THE GEOLOGY OF OPHIOLITIC AND ADJOINING ROCKS OF CHAGNON MOUNTAIN, SOUTHERN QUEBEC

A thesis presented to the Faculty

of the State University of New York

at Albany

in partial fulfillment of the requirements

for the degree of

Master of Science

College of Science and Mathematics

Department of Geological Sciences

Janet M. Harris

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ABSTRACT

Chagnon Mountain is located near the southern end of the Baie Verte-Brompton Line in the Eastern Townships of southern Quebec. The lithologic units in the area of study, from west to east and going up structure, are: gabbro, quartz-diorite, diabase, volcanics, the St. Daniel Formation and the Peasley Pond Conglomerate of the Glenbrooke Group. All these rocks have been metamorphosed to the greenschist facies. Contacts between the plutonic rocks are irregular and gradational indicating only one parent magma. Diabase dikes are present in the diabase unit and in the volcanics indicating the dikes acted as feeders to the volcanics. Geochemical analyses on several samples supports a tholeiitic origin for the mafic rocks and infer this magma to be from an ocean floor setting.

The St. Daniel Formation lies structurally above the volcanics with the contact in some places conformable and in others, unconformable. The contact between the two could be a normal fault or set of faults which would give rise to a situation where sedimentation of muds would occur onto surfaces existing before faulting in some places and onto degrading fault scarps in others. The Peasley Pond Conglomerate was deposited after emplacement of the Baldface-Orford-Chagnon (BOC) ophiolites. It is a basal conglomerate which unconformably overlies the volcanic rocks and the St. Daniel Formation in the Chagnon Mountain area. The sediments of this unit contain chromite grains and silicic volcanic clasts indicating sources both the northeast (BOC source) and southwest (Ascot-Weedon source).

ACKNOWLEDGMENTS

I wish to acknowledge Dr. Akiho Miyashiro for introducing me to the Vermont-Quebec Serpentinite Belt and for financial support during the 1980 summer field season. I also would like to thank Dr. Barry Doolan from the University of Vermont for discussions on the Chagnon Mountain Area both in the field and out. Gratitude is also expressed to Dr. George Putman for petrographic aid and also to Dr. John Bender for guidelines on geochemical procedure. Many others played a role through late night discussions; Dave Rowley and Bruce Idleman among them. Sincerest appreciation is expressed to Diane Paton who carefully typed and made sure all organizational details were taken care of.

I am deeply indebted to Dr. Bill Kidd, who gave constructive criticisms and suggestions on the problems associated with ophiolites, who gave help both in the field and at the microscope, and whose support made this thesis possible.

My parents and family must also be remembered for the belief they had in me. Finally, these acknowledgments would not be complete without mentioning the constant encouragement and help of my one time field assistant and now husband, Sam DiMaggio.

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CHAPTER I

INTRODUCTION

PURPOSE

A long narrow zone containing mafic-ultramafic complexes extends from south of Brompton Lake in southern Quebec to Baie Verte, Newfoundland (see Figure 1). This zone has been named the Baie Verte-Brompton Line. In general, rocks and structures west of the line record the evolution and destruction of the ancient continental margin of eastern North America, while ocean crust generation and volcanic arc sequences are recorded to the east (Bird and Dewey, 1970; Williams and St. Julien, 1978).

In the Eastern Townships of Southern Quebec, three relatively complete stratiform ophiolites, Thetford Mines, Asbestos, and Orford, lie southeast of the Sutton-Notre Dame Mountains in a 250 km long zone known as the Serpentinite Zone(Lamarche, 1972, 1973; Laurent, 1975, 1977; Winner, 1981). Some dismembered ophiolites, peridotite lenses and sheets are found scattered throughout this zone. This is especially true near the international border where only isolated occurrences of meta-igneous rocks are found (Cooke, 1950; Cady, et al., 1963; St. Julien and Hubert, 1975; Winner, 1981).

Rocks of two volcanic suites could be present in the Chagnon Mountain area. The possible existence of two chemically different parent liquids has been proposed for the line of ophiolites of the same age and tectonic setting to the north (Laurent, et al., 1979; Winner, 1981). These parent liquids may both be of ophiolitic derivation (including off-axis intraplate basalts) or tholeiitic and calc-alkaline island arc volcanics.

