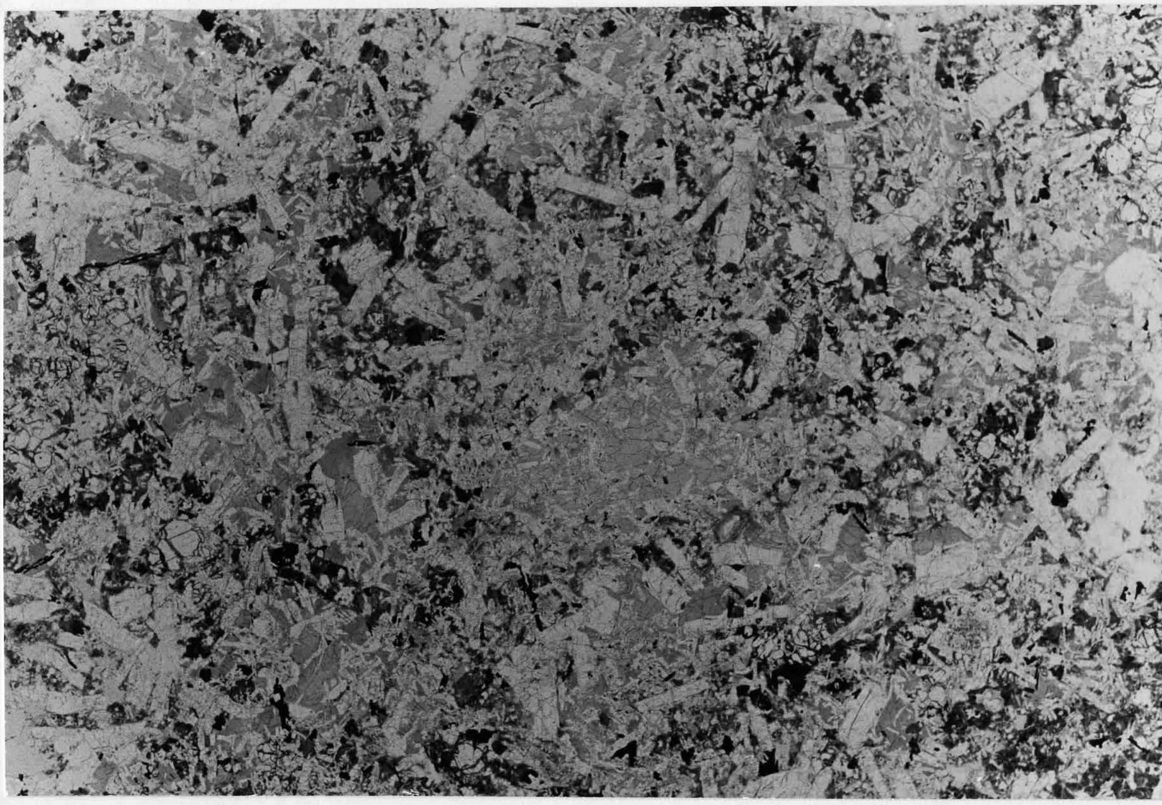
The texture of the interior of the micro-sills is similar to that of the blocky foreign bodies except for the lesser amount of olivine. The finely crystalline upper surface and the presence of skeletal opaques (see above) however, indicates that this region was more rapidly cooled. Since this region is very thin (about 5mm) and since the interior has comparable crystal sizes to those of the basalt of the main body in which these are imbedded, it is not likely that the micro-sills are quenched tops of flows. It appears likely that these entities are correctly named, that is, they are probably a late intrusion of magma into the basalt of Tow Hill.

Contrary to the evidence from hand sample, the silty shale which appears baked from the contact with the overlying thin sill, does not contain any of the diagnostic minerals associated with low to medium-grade contact metamorphism of shale. Phenocrysts such as white mica, biotite, quartz, and andalusite which characterize such zones are absent. Chlorite which is another diagnostic mineral is abundant but it is thought to be primary. In addition, no recrystallization appears to have occurred and primary porosity has not been obliterated. Evidently, the contact with the hot magma did not heat the shale past the required temperature of about 490 degrees Celsius to initiate metamorphism (Winkler, 1979). Perhaps the heat offered by the intrusion merely acted to further lithify the sediments near this contact. When comparing these shales to those immediately below (<25cm), the "baked" shales are obviously more cohesive and tougher. This may, however, be due to sedimentologic processes.

In summary, petrographic studies of the basalts of the main body reveal no evidence of fragmentation. Accordingly, the hydroclastic model for the construction of Tow Hill can be rejected. Neither of the other hypotheses can be definitely accepted or discarded due to the mixed evidence supporting one or the other. The sill hypothesis is the more likely of the two, but evidence is not totally adequate in support. For example, the foreign bodies can be explained by each model. The micro-sills do appear, in both the outcrop scale and in thin section, to be late stage sill intrusions.

Plate 3.1a. Photomicrograph of typical main body basalt under PPL. Glomerocrysts of olivine are present on both the left and right edges of the photo. Field of view is 20mm.

Plate 3.1b. Same view under XPL. Note the large augite phenocryst in the center of the photo displaying subophitic texture with the small plagioclase crystals. The larger plagioclase laths are not as intimately associated with the augite.



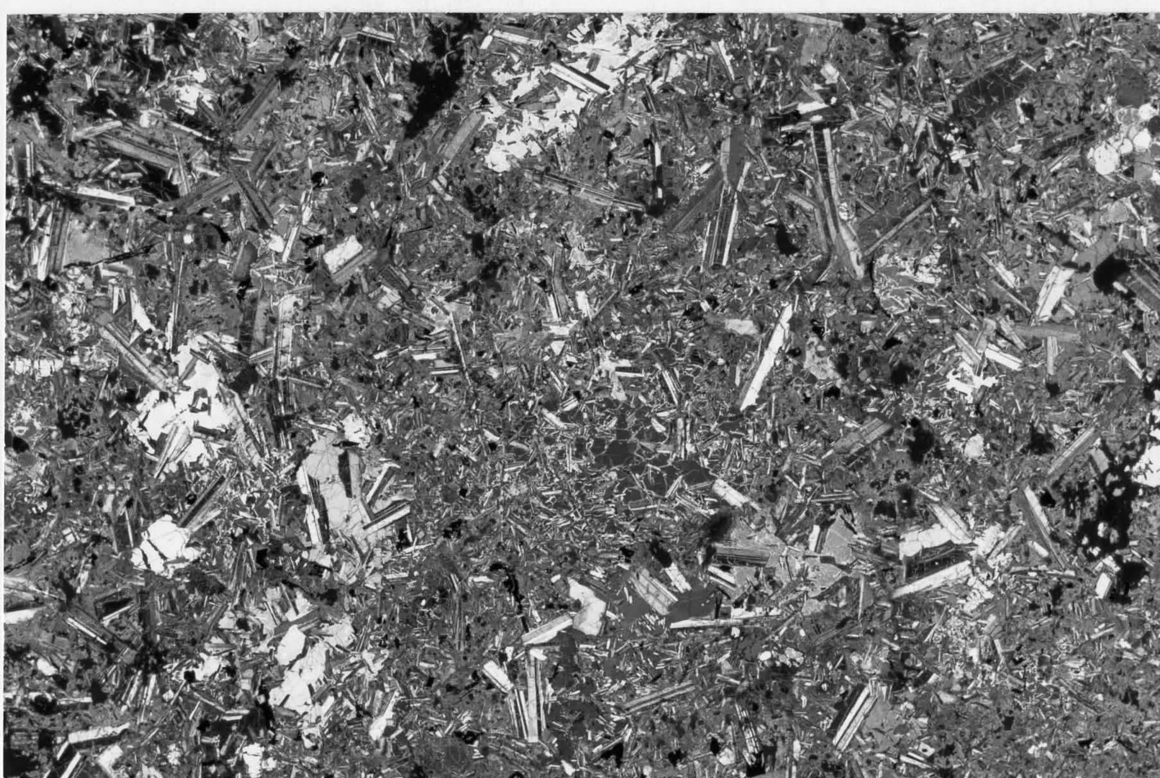
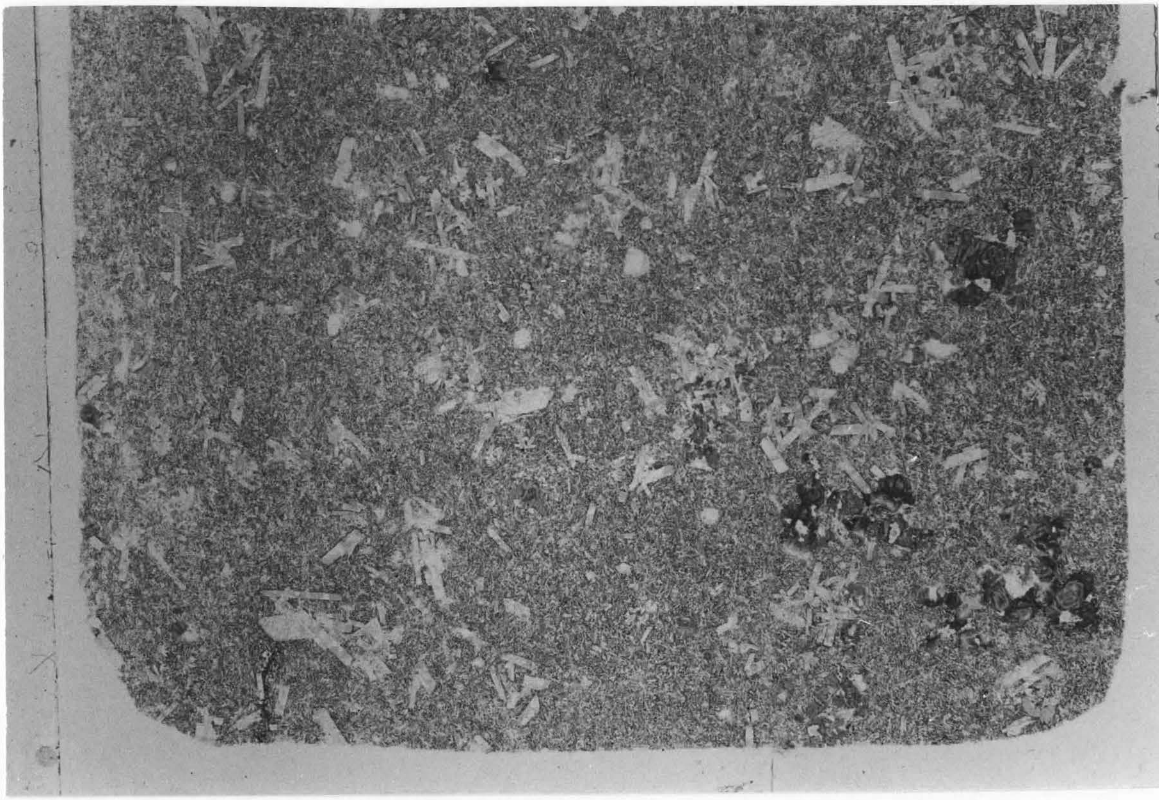


Plate 3.2a. Photomicrograph of thin sill basalt under PPL. Glomerocrysts of serpentinized olivine show up as dark patches. Field of view is 22mm.