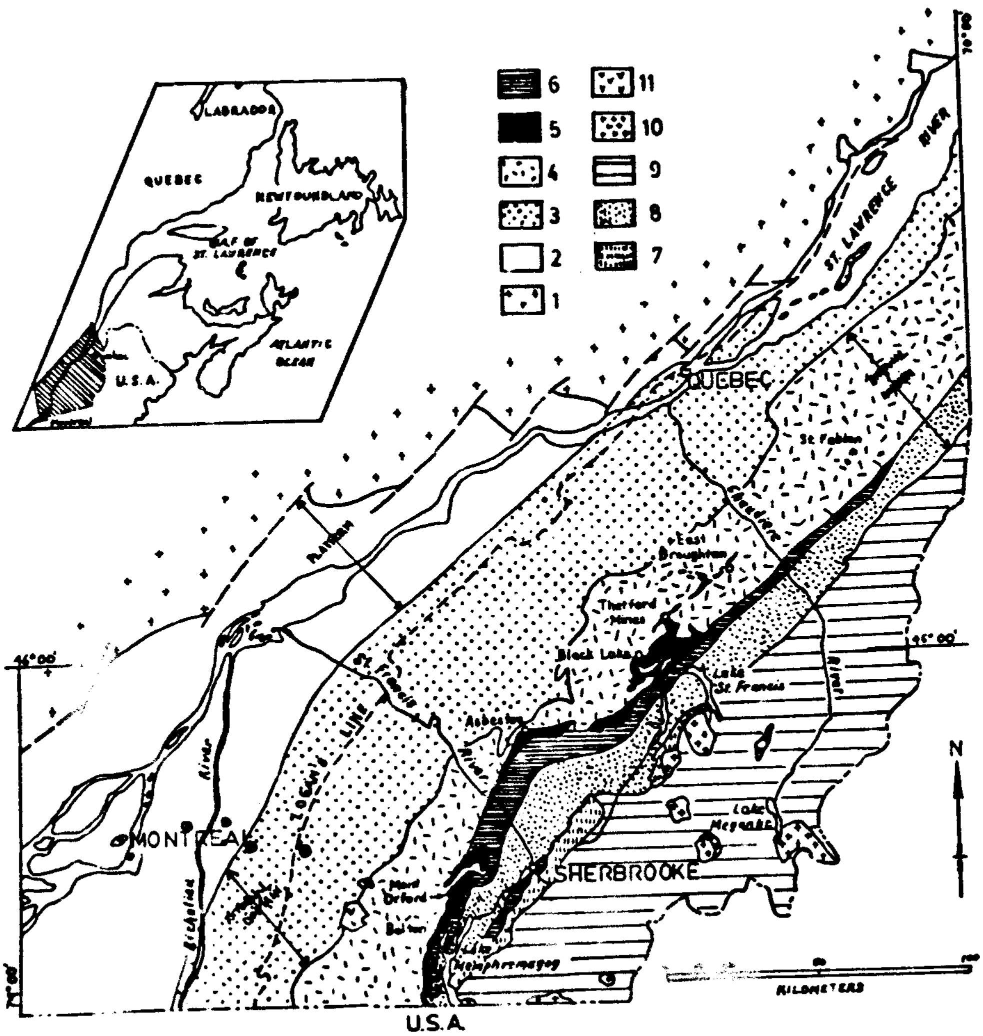

Figure 1: Map of the Appalachians of southeastern Quebec showing the main structural zones and the major ophiolite localities along the Baie Verte-Brompton Line (after Laurent, 1980). 1, Precambrian crystalline basement; 2, Sedimentary cover of the St. Lawrence platform (mainly Ordovician); 3, Cambro-Ordovician outer zone or Appalachian allochthon; 4, Cambro-Ordovician inner zone or Notre Dame schist belt; 5, Ophiolites; 6, Early Ordovician St. Daniel Formation (melanges); 7, Lower to Middle Ordovician Formations of Weedon and Ascot; 8, Middle Ordovician flysch of the Magog Group; 9, Siluro-Devonian belt of the Gaspe-Connecticut Valley snyclinorium; 10, Devonian granites; 11, Mesozoic alkaline syenitic and gabbroic intrusive rocks of the Monteregian Hills.

Hence, one purpose of this study is to map this Cambro-Ordovician age ophiolite and to determine if this ophiolite is composed of two geochemically distinct units. In addition, some debate has arisen over the nature of the contact between the ophiolite and the overlying metasediments. Hence, another aim of this research is to look at the St. Daniel Formation, an olistostromal black slate unit, and adjacent Silurian rocks of the Glenbrooke Group.

LOCATION AND ACCESS

The study area occupies an area of approximately 3 km x 2.5 km and is located between North Road on the south and the southern side of Chagnon Mountain which is about 2.3 km south of Lac Orford (Figure 2). Access to the northern third of the area is gained by heading east from Eastman, Quebec approximately 3.5 km. On the right is North Road which heads south. Follow North Road for 2.6 km until a road on the right leading to Webster and Malaga Ponds appears. Take the south left fork of this road, which leads to a summer cabin development that occupies most of the northern third of the study area. Access to the southern two thirds of the area is gained by taking North Road south until the first main crossroads, approximately 3.6 km. Turn right and follow this road (also marked North Road) for 2.8 km until you reach a small side road on the right leading to a scout camp. Head north on this road for access to the study area.