Plate 3.2b. Same view under XPL. The plagioclase glomerocrysts are easily distinguished and their unaltered appearance is evident. In both views (a and b), the glomerocrysts of olivine and plagioclase are surrounded by an augite-plagioclase groundmass.



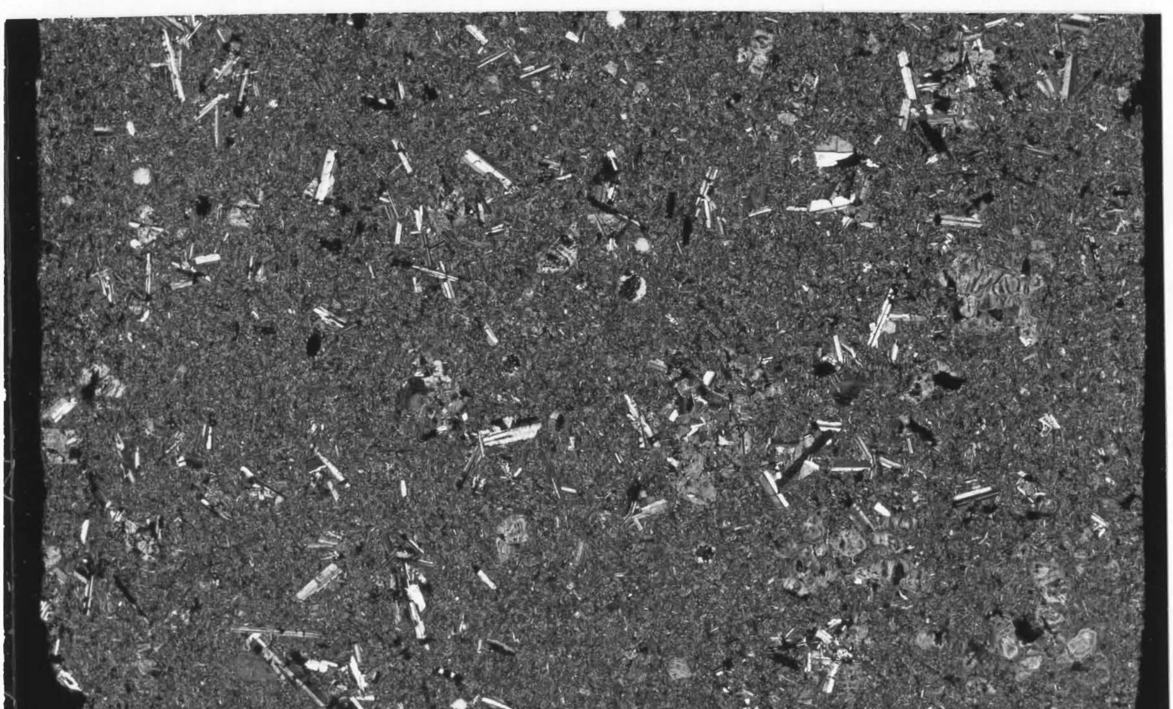
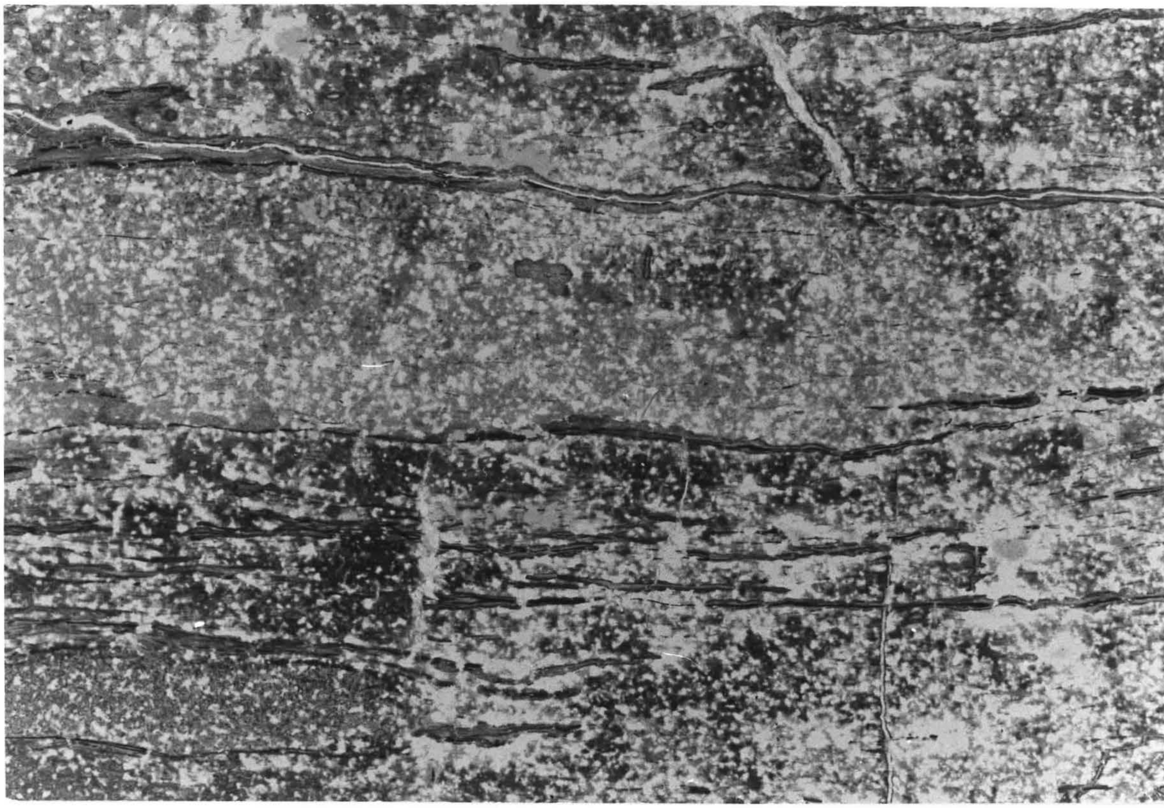


Plate 3.3a. Photomicrograph (PPL) of "baked sediments" at the contact with a thin sill above. Note the lack of metamorphic porphyroblasts. The horizontal stringers are organic material. Field of view is 18mm.

Plate 3.3b. Same sample under XPL. Pore space shows up as black patches. The light coloured material is calcite veins. Field of view is 30mm.