PREVIOUS WORKS

Various studies of the Serpentine Belt in southeastern Quebec have been undertaken during the past seventy-five years (Figure 3). In 1906, Dresser published one of the earlier papers where, in referring to the

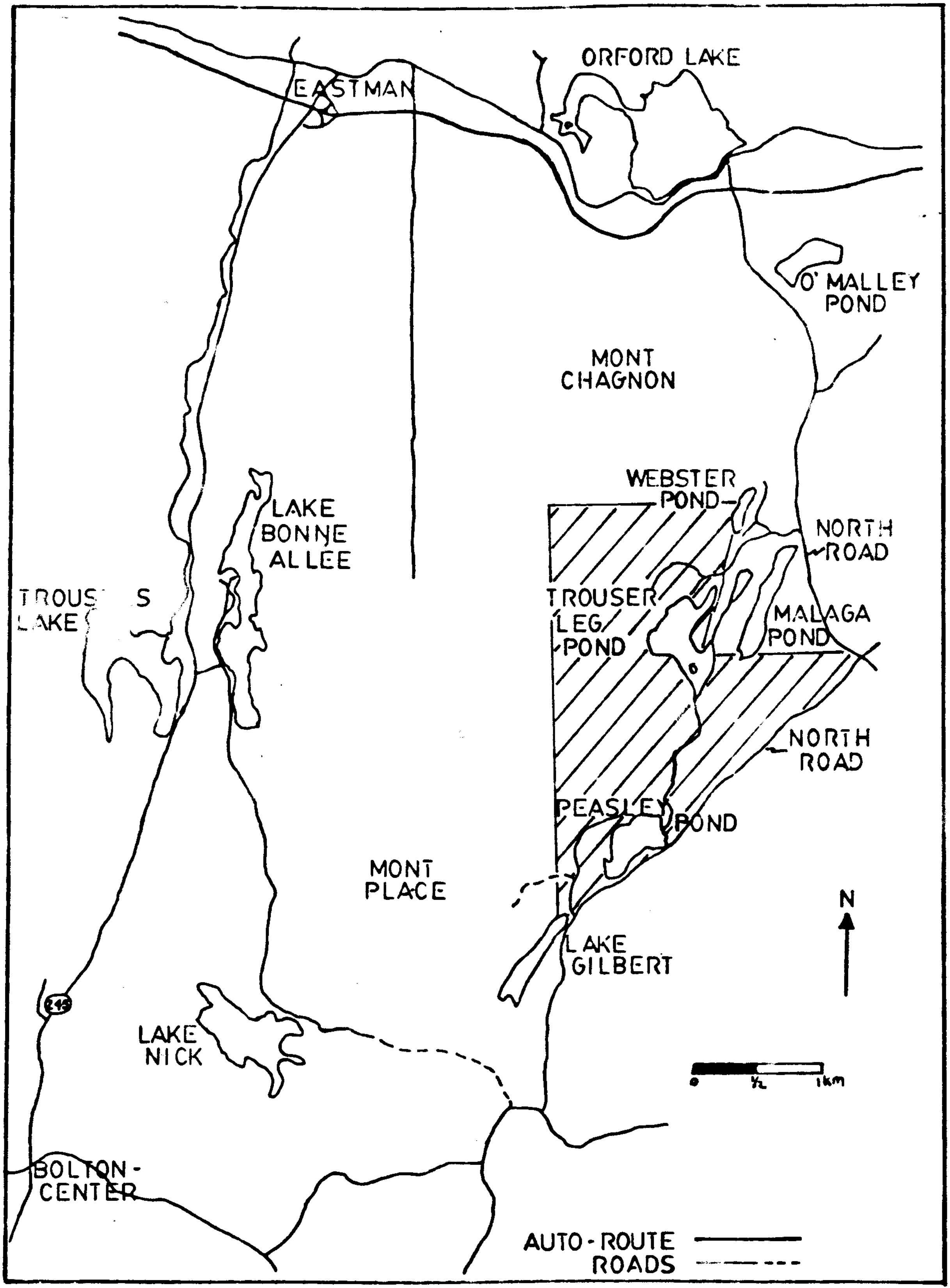

Figure 2: Map of access and location of the study area (shaded area).