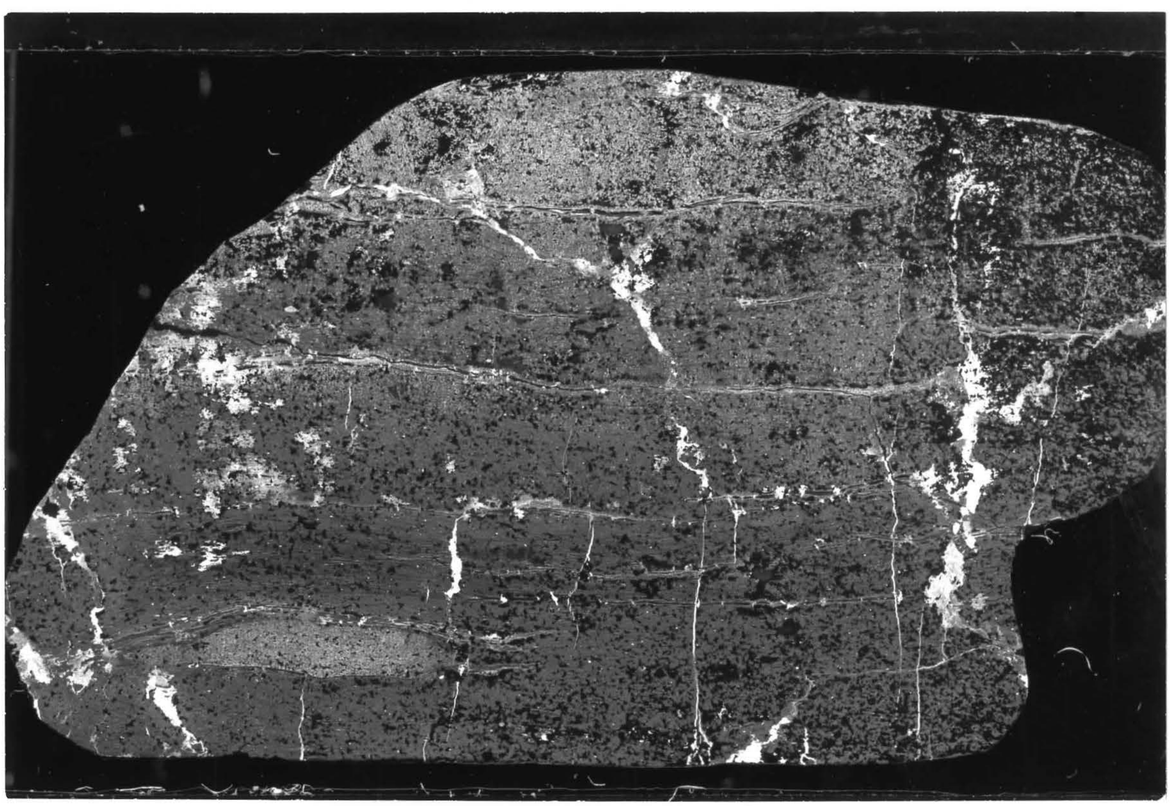
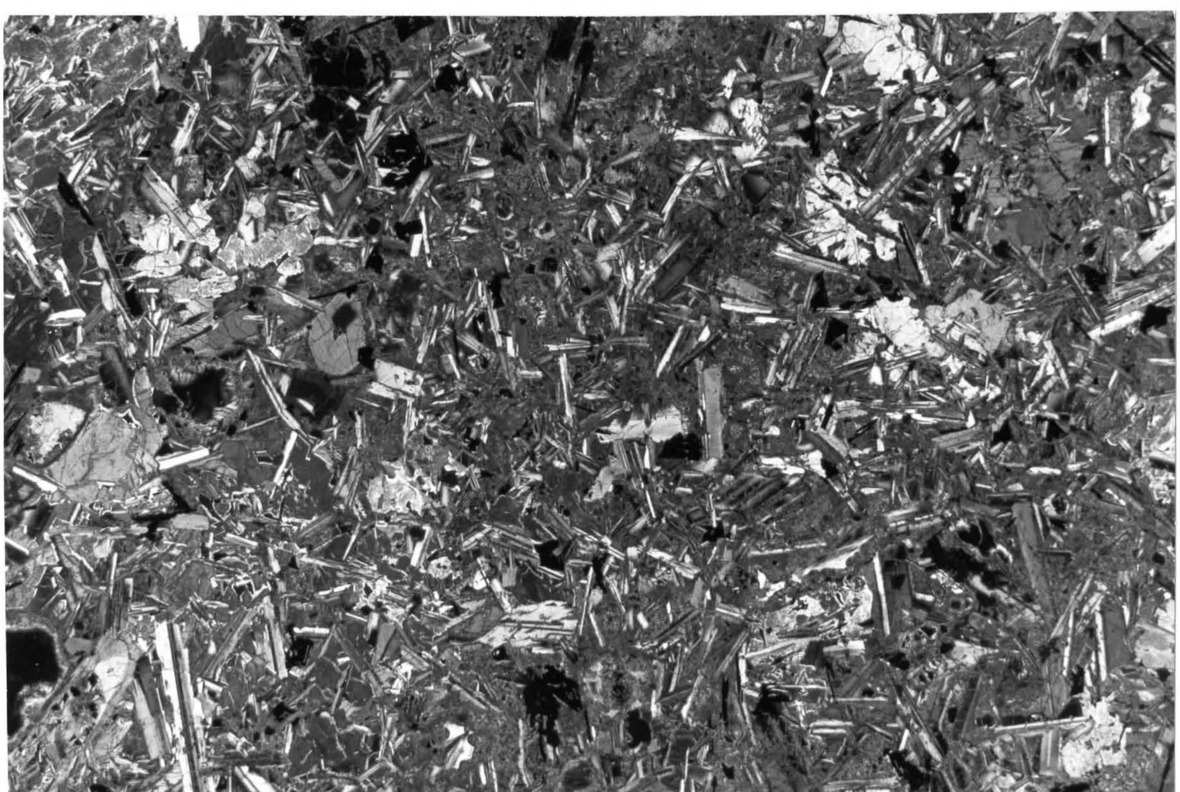


Plate 3.4a. Photomicrograph of the "most fragmental looking" basalt of the main body (PPL). A number of vesicles in the left of the photo are filled with zeolites. They also have a chloritized rim (dark material). Note the subophitic texture of the augite and plagioclase on the left side and top right of the photo. Field of view is 22mm.

Plate 3.4b. Same view under XPL. Subophitic texture is more distinguishable in this view. It is unlikely that this sample is fragmental.



CHAPTER 4

GEOCHEMISTRY AND TECTONIC SETTING

Ten samples including one from each of the thin sills, one from a micro-sill, and six from the main basalt body were selected for whole rock chemical analyses. The major element oxides, and the trace elements (Appendix, Tables 3,4, and 5) were analyzed by X-ray fluorescence and the trace elements and rare earth elements (REE) given in Appendix, Table 6 were analyzed by neutron activation. CIPW norms were then calculated using a computer program (Appendix, Table 7).

4.1 General Trends of the Tow Hill Basalts

The chemistry of all the basalts at Tow Hill is relatively constant and there are no dramatic changes with stratigraphic height. Only MgO shows a variation with height (Figure 4.1); note the two large deflections to the right which indicate that samples CT-TH-07 and CT-TH-09 are enriched in MgO. This can be attributed to a greater abundance of augite in the former sample and a larger amount of both olivine and augite in the latter. Ni and Cr which tend to be incorporated into olivine and Mg-rich pyroxenes respectively, are plotted in the same diagram. Their trends further reflect the enrichment of both olivine and augite in these samples. However, sample

CT-TH-07 does not contain abundant olivine and/or serpentine in thin section and therefore the MgO must reside in the chlorite which is plentiful. A comparison of the chemistry between samples of the more resistant and less resistant layers (samples CT-TH-13X and CT-TH-13Y respectively) exhibit little variations and in all diagrams presented in this chapter, they plot very close together. Thus, the layers do not represent horizontal chemical heterogeneities within the basalt. This supports the earlier contention that the layers probably have a structural origin rather than one governed by chemical differentiation.

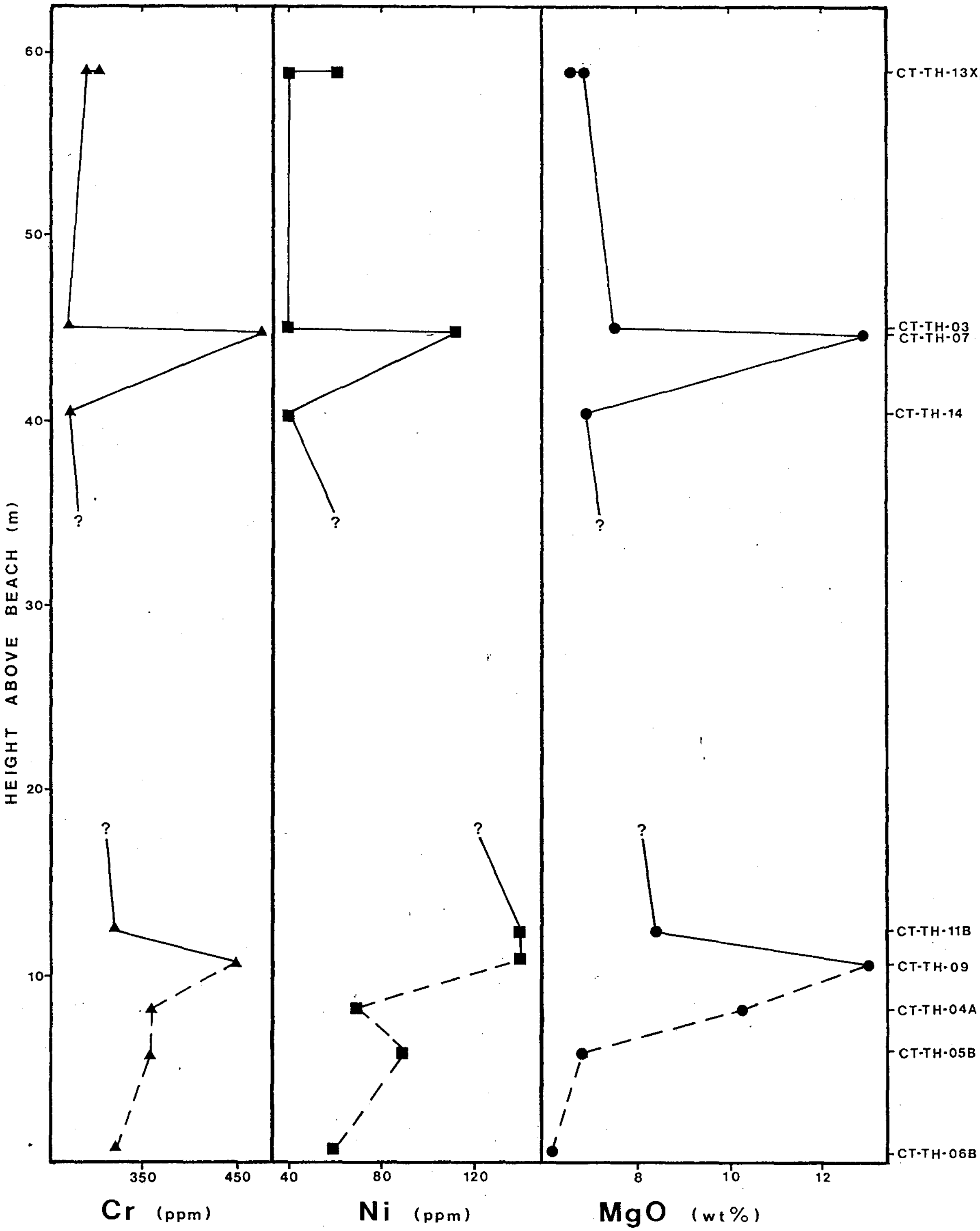
The rather constant major element chemistry also reflects the fact that there is no internal trend of differentiation in the main basalt body or in the thin sills. An AFM diagram (Figure 4.2) reveals the undifferentiated nature of the Tow Hill basalts compared with the highly fractionated trend of the tholeiitic Skaergaard intrusion in Greenland.