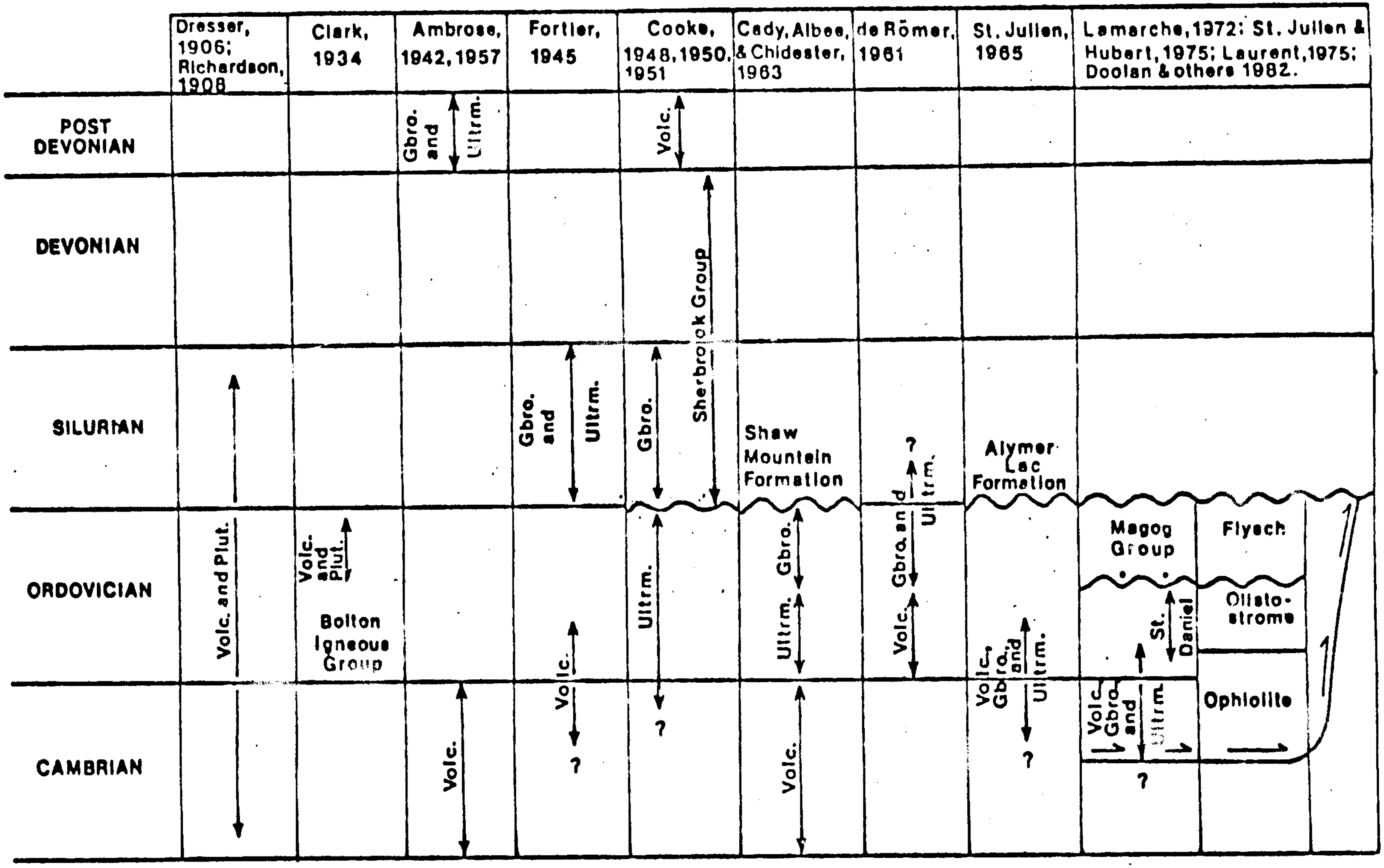

Figure 3: Summary of age interpretations by previous workers of meta-igneous rocks investigated in this study. Volc = volcanics; Plut = plutonics; Gbro = gabbro; Ultrm = ultramafics; * = graptolite fossil control. (after Winner, 1981)

volcanic and plutonic rocks he noted (p. 514) "...the probability of all being differentiation products of a single primary magma...". He envisioned the volcanic rocks to be the oldest, followed by the serpentines, and then the diabases and gabbro-diorites. Age constraints for these rocks were left vague, ranging from Cambrian to late Silurian.

Fairbairn (1933) studied the metabasalt situated along the west side of Lake Memphremagog in Southern Quebec. On the basis of chemical analyses, he indicated the presence of two lithologic types, denoted by him as a uralite rock and ankerite ($CaCo_3$-rich) rock. He claimed the uralite rock made up the greater portion of the metabasalt and graded into the ankerite type which showed an irregular distribution. In 1934 T.H. Clark published work involving the area south of Mont Place and north of the international boundary. He interpreted the metagabbro as the intrusive equivalent to the metabasalt and termed both of these rock types the Bolton Igneous Series. He also included metaperidotite in this grouping; however, the possibility of it being genetically distinct was mentioned. Clark suggested the Bolton series to be middle to late Ordovician in age. He felt the intrusives penetrated and the volcanics flowed out on top of the Magog slates which now includes the St. Daniel formation as well as fossiliferous, medial Ordovician Beauceville Formation of the Magog Group. Silurian strata, including a basal conglomerate which rests unconformably on both the Bolton series and Magog slates, confined the upper age limit of the metabasalts and metagabbros to older than Silurian. Other Silurian units include sandstones, shales, and a dark carbonaceous limestone containing an abundance of corals, finally succeeded by a light colored limestone (Clark, 1934). In 1936, Clark and Fairbairn repeated much of Clark's 1934 paper. They, however, renamed the Bolton Igneous Series to Bolton Igneous Group and strongly denied that the volcanics were interbedded with the Magog slates.