Trace and REE data also provide evidence for an internal undifferentiated trend in the Tow Hill basalts. The plots of all samples mark an even, narrow band on the chondrite-normalized/REE graph (Figure 4.3) which indicates that no significant differences exist in the REE concentrations or enrichments throughout the sampled outcrop.

Despite the fact that the basalts are not internally differentiated, they were derived from a slightly differentiated source. Evidence is provided by the depleted nickel concentration (<200 ppm) which is a sensitive recorder of olivine fractionation. The low values indicate that some fractionation of olivine prevailed although it was not complete because all samples contain olivine or their serpentinized pseudomorphs. Fractionation was limited to olivine; Ca-rich phases such as pyroxene and plagioclase were not effected as evidenced by the lack of a negative Eu anomaly and no depletion in either Cr or Sr. Very slight fractionation of the heavy REE has resulted in the gentle slope of the chondrite-normalized/REE plot.

Generally, the large compatible cations such as Ba, Sr, and Rb as well as K_2O are slightly enriched in the Tow Hill basalts compared to mid-ocean ridge basalt (MORB) concentrations and in the case of Ba, greatly exceed MORB values. Typically, MORB contains 5 to <50 ppm Ba, 90 to 200 ppm Sr, <5 ppm Rb, and <0.3 weight percent K_2O (Basaltic Volcanism Study Project, 1981). Average Tow Hill values are 159 ppm Ba, 220 ppm Sr, ~8 ppm of Rb, and 0.5 weight percent K_2O. This enrichment of compatible elements indicate that the basalts of Tow Hill were derived from a more primitive source.

Figure 4.1. Graph showing relationship of MgO, Ni, and Cr with height. Refer to text. Again, there was insufficient sampling in the central section of the column. The dashed lines represent the trend through the thin basalt sills.


HEIGHT ABOVE BEACH (m)
60
50
40
30
20
10
?
350
450
40
80
120
8
10
12
Cr (ppm)
Ni (ppm)
MgO (wt%)
CT-TH-13X,Y
CT-TH-03
CT-TH-07
CT-TH-14
CT-TH-11B
CT-TH-09
CT-TH-04A
CT-TH-05B
CT-TH-06B

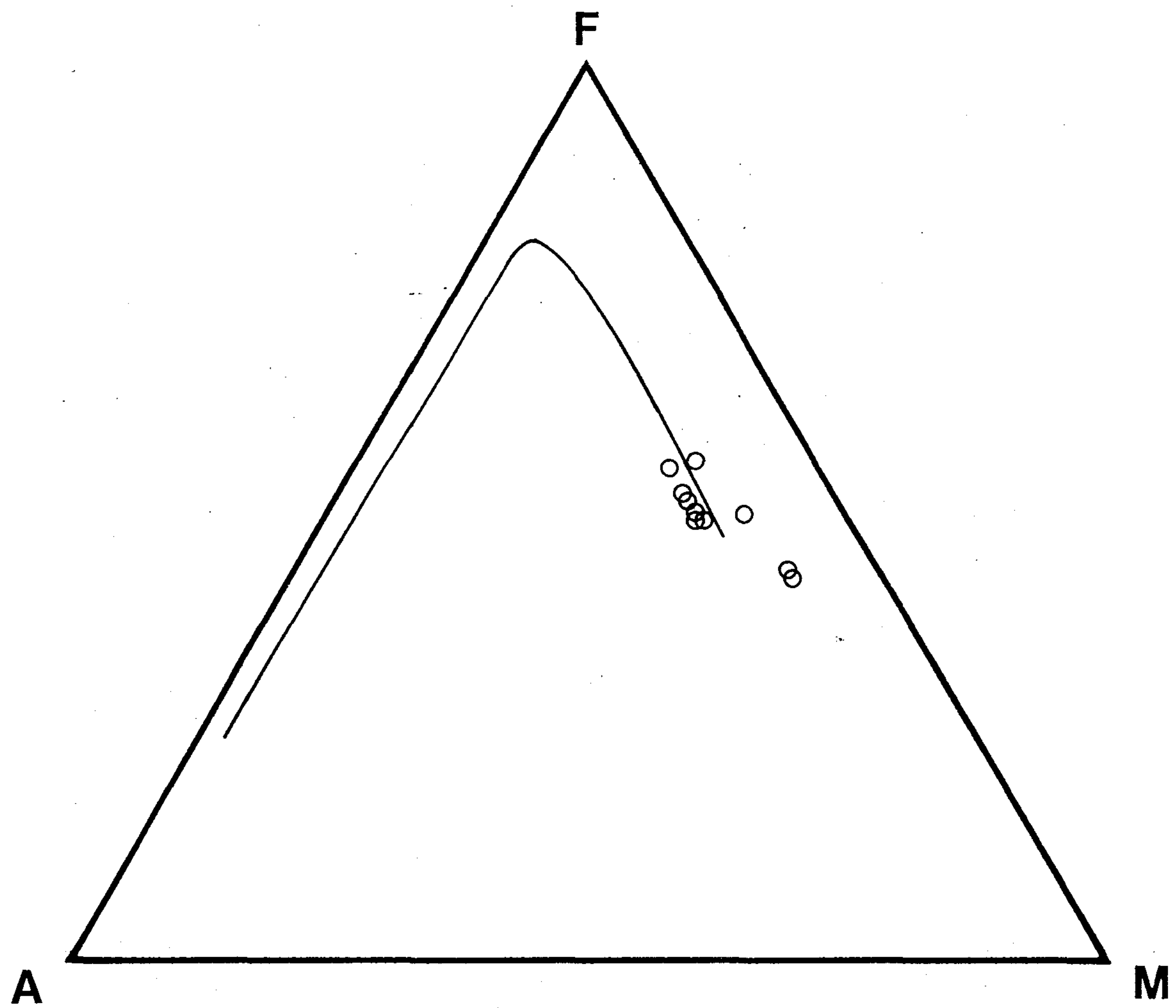
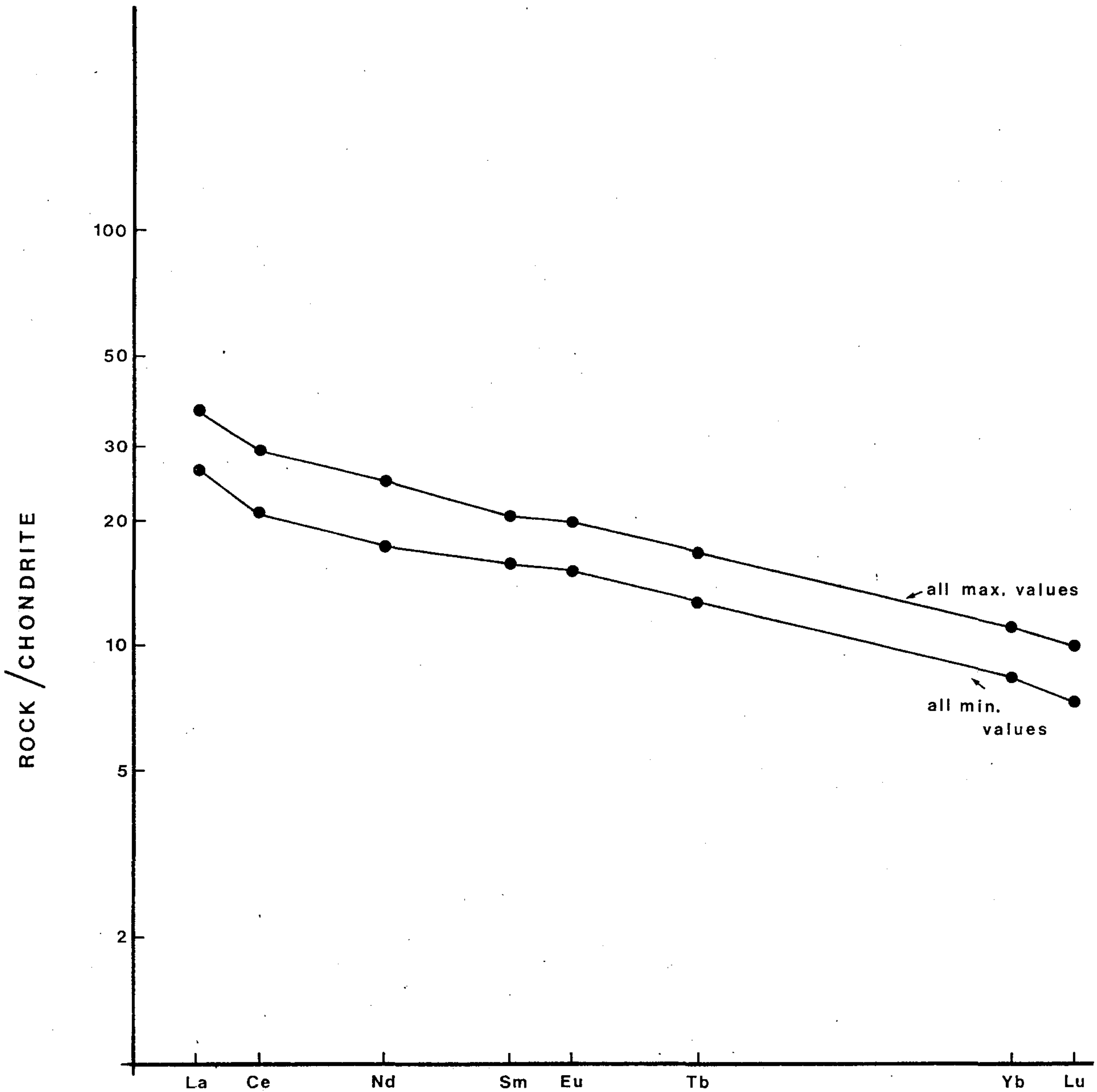


Figure 4.2. An AFM plot comparing the undifferentiated Tow Hill basalts (open circles) with the fractionated trend of the Skaergaard intrusion (solid line).

Figure 4.3. Chondrite-normalized/REE plot. Note the narrow band which contains all trends of the Tow Hill samples. The slope is gentle, indicating a slight depletion of the heavy REE. There is no negative Eu anomaly.


ROCK / CHONDRITE
100
50
30
20
10
5
2
La
Ce
Nd
Sm
Eu
Tb
Yb
Lu
all max. values
all min. values

4.2 Classification of the Tow Hill Basalts and Tectonic Setting Discrimination

The classification of basic volcanic rocks has been rather controversial in the past (see commentary in Carmichael et al., 1974); however, for the purpose of defining a tectonic setting for the Tow Hill basalts, a series of major element, trace element, and REE plots have been prepared.

A plot (Figure 4.4) of total alkalies against silica indicates that the basalt is undersaturated with respect to silica and is tholeiitic. The basalts of the two lowermost thin sills lack normative olivine which indicates that they are strictly tholeiitic. However, some of the main body basalts contain >5% olivine (as phenocrysts) by volume, normative hypersthene, and no low-Ca pyroxene, so these basalts can be classified as olivine tholeiites.

Trace element analyses of basic rocks can be used to determine a tectonic setting. A complete outline of the method is given elsewhere (Pearce and Cann, 1973). Here, the procedure is followed without further theoretical discussion. Firstly, the ratio Y/Nb is plotted against TiO_2 in order to determine the character of the basalt (Figure 4.5). A Y/Nb ratio greater than 1, as here, signifies that the basalt is tholeiitic; this agrees with the conclusion from the alkali-silica plot (Figure 4.4). Furthermore, according to Floyd and Winchester (1975), oceanic tholeiites exhibit a wide scatter of Y/Nb ratios ranging from values of 1 to >10 and

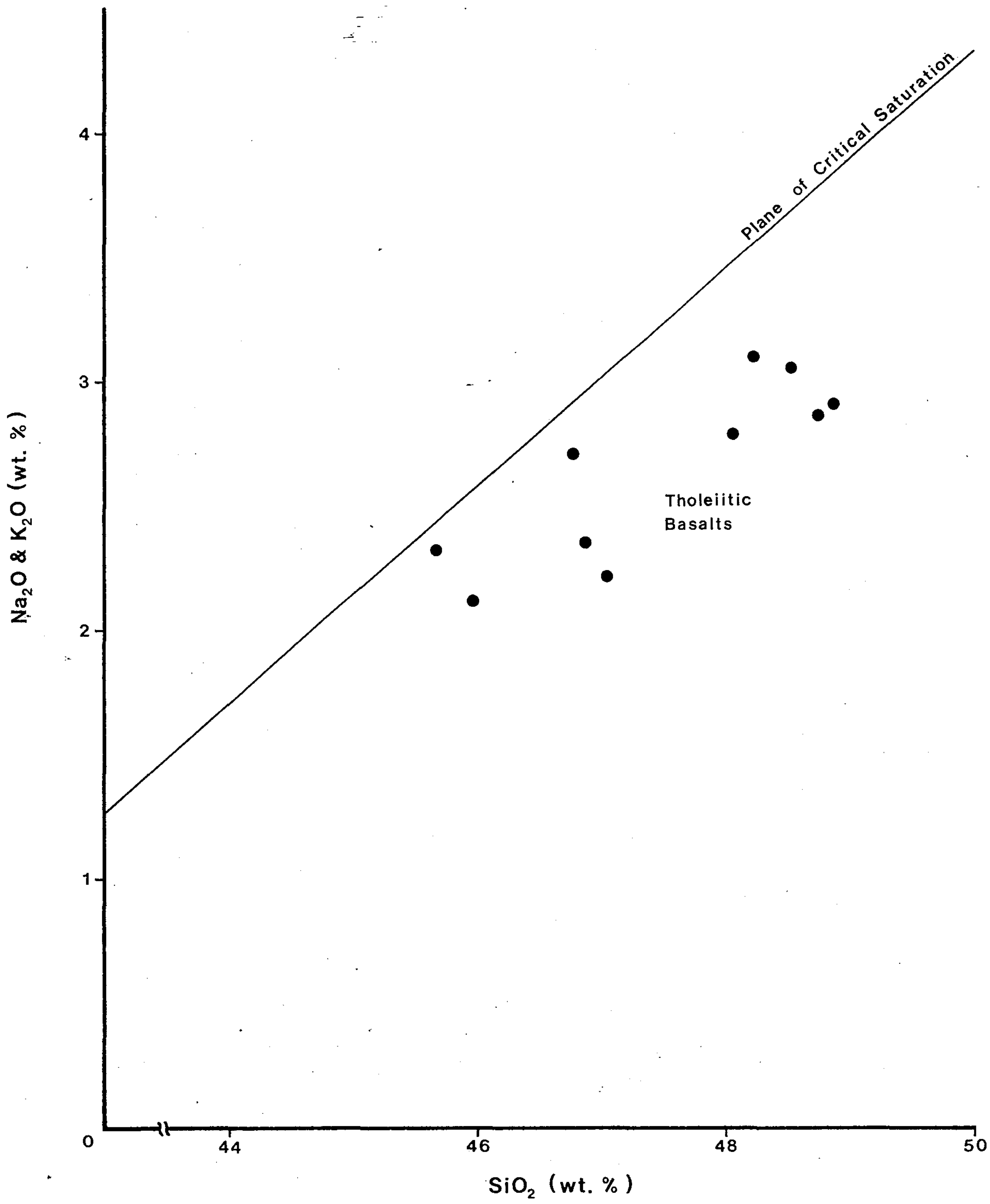
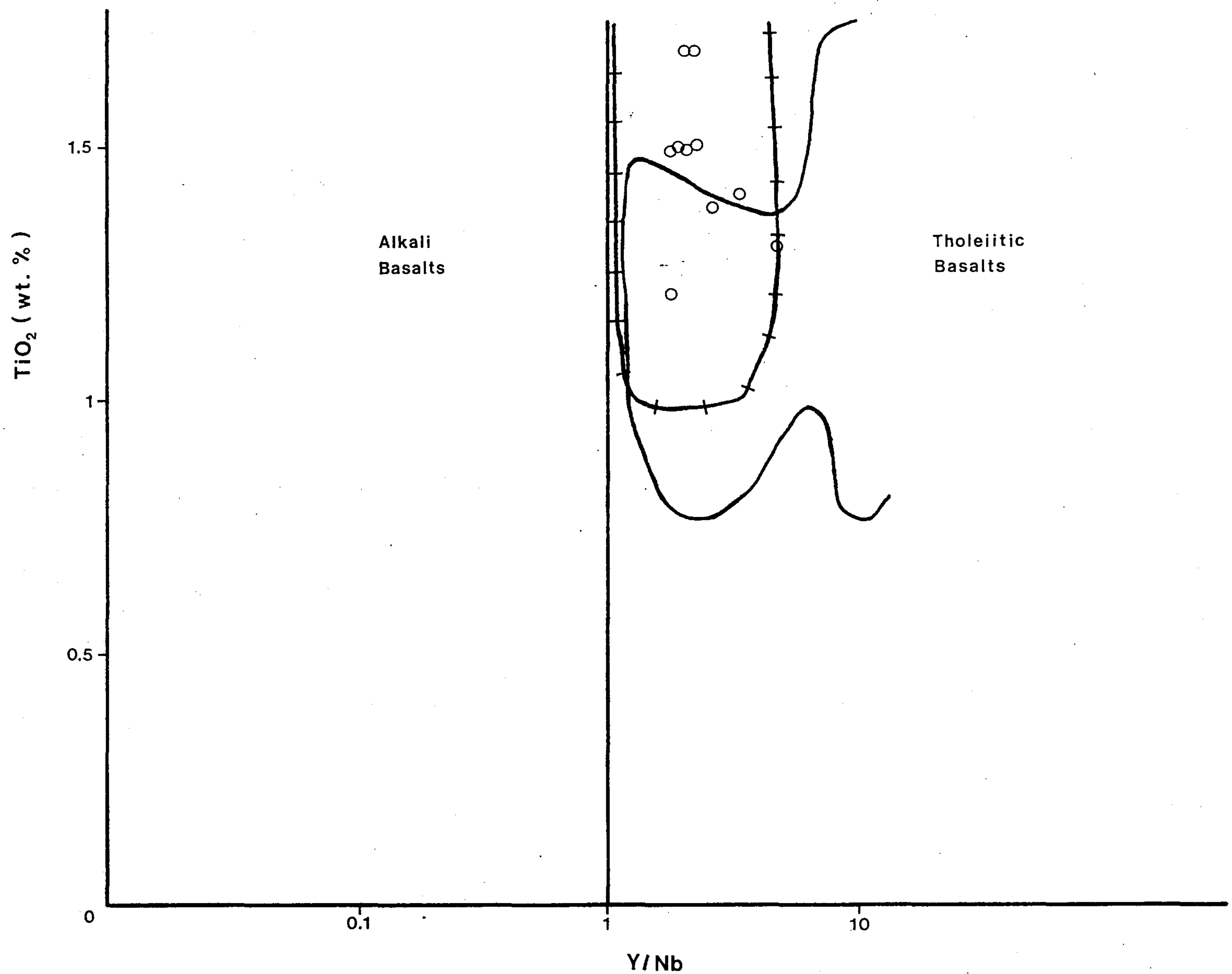


Figure 4.4. Plot of total alkalies vs. silica. The Tow Hill basalts are undersaturated with respect to silica and are tholeiitic.

Figure 4.5. Step 1 in Pearce and Cann's (1973) method to determine a tectonic setting of the basalts. The Tow Hill basalts are clearly tholeiitic and plot in the undifferentiated continental tholeiite field (marked by the crossed line). The oceanic tholeiite field is designated by the plain solid line. These fields are taken from Floyd and Winchester, 1975.


Alkali
Basalts
Tholeiitic
Basalts
TiO2 (wt. %)
1.5
1
0.5
0
0.1
1
10
Y / Nb

relatively low TiO_2 values. In contrast, continental tholeiites show two different trends depending on whether or not basic differentiation has occurred. With progressive differentiation, the Y/Nb increases only marginally which results in a steep negative trend. More primitive continental tholeiites with low TiO_2 values develop positive trends with Y/Nb approaching a ratio of 5. The Tow Hill basalts appear to fall into the undifferentiated continental tholeiite field (Figure 13). However, many of the samples overlap in the oceanic tholeiite field so that a unique inference as to the specific type of tholeiite cannot be drawn from this plot.