In 1942, Ambrose, whose work was also largely south of Mont Place, assigned the volcanics of the Bolton Group a Cambrian to Ordovician age based on their pre-Middle Ordovician fold pattern and conformable nature with the Brompton slates and quartzites. Unlike earlier workers, however, he assigned the gabbros a post-Devonian age although he noted they only cut rocks supposed to be of Cambro-Ordovician age. He further confused the matter when he stated the volcanics and gabbros were co-genetic. Furthermore, he felt the serpentine was younger than the gabbro and, hence, also at least post-Devonian in age.

Fortier (1945) contradicted Clark and Fairbairn's earlier work by stating that the volcanics were interlayered with the shales thus giving a Cambrian to Ordovician age. He recognized differences in the ultramafics and separated them into dunites, peridotites, and pyroxenites. Fortier also noted the serpentinite was brecciated and reasoned that differentiation of the ultramafic rocks happened in situ at depth. Based on the straight map pattern the intrusive rocks exhibited and on their internal brecciated nature he asserted a post-Ordovician (Taconic) pre-Devonian (Acadian) age for them.

Cooke investigated the area from Mont Orford south towards the international border. He published two reports (1948, 1950) in which he asserted the "Bolton lavas" were post-Devonian in age based on field relations just north of Peasley Pond, in this study area. Here, rocks of the Glenbrooke Group (Silurian) were mapped as cut off by a fault, with Beauceville slates (Magog slates of Clark, 1934; now known at least in part as the St. Daniel Formation) outcropping across the fault. The volcanics are unbroken by the fault and are continuous across it. Cooke felt that although the gabbro might be the intrusive equivalent of the volcanics, that the intrusion occurred after the lava was folded and faulted, and thereby he restricted use of the term "Bolton" to the lavas only. Cooke also states that the Bolton lavas of previous workers are actually two separate units; some of the lavas being part of the Caldwell group (Cambrian). Moreover, Cooke states Fairbairn (1933) did not differentiate between the Caldwell lavas and what Cooke calls Bolton lavas when distinguishing uralite type and ankerite type volcanics since all of the ankerite type are found solely within the Caldwell lavas (Cooke, 1950). In addition, he assigned the peridotites, an Ordovician or older age based on the assertion that they were intrusive only into Cambro-Ordovician sediments. Also, because he interpreted the gabbro to be intrusive into the serpentine, he designated them as of post-Ordovician pre-Devonian age.

Ambrose published a second paper in 1957 where he reiterates his earlier findings; "...the 'Bolton' lavas belong with, and are interbedded with Ordovician (?) slates...The 'Bolton' lavas are, therefore, not post-lower Devonian, but are interbedded with and form part of the Ordovician (?) series in Memphremagog district." (p. 170) Ambrose questioned the presence of a disconformity by which Cooke justified his separation of Bolton from Caldwell volcanics. He further indicates that the metamorphism of both lavas to greenschist facies indicates a similarity of histories. Finally, Amborse asserted the intrusive rocks were younger than the volcanics because they cut folded volcanics. Hence, he thought it improbable that they were co-magmatic.

H.S. de Romer (1960, 1963) worked in the Chagnon-Orford area as part of his Ph.D. dissertation research. He interpreted the mafic-ultramafic complex as a laccolith which had undergone differentiation by crystal settling thus producing the observed zonal arrangement. In addition, he outlined a sequence of events whereby an undifferentiated magma chamber extruded large volumes of basaltic lava by feeder dikes. Upon this lava, the "Beauceville slates" (which includes the pre-Beauceville St. Daniel formation) was deposited. Sometime later, a large sheet-like body probably from the same source was intruded into the Cambrian sediments and the previously extruded basalts acted as a roof to this body. Differentiation resulted in peridotite at the base, through pyroxenite interlayered with peridotite, to gabbro, and finally to the leucocratic rocks at the top.

Poole, Boland, and Wanless (1963) substantiated a middle Ordovician minimum date for the ultramafic rocks of the Serpentine Belt. K-Ar determinations on muscovite from two granite bodies entirely enclosed by the ultramafics in the Thetford Mines-Black Lake area gave dates of 477 and 481 m.y.

Lamarche (1972, 1973) was the first to recognize the allochthonous nature of the mafic-ultramafic complexes and describe them as ophiolites. Furthermore, he interpreted the contact between the ophiolite complexes and the overlying St. Daniel formation as conformable. He also asserted that the slates of the St. Daniel were unconformably overlain by the Magog slates which contain graptolites of the Nemagraptus gracilis and Diplograptis multidens zone. (Castle Brook and Cherry River localities, St. Julien, 1967; Riva, 1974).