A ternary plot of Ti, Zr, and Y is used next to discriminate between four different magma types: low potassium tholeiites, calc-alkali basalts, ocean-floor basalts, and "within plate" basalts (Figure 4.6). These elements are chosen (1) because they can vary greatly in their concentration in the different magma types; (2) because they withstand effects of weathering and metamorphism rather well; and (3) because they can be measured with good reproducibility. Tow Hill basalts all plot within field D, indicating that they are "within plate" basalts.

Unfortunately, it is impossible to further divide the within plate basalts into continental intraplate basalts and oceanic intraplate basalts with these data or with any diagrams using TiO_2 vs. Zr, P_2O_5 vs. Zr, TiO_2 vs. Zr/P_2O_5, or Nb/Y vs. Zr/P_2O_5 (Floyd and Winchester, 1975). Therefore, it

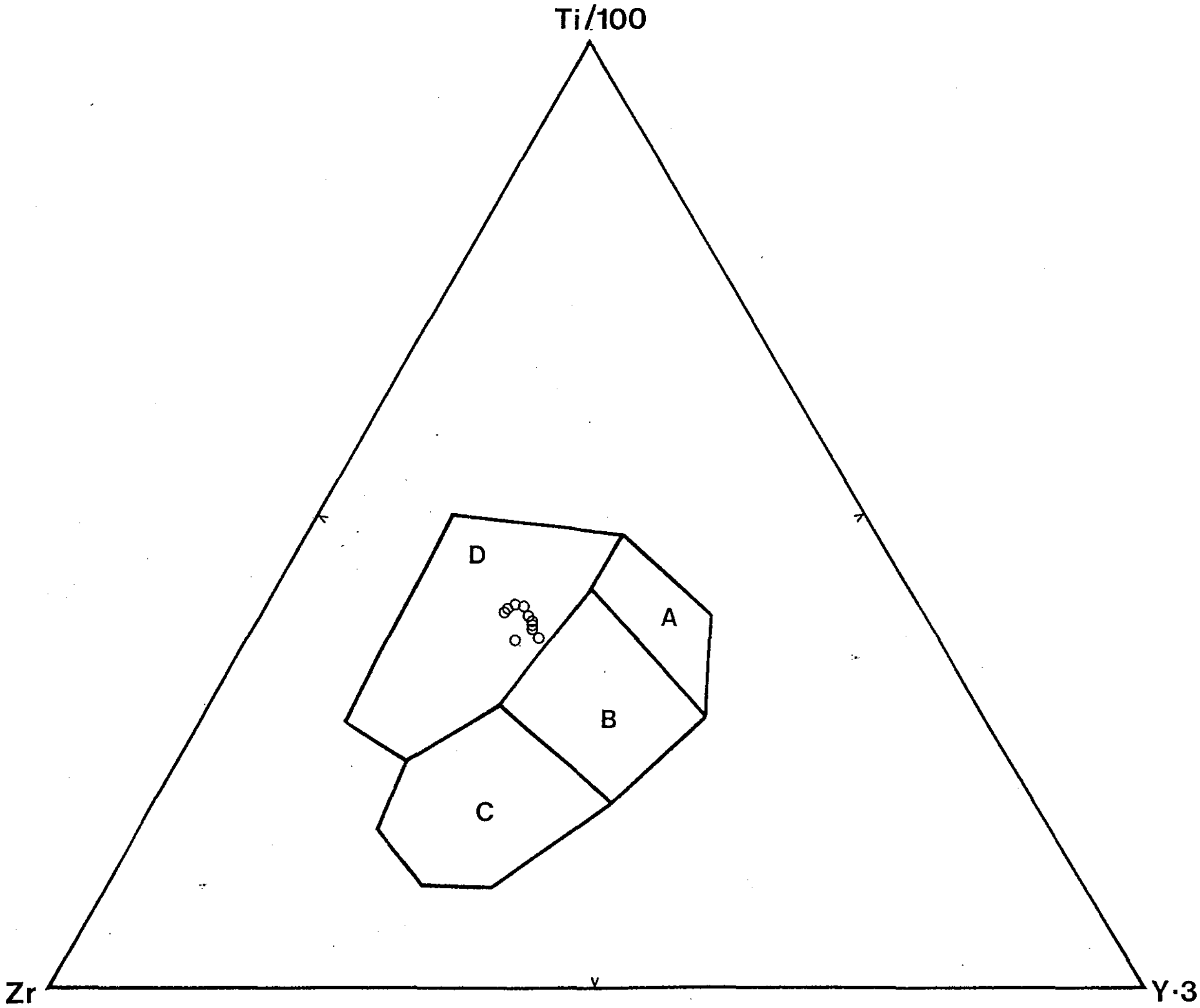


Figure 4.6. A ternary plot of Ti, Zr, and Y clearly shows that the Tow Hill basalts plot in field D - "within plate" basalts. Field A represents low-potassium tholeiites; field B ocean floor basalts; and field C calc-alkali basalts. Fields are taken from Pearce and Cann, 1971.

is necessary to compare the style of volcanic activity in each of the oceanic intraplate, continental flood, and continental rift regimes. It must be stressed that this method is inexact at best.

Oceanic intraplate volcanism is largely associated with partial melting which occurs at localized "hot-spots" within the mantle rather than along a rift. Usually, eruptions take place over long periods of time and in such volumes that a volcano or a chain of volcanoes such as the islands of Hawaii are built up (Basaltic Volcanism Study Project, 1981). Tow Hill contrasts this because there is the lack of other similar injections of magma/lava in the immediate area of Tow Hill which would mark a hot-spot. Masset volcanism is the next oldest magmatic activity which occurred on Graham Island but most of it occurred 20 to 25 Ma ago and all activity ceased by the late Miocene (Hickson, 1989). In addition, it has already been concluded above that the basalts of Tow Hill were emplaced in one episode which further indicates that volcanic activity in the area at 5 Ma was short-lived.

Similarly, continental flood volcanism produces enormous thicknesses of flat-lying basalt lavas which cover large areal expanses. Tow Hill clearly does not represent this effusive style of volcanism.

Continental rift volcanism is most likely spurred by asthenosphere upwelling and subsequent pulling apart of continents along zones of weakness. The associated volcanism has variable styles including sporadically distributed small centers of activity. Volcanism is usually episodic and single eruption cones may be common (Basaltic Volcanism Study Project, 1981). Tow Hill could feasibly represent a such a single localized burst of magmatic activity related to continental rifting. Additional supporting evidence may be provided from the presence of another basalt body (Lawn Hill) on the east coast of Graham Island and other olivine-rich basalt bodies on the west coast of British Columbia adjacent to Hecate Strait (Woodsworth, pers.comm.). Although some doubt has arisen as to the affiliation of Lawn Hill to Tow Hill based on the low abundance of olivine and the trachytic texture of plagioclase in the former (Sutherland Brown, 1968), these differences could be due to the wide range of styles and compositions associated with continental rifting.

In summary, Tow Hill is composed of olivine tholeiite and tholeiite associated with "within plate" magmatic activity. Activity was obviously short-lived and at a small-scale. Therefore, it is thought that Tow Hill is related to an episode of continental rifting.

4.3 Review of the Tectonics of the Queen Charlotte Islands

The tectonics of the Queen Charlotte Islands have been modelled by Yorath and Chase (1981) and Yorath and Hyndman (1983). More recent examination of this area has been completed in 1988 by the Frontier Geoscience Program, Queen

Charlotte Islands and although many of the conclusions made are preliminary, some additional clues as to the tectonics of this area are provided. According to Yorath and Chase (1981) and Yorath and Hyndman (1983), the tectonic history of the Queen Charlotte Islands and the adjacent areas includes the amalgamation of two allochthonous assemblages and their subsequent disruption by faulting which arose from rifting in Queen Charlotte Sound. It is thought that the Alexander and Wrangellia Terranes collided during the late Jurassic or early Cretaceous and the resulting suture is marked by the Sandspit Fault and the Rennell Sound Fault (Figure 4.7). This fault system and the Louscoone Inlet Fault was the site of transcurrent motion as the Queen Charlotte Islands were displaced northwards during a period of regional uplift and rifting in Queen Charlotte Sound up to 17 Ma ago. Since at least the last 100 Ma, periods of oblique convergence of the Pacific Plate and underthrusting of the Kula and Farralon Plates along the continental margin have prevailed. At 6 Ma, (Yorath and Hyndman, p.155, 1983) one such phase commenced beneath the entire western margin of the Queen Charlotte Islands and it has been proposed that lithosphere flexure uplifted the western margin of the region and concurrently depressed Hecate Strait and Queen Charlotte Sound. Subsidence has continued at a decreasing rate until the present.

This theory has been challenged by Thompson and Thorkelson (1989) who have found conflicting structural evidence. They have found no confirmation of Tertiary strike-slip displacement along the Rennell Sound and Louscoone Inlet Faults. Based upon preliminary analysis, they suggest that block faulting which was active episodically throughout late Jurassic to possibly Paleogene time also occurred along the Sandspit Fault in late Tertiary time and was responsible for the subsidence of Hecate Strait.

Despite conflicting interpretations of details, tectonic activity, specifically faulting, did prevail during the time Tow Hill was emplaced. The basaltic activity marked by Tow Hill possibly constrains any tectonic model of the Queen Charlotte Islands region during the late Tertiary. It is imperative that a correct model involve transtension and/or rifting during this time.