M.K. Seguin and R. Laurent (1975, 1978) studied the magnetic properties and petrologic features of ophiolitic (Thetford Mines) and continental margin (Caldwell) pillow lavas from southern Quebec. They found the ophiolitic lavas could be divided into two groups: a) a lower group consisting of metabasaltic lavas, pillow breccias and tuffs with a sedimentary cover of red cherty argillite, and b) an upper group containing basaltic lavas, pyroclastic agglomerates and breccias, siliceous volcaniclastic tuffs and mudstones. In the lower volcanic group, two types of lava were chemically distinguished, a high Mg-low Ti type (olivine metatholeiite) and a low Mg-high Ti type (metatholeiite). In addition, it was shown that the ophiolitic pillow lavas were texturally zoned and had a consistent N.R.M. vector. The Caldwell pillow lavas, however, were homogeneous and richer in iron than the ophiolitic lavas. Furthermore, the magnetic signature of these two formations was different (Seguin and Laurent, 1978).

Laurent (1975, 1977) continued his study of the southern Quebec ophiolites and compared them to the Vourinos ophiolite of Greece; "The stratified sheets of Thetford Mines, Asbestos and Orford...have a simple, regularly layered structure and no well-developed sheeted-dike complex." (Laurent, 1975, p. 443). Laurent also presented field relationships between the ophiolites and the pre-Ordovician country rocks in addition to geophysical data which strongly supported the allochthonous character of these meta-igneous mafic-ultramafic bodies. Moreover, he provided generalized petrologic and petrographic descriptions of each unit in the ophiolite complexes. In 1979, Laurent attributes the schistosity present in the pre-Ordovician Notre Dame rocks but not in rocks of the St. Daniel or Magog Group to a pre-Taconic orogenic episode related to the tectonic emplacement of the ophiolites. He reasoned that since the ophiolites were "...partly recrystallized in a greenschist regime of low pressure and moderate temperature", that they were not subducted into a trench but obducted onto the continental margin (1977, p. 29).

Regional correlations of the Quebec ophiolites with those from Newfoundland led to the proposition of a suture zone known as the Baie Verte-

Brompton Line (St. Julien, et al., 1976; Williams, et al., 1977; Williams and St. Julien, 1978). The ophiolitic rocks of the Quebec Serpentine Belt are bounded on the northwest by the Sutton-Bennett Schists, a quartzo-feldspathic mica schist and phyllite, metagreywacke, greenstone, and carbonaceous phyllite assemblage belonging to the North American continental margin (Doolan, et al., 1982). To the east, they are followed by finely laminated black slates with olistostromal horizons (the St. Daniel Formation). Farther to the southeast lies a calc-alkaline volcanic sequence known as the Ascot and Weedon Formations.

Laurent, Herbert and Herbert (1979) and Laurent (1980) proposed a primary magma for the Quebec ophiolites of picritic or komatiitic affinity. Major element chemistry shows a differentiation trend typical of a MgO-CaO-rich and FeO-poor magma. In addition, chemical compositions of the volcanics confirmed the presence of two distinct magmatic suites, an olivine metatholeiite and a metatholeiite both of which are similar to basalts erupted at spreading ocean ridges (Laurent, et al., 1979).

Doolan and others (1982) have conducted studies along a sixty km segment of the Vermont-Quebec ultramafic belt. They have recognized five major correlative tectono-stratigraphic units and have postulated a common origin for the ultramafic rocks across the International Border. They suggest these rocks represent ophiolites and ophiolitic fragments which were obducted as a result of oblique collision of a volcanic arc complex and ocean crust during the Ordovician. Winner's work (1981) on the comparison of ultramafic, gabbroic, and volcanic rocks near North Troy, Vermont with the allochthonous and presumably ophiolitic rocks of Chagnon supports the work of Doolan and others (1982). In both localities, the mafic-ultramafic complexes were found in fault bounded contacts with serpentine melange. In addition, volcanics from the North Troy area were petrographically and chemically similar to the upper volcanics from Chagnon Mountain.

REGIONAL GEOLOGY AND TECTONICS OF QUEBEC

Introduction

In order to fully understand the geology in the Chagnon area, a knowledge of the regional geology must be obtained (Figure 1). Various authors have made attempts to synthesize the regional geology of the Quebec Appalachians into a general tectonic framework (St. Julien and Hubert, 1975; Laurent, 1975, 1977, 1980; Osberg, 1978; Laurent, et al., 1979; Doolan, et al., 1982). As such, they recognize the lithostratigraphic units present as continental shelf, slope and rise deposits, ocean crust, and island arc assemblages. Following the terminalogy of St. Julien and Hubert (1975), the Cambrian and Ordovician rocks may be grouped into three major tectonic domains: the autochthonous domain, the external domain, and the internal domain. These divisions are analogous to those of Bird and Dewey (1970) where the autochthonous and external domains correspond to their Logan Zone and the internal domain is the western or northwestern part of their Piedmont Zone. Each of these, in addition to later overlying units, are discussed below.

AUTOCHTHONOUS DOMAIN

Eleven lithostratigraphic groups have been recognized in the Quebec Appalachians (St. Julien and Hubert, 1975). Three of these; shelf, flysch, and regressive sequences, are present in the autochthonous domain. The shelf and flysch also occur in the external domain. The shelf sequence is composed, from base to top, of the Potsdam Group, basal Upper Cambrian sandstones, overlain by the Beekmantown Group, Lower Ordovician dolomites, the Chazy, Black River and Trenton Groups, Middle Ordovician limestones (Clark, 1972; St. Julien and Hubert, 1975). These units successively overlap each other and rest on the Precambrian basement northeastward.

The flysch sequence contains the Middle and Upper Ordovician Utica Shale; sandstones, shales, and mudstones of the Lorraine Group; and part of the Cloridorme Formation (Enos, 1969). The sandstones in the sequence are generally lithic, contain fossil debris, and have the characteristics of turbidites (Bouma, 1962; St. Julien and Hubert, 1975). Breccia, consisting of limestone, sandstone, and mudstone fragments which resemble lithologies contained in the nappes of the external domain, are set in a black pelitic matrix. This breccia has been interpreted by St. Julien and Hubert (1975) as wildflysch whose deposition is synchronous with the emplacement of the nappes in the external domain.

The Becancour Formation, which consists of red and green shales alternating with thin sandstone beds, is the only unit in the regressive sequence (Clark, 1964; St. Julien and Hubert, 1975). It is thought to be of late Upper Ordovician age and, therefore, post-orogenic. St. Julien and Hubert (1975) have noted two localities where the basal portion is involved in the thrust-imbricated structures of the outer part of the external domain. Hence, they feel this indicates the lower part of this sequence may be synchronous with the development of these structures in the external domain and that the imbricate thrusting of the external domain continued into the late Ordovician.

EXTERNAL DOMAIN (PARA- AND/OR NEO-AUTOCHTHON)

The external domain consists of two belts: an outer belt of thrust imbricated structures and an inner belt of nappes. As previously mentioned, the shelf and flysch sequences which occur in the autochthonous domain are also present here. All of the units, except the Potsdam sandstones of the shelf sequence, are found along major thrust faults where they are brought to the surface in the thrust-imbricated belt of the external domain (St. Julien and Hubert, 1975).

The inner belt of nappes contains three lithostratigraphic sequences: Cambrian shelf-feldspathic sandstone, Upper Cambrian-Lower Ordovician shale-limestone conglomerate, and Middle Ordovician shale-argillaceous limestone assemblages. The Cambrian shale-feldspathic sandstone assemblage constitutes the bulk of the Chaudiere, Granby, and Lower St. Lawrence Valley nappes. These sequences contain rocks of the Charny Group, Anse Maranda, Granby sandstone, Mawcook slate, the St. Roch Formation, St. Damase Formation, and have strong similarities to the Sillery assemblage (St. Julien and Hubert, 1975). Some of the units are fossiliferous and give a Middle to Late Cambrian age (Rasetti, 1946, 1948a, b; Hubert, et al., 1969).

The shale-limestone conglomerate of Upper Cambrian-Lower Ordovician age occurs in several nappes near Quebec City (e.g., the Pointe-de-Levy, Bacchus, St. Henedine, Stanbridge, and Lower St. Lawrence Valley nappes). The limestone conglomerate is polymictic in composition with the limestone clasts clearly derived from a shallow carbonate shelf (Osborne, 1956; Hubert, et al., 19[illegible]) Dendroids and graptolites contained in the shales of this sequence indicate this assemblage is partly Tremadoc, partly Arenig, and partly Llanvirn in age (St. Julien and Hubert, 1975). Rocks contained in this sequence are the Levis Formation, the Pointe-de-la-Martiniere Formation, the St. Henedine Formation, the Stanbridge Formation, the Kamowaska Formation, the Ladriere Formation, and the Cap-des-Rosiers Formation (St. Julien and Hubert, 1975).

The Middle Ordovician shale-argillaceous limestone assemblage includes the Quebec City Formation in the Quebec Promontory nappe, the Deslandes Formation, and part of the Cloridorme Formation (St. Julien and Hubert, 1975). In addition, all the rocks of this sequence are very fossiliferous and are from the Nemagraptus gracilis and Diplograptus multidens zones (Riva, 1974).

INTERNAL DOMAIN (ALLOCHTHON)

The internal domain is made up of allochthonous units including Lower Cambrian clastic carbonate, Cambrian shale-feldspathic sandstone, Middle Ordovician shale-argillaceous limestone assemblage consisting of the Oak Hill sequence, the Bonsecours and Sweetsburg Formations which make up the core of the Sutton Mountain anticlinoria. The only known fossiliferous units in this assemblage come from the Gilman quartzite and Dunham dolomite units of the Oak Hill, which give an Early Cambrian age (Clark, 1934; Osberg, 1965), and from the Sweetsburg Group on the west side of the Anticlinorium, which gives a Late Cambrian age (Doolan, 1982, written communication). Because of the lithologic similarity of the Rosaire Group coring the Notre Dame anticlinoria to parts of the Oak Hill of the Sutton Mountains, these sequences have been correlated (St. Julien and Hubert, 1975). In addition, the Oak Hill has been traced into Vermont where it appears to rest unconformably on Precambrian, Grenville-like basement (Doll, et al., 1961). Hence, St. Julien and Hubert (1975) argue that the same situation exists in Quebec.