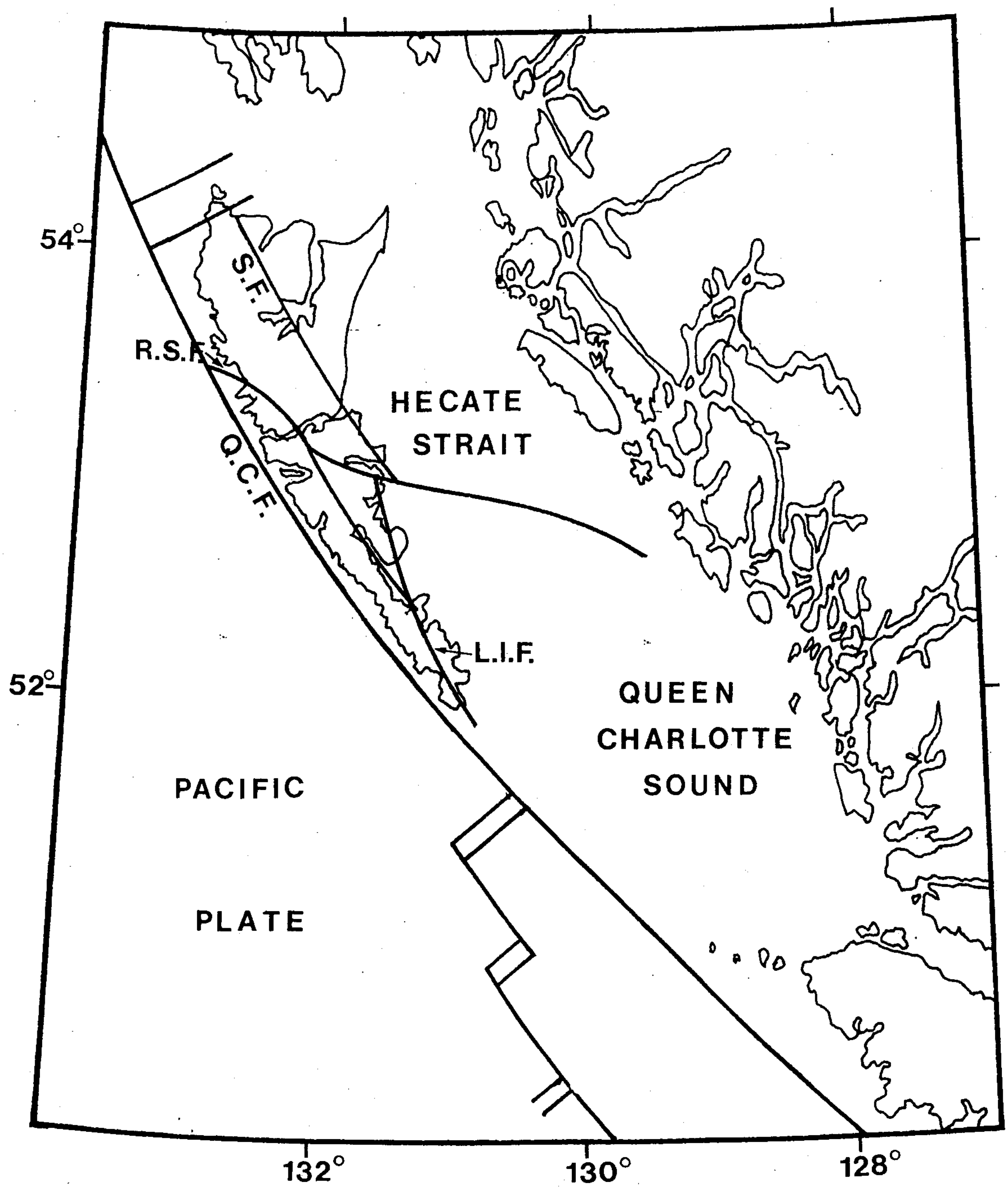


Figure 4.7. Map showing the positions of the Sandspit Fault (S.F.), Louscoone Inlet Fault (L.I.F.), Rennell Sound Fault (R.S.F.) and Queen Charlotte Fault (Q.C.F.). (Modified from Yorath and Hyndman, 1983).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

5.1 Conclusions

Tow Hill consists of a massive 105m thick layer of olivine tholeiite. Beneath the body are three thin sills of tholeiite basalt which have intruded Skonun shales and sandstone. Three hypotheses have been proposed concerning the origin of the main basalt body of Tow Hill; 1. sill intrusion; 2. lava flow(s); and 3. hydroclastic material. Petrographic studies indicate that the basalt is not fragmental nor made up of recrystallized fragments, so it is unlikely that the latter hypothesis is correct. Neither the sill nor lava flow hypothesis can be strictly accepted nor rejected based upon macroscopic or petrographic observations since the observations can be explained at least adequately by each hypothesis. However, some conclusions can be drawn regarding the features exhibited on Tow Hill:

1. The main body of basalt cooled as a single unit in a quiet environment such as in a shallow intrusion or a lava lake.
2. The mineralogy of the foreign bodies, vesiculated rings, and micro-sills is identical with the host basalt although subtle differences in the mineral abundances, texture, and the shape of some crystals are present.
3. The micro-sills do seem properly named in that they are probably late stage injections of magma which intruded Tow Hill basalts.

4. The contact below the uppermost thin sill does not appear to have undergone contact metamorphism in thin section.

Chemical analyses of the Tow Hill basalts indicate that no differentiation of the main basalt body occurred and that chemically, variations between the host basalt, foreign bodies, vesiculated rings, and micro-sills are absent. The basalts of Tow Hill were derived from a primitive source that had undergone slight fractionation of olivine.

The tectonic setting of Tow Hill is one of intraplate volcanism and most likely associated with rifting and/or transtension in a continental environment. Although the tectonic regime of the Queen Charlotte Islands is not well understood, the tectonic setting of Tow Hill as determined from chemical analysis, fits into the grand scheme of the tectonics of the region.

5.2 Recommendations for Further Study

Further examination of Tow Hill is required in order to determine whether the origin of Tow Hill was from a sill intrusion or from a lava flow(s). More detailed mapping of the perimeter of Tow Hill and of the contacts with the underlying sediments may help in defining the geometry of the body. Further examination of the top of the hill with a spade may disclose the nature of the upper contact (if present). Additional and more specific sampling of the entire cliff face may help in defining any horizontal changes in petrography or chemistry not observed in the lower 50m of the section examined in this project.

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Table 1

Thickness of Layers (cm)

RANDOM LOCATION	vertical trends ←——→
A	1. 30,25,20
	3. 35,28,24
	4. 32,30,30,29
	5. 32,27,33,25,27
	average = 28.5
B	1. 47,45,30,39,22,37,25,26,31
	2. 32,38,31,31,41,40,33,27,27
	average = 31.7
	lateral trends
	WEST---------EAST
C	1. 37,35,36,45,40,35,34,45
	average = 38.4

Table 2

MINERAL MODAL PERCENTAGES

Sample	plagioclase	augite	ol. & serp.	opagues	chlorite
CT-TH-03	46.37	15.61	1.48	2.76	30.4
CT-TH-04A	34.33	15.54	8.85	4.03	36.1
CT-TH-06B	45.64	11.06	3.84	6.08	31.84
CT-TH-07	45.1	19.66	2.01	5.22	24.88
CT-TH-09	29.84	14.94	18.46	2.38	33.05
CT-TH-10D	44.91	10.97	17.99	2.17	18.53
CT-TH-11A	46.83	12.14	10.21	4.35	20.8
CT-TH-12A	12.57	13.54	3.65	5.36	23.38
CT-TH-13	44.1	13.6	3.02	3.33	31.15
CT-TH-14	57.1	15.2	11.4	2.9	12.2

Sample	zeolites	calcite	pores	TOTAL
CT-TH-03	0.72	0.1	2.66	100.1
CT-TH-04A	0	0	1.18	100.03
CT-TH-06B	0	0.55	1.05	100.06
CT-TH-07	1.67	0.56	0.99	100.09
CT-TH-09	1.09	0	0.3	100.06
CT-TH-10D	4.45	0	0.99	100.01
CT-TH-11A	5.03	0	0.68	100.04
CT-TH-12A	40.77	0	0.68	99.95
CT-TH-13	0.81	0	3.98	100
CT-TH-14	0.3	0	1.3	100.4

SAMPLES - THIN SECTIONS

CT-TH-03 - main basalt body
CT-TH-04A - thin sill basalt
CT-TH-04B - baked sediment
CT-TH-05A - silty sand stone
CT-TH-06B - thin sill basalt
CT-TH-07 - main basalt body
CT-TH-09 - main basalt body
CT-TH-10D - foreign body - blocky type
CT-TH-11A - micro-sill
CT-TH-12A - foreign body - string-like
CT-TH-13 - main basalt body
CT-TH-14 - main basalt body

Table 2 con't

CT-TH-05A

Mineral	% TOTAL
quartz	14.00
plagioclase	12.98
biotite	6.58
hornblende	0.58
olivine	0.58
muscovite	1.66
augite	0.63
garnet	0.29
opaques	8.00
organic material	9.61
calc. cement	36.15
pores	8.93
	99.99

Table 3

MAJOR ELEMENT CHEMISTRY (wt %)

ELEMENTS	CT-TH-03	CT-TH-04A	CT-TH-05B	CH-TH-06B	CT-TH-07
SiO2	48.07	46.24	46.48	47.51	45.13
TiO2	1.38	1.47	1.66	1.66	1.28
Al2O3	16.26	15.03	16.7	16.65	14.29
FeO	9.79	11.59	10.66	10.34	10.87
MnO	0.15	0.16	0.13	0.13	0.15
MgO	7.29	9.51	6.29	5.77	12.2
CaO	9.24	7.33	8.13	8.78	6.89
Na2O	2.52	1.99	1.88	2.22	1.88
K2O	0.51	0.33	0.32	0.53	0.42
P2O5	0.29	0.29	0.3	0.29	0.26
LOI	3.47	4.78	6.27	4.96	5.51
Total	98.97	98.72	98.82	98.84	98.78

ELEMENTS	CT-TH-09	CT-TH-11B	CT-TH-13X	CT-TH-13Y	CT-TH-14
SiO2	45.44	47.65	48.35	46.28	48.17
TiO2	1.21	1.4	1.48	1.5	1.47
Al2O3	14.29	14.63	16.64	18.73	16.14
FeO	10.5	10.48	9.89	9.3	9.99
MnO	0.16	0.15	0.14	0.25	0.16
MgO	12.01	8.01	6.46	6.63	6.7
CaO	6.34	9.08	9.73	9.38	9.81
Na2O	1.75	2.48	2.31	2.23	2.33
K2O	0.35	0.57	0.56	0.45	0.49
P2O5	0.2	0.26	0.31	0.07	0.31
LOI	6.68	4.12	3.03	4.15	3.23
Total	98.93	98.83	98.9	98.98	98.8

SAMPLES - CHEMICAL ANALYSIS

CT-TH-03 - main basalt body
CT-TH-04A - thin sill basalt
CT-TH-05B - thin sill basalt
CT-TH-06B - thin sill basalt
CT-TH-07 - main basalt body
CT-TH-09 - main basalt body
CT-TH-11B - micro-sill
CT-TH-13X - main basalt body - resistant layer
CT-TH-13Y - main basalt body - nonresistant layer
CT-TH-14 - main basalt body

Table 4

NORMALIZED MAJOR ELEMENT CHEMISTRY (%)

ELEMENTS	CT-TH-03	CT-TH-04A	CT-TH-05B	CH-TH-06B	CT-TH-07
SiO2	50.33	49.22	50.22	50.61	48.39
TiO2	1.44	1.56	1.79	1.77	1.37
Al2O3	17.03	16	18.04	17.74	15.32
FeO	10.25	12.34	11.52	11.01	11.65
MnO	0.16	0.17	0.14	0.14	0.16
MgO	7.63	10.25	6.8	6.15	13.08
CaO	9.68	7.8	8.78	9.35	7.39
Na2O	2.64	2.12	2.03	2.36	2.02
K2O	0.53	0.35	0.35	0.56	0.45
P2O5	0.3	0.31	0.32	0.31	0.28
Total	100	100	100	100	100

ELEMENTS	CT-TH-09	CT-TH-11B	CT-TH-13X	CT-TH-13Y	CT-TH-14
SiO2	49.26	50.31	50.43	48.8	50.4
TiO2	1.31	1.48	1.54	1.58	1.54
Al2O3	15.49	15.45	17.36	19.75	16.89
FeO	11.38	11.06	10.32	9.81	10.45
MnO	0.17	0.16	0.15	0.26	0.17
MgO	13.02	8.46	6.74	6.99	7.01
CaO	6.87	9.59	10.15	9.89	10.26
Na2O	1.9	2.62	2.41	2.35	2.44
K2O	0.38	0.6	0.58	0.47	0.51
P2O5	0.22	0.27	0.32	0.07	0.32
Total	100	100	100	100	100

Table 5

MINOR AND TRACE ELEMENT CHEMISTRY (ppm)

ELEMENTS	CT-TH-03	CT-TH-04A	CT-TH-05B	CH-TH-06B	CT-TH-07
Rb	7.8	5.4	2.1	4.3	3.5
Sr	348	271	347	363	221
Y	21.1	17	21.8	19.5	15.6
Zr	90.7	88.7	100	96.6	74.6
Nb	8	8.3	10	9.5	3.3
S(wt%)	0.02	0.02	0.02	0.02	0.01
La	10	11	12	12	8
Nd	10	19	12	10	12
Ce	23	24	22	22	24
Ga	30	29	29	29	29
Ba	206	276	232	233	240

ELEMENTS	CT-TH-09	CT-TH-11B	CT-TH-13X	CT-TH-13Y	CT-TH-14
Rb	9.9	10.2	7.2	7.1	6.9
Sr	200	283	341	335	358
Y	14.4	19.5	22.1	20.9	21.5
Zr	75.8	93.6	92	92.3	93.2
Nb	8.2	5.9	11.4	8.9	11.7
S(wt%)	0.01	0.02	0.02	0.02	0.02
La	8	10	4	8	8
Nd	10	5	3	3	3
Ce	24	25	24	25	19
Ga	28	27	27	27	27
Ba	253	198	187	176	198

Table 6

REE AND TRACE ELEMENT CHEMISTRY (ppm)

ELEMENTS	CT-TH-03	CT-TH-04A	CT-TH-05B	CH-TH-06B	CT-TH-07
Ag	<2	<2	<2	<2	<2
As	<1	<1	<1	<1	<1
Au(ppb)	7	18	7	6	4
Ba	180	220	170	210	250
Br	<0.5	<0.5	1.5	<0.5	2.6
CaO(wt%)	9.1	6.9	7.3	8.9	6
Co	48	54	54	50	62
Cr	320	360	360	320	480
Cs	0.8	<0.5	<0.5	0.6	0.8
Fe2O3(wt%)	11.8	12.7	12.1	11.8	13
Hf	2.9	2.8	2.9	3.7	2.6
Mo	<2	9	<2	<2	2
Na2O(wt%)	3.23	2.96	3.48	3.5	3.2
Ni	<50	70	90	60	110
Rb	<10	<10	<10	10	<10
Sb	<0.1	0.2	0.3	<0.1	0.1
Sc	30.1	31.7	33.3	33.8	30.3
Se	3	2	2	<1	1
Sr	<100	300	300	200	100
Ta	0.6	0.7	0.7	<0.5	0.6
Th	1.1	0.9	1.3	1	1
W	36	12	14	22	92
Zn	150	190	170	150	<20
Ir(ppb)	<5	<5	<5	<5	<5
La	11.4	10.6	12.1	12.6	10.6
Ce	26	26	25	25	23
Nd	15	14	15	16	14
Sm	3.83	3.48	4.03	3.95	3.41
Eu	1.26	1.14	1.35	1.37	1.22
Tb	0.6	0.7	0.7	0.7	0.6
Yb	2.3	2.03	2.43	2.43	2.17
Lu	0.32	0.3	0.32	0.33	0.3
U	0.5	<0.1	0.6	0.5	<0.1

Table 6 con't

REE AND TRACE ELEMENT CHEMISTRY (ppm)

ELEMENTS	CT-TH-09	CT-TH-11B	CT-TH-13X	CH-TH-13Y	CT-TH-14
Ag	<2	<2	<2	<2	<2
As	<1	<1	<1	<1	<1
Au(ppb)	<2	5	7	6	<2
Ba	230	160	120	110	170
Br	2	4.5	2.6	4.2	3
CaO(wt%)	6.1	7.5	9.8	8.3	9.5
Co	58	49	46	44	44
Cr	450	320	300	290	270
Cs	1.3	<0.5	<0.5	<0.5	<0.5
Fe2O3(wt%)	12.4	11.3	12	11.2	11.4
Hf	2.1	2.7	2.8	2.7	<0.2
Mo	<2	<2	14	3	<2
Na2O(wt%)	3.31	3.21	3.17	3	2.94
Ni	140	140	60	<50	<50
Rb	10	<10	10	10	<10
Sb	0.1	<0.1	<0.1	<0.1	<0.1
Sc	29.6	28.5	30.7	30.8	30.1
Se	2	2	2	2	3
Sr	200	300	200	300	400
Ta	0.6	0.5	0.7	0.6	0.7
Th	0.8	0.9	1	0.7	1.1
W	<1	23	21	30	37
Zn	150	150	150	140	140
Ir(ppb)	<5	<5	<5	<5	<5
La	9.1	10.6	11.9	10.5	12
Ce	19	22	27	25	27
Nd	11	13	15	14	16
Sm	3.11	3.29	3.99	3.57	3.89
Eu	1.11	1.21	1.45	1.33	1.33
Tb	0.6	0.7	0.8	0.7	0.8
Yb	1.88	2.21	2.3	2.16	2.28
Lu	0.25	0.27	0.34	0.31	0.34
U	0.2	0.7	0.7	<0.1	0.3

Table 7

NORMATIVE CHEMISTRY (CIPW)

ELEMENTS	CT-TH-03	CT-TH-04A	CT-TH-05B	CH-TH-06B	CT-TH-07
Ap	0.72527	0.77825	0.8568	0.79404	0.65813
Il	2.99	3.41	4.1	3.93	2.8
Or	3.42	2.38	2.45	3.9	2.85
Ab	24.24	20.54	20.65	23.38	18.3
An	35.86	37.94	46.97	42.19	33.41
Di	11.94	3.49	2.39	8.12	3.4
Hy	10.71	18.08	21.19	17.52	13.35
Ol	10.11	13.38	nd	nd	25.23
Q	nd	nd	1.38	0.17308	nd
Total	100	100	100	100	100
A	15.07	9.91	11.49	14.58	9.07
M	36.25	40.61	32.85	30.59	48.09
F	48.68	49.49	55.67	54.83	42.85
Q	49.77	49.84	49.21	48.88	50.75
M	20.42	22.13	15.99	16.85	25.54
L	29.82	28.03	34.8	34.27	23.72

ELEMENTS	CT-TH-09	CT-TH-11B	CT-TH-13X	CT-TH-13Y	CT-TH-14
Ap	0.54122	0.64587	0.79482	0.17396	0.79184
Il	2.83	3.01	3.28	3.23	3.25
Or	2.54	3.8	3.86	3	3.36
Ab	18.21	23.69	22.78	21.31	22.89
An	37.03	30.6	38.9	44.92	37.31
Di	0.0458	15.55	12.66	6.03	14.23
Hy	19.89	9.39	13.15	8.93	12.54
Ol	18.91	13.3	4.58	12.4	5.63
Q	nd	nd	nd	nd	nd
Total	100	100	100	100	100
A	8.53	14.16	14.93	14.4	14.45
M	48.8	37.19	33.61	35.63	34.34
F	42.67	48.65	51.46	49.97	51.2
Q	50.34	49.95	49.33	49.83	49.4
M	23.77	23.26	19.04	18.27	20.08
L	25.89	26.79	31.64	31.9	30.51