The Cambrian shale-feldspathic sandstone, as previously mentioned, occurs in nappes in the external domain and is also found as inliers in the internal domain. The rocks are similar in both domains, although in the internal domain they are a metamorphosed assemblage with intercalations of basic volcanics. These units include rocks of the Mansonville Formation, part of the Brompton Formation, the Caldwell Group, and the Armagh Formation, and are found along the eastern flank of the Sutton and Notre Dame anticlinoria (St. Julien and Hubert, 1975). Unlike the shale-feldspathic sandstone assemblage in the external domain, the corresponding rocks here are unfossiliferous.

The tuffaceous pelite in the lower part of the Magog Group is laterally equivalent to the shale-argillaceous limestone assemblage of the external domain and to part or all of the Mictaw Group on Chaleur Bay (St. Julien et al., 1972; St. Julien and Hubert, 1975). As in the external domain, the shale-argillaceous limestone assemblage of the internal domain is very fossiliferous and belongs to the Nemagraptus gracilis and Diplograptus multidens zones (Riva, 1974).

Ophiolitic sequences occur only in the internal domain and are composed of harzburgite, dunite, pyroxenite, gabbro, diabase, and mafic volcanics (Riordon, 1953; de Romer, 1960; Lamarche, 1972; Laurent, 1973, 1975, 1977, 1980; Winner, 1981; this study). It is believed they represent fragments of oceanic crust and upper mantle obducted onto the continental margin in early Ordovician time (Laurent, 1975, 1979; St. Julien and Hubert, 1975; Doolan, et al., 1982; Winner, 1981). In addition to these massifs, there are several thin peridotite sheets (e.g., the Pennington Dike) that appear to have been tectonically intruded in Cambrian aged rocks of the Oakhill, Rosaire, and Caldwell Groups. Laurent (1975) believes they may be the result of branching off from the basal peridotite of the larger ophiolitic bodies. St. Julien and Hubert (1975) feel they are remobilized masses of ultrabasic rocks as they are always located in major thrust faults.

The St. Daniel Formation is a shale melange assemblage which is restricted to the internal domain. The black and grey slate is typically laminated and chaotically deformed and is frequently interbedded with graywacke or quartz arenite beds identical to those of the Caldwell/ Brompton Sequence (Smith, 1981). The melange is composed of shale, siltstone, graywacke, quartz arenite, with locally occuring serpentinite blocks (St. Julien and Hubert, 1975). In the Chagnon area, only slivers of serpentinite have been noted (Doolan, et al., 1982). This assemblage occurs on the southeast side of the Quebec ophiolites and is apparently a consistent horizon along the entire Baie Verte-Brompton Line (St. Julien, et al., 1976; Doolan, et al., 1982). Doolan and others (1982) claim the brecciated nature of these rocks are the result of both an unstable depositional environment and tectonic imbrication or argillites, shale, and graywacke with dismembered ophiolites. The nature of the contact between the St. Daniel and the basic volcanics of the ophiolite suites appears to be unconformable or tectonic. In places, however, a transition between the two units has been reported with intercalations of basic flows in shales or breccia (St. Julien and Hubert, 1975). No fossils have ever been found in the St. Daniel Formation. However, graptolites of the Nemagraptus gracilis and Diplograptus multidens zones have been found in the overlying Magog Group (Riva, 1974). Thus, the age of the St. Daniel can only be approximately defined as pre-Middle Ordovician.

The Magog Group, which lies in the St. Victor synclinorium, is composed of the Beauceville Formation and the St. Victor Formation (St. Julien, et al., 1972). The Beauceville includes graphitic slate, tuffaceous sandstone, and chert units, in addition to pyroclastic material.

Riva (1974) identified graptolites of the Nemagraptus gracilis and part of the Diplograptus multidens zones in it thus giving it a Middle Ordovician age. The overlying St. Victor, which also contains graptolites belonging to the Diplograptus multidens zone, is characterized by thick and thin silicic tuff bands in a flysch sequence; and like the Beauceville Formation, it also contains abundant pyroclastic material (St. Julien, et al., 1972). This has led St. Julien and Hubert (1975) to propose that these two units are synchronous with the Ascot-Weedon calc-alkaline assemblage.

CALC-ALKALINE ASSEMBLAGE (ASCOT AND WEEDON FORMATIONS)

A calc-alkaline volcanic assemblage is found east of Lake Memphremagog in the Stoke Mountain Anticlinorium. This assemblage is seemingly conformable with underlying graphitic phyllite-melange assemblage. This melange assemblage has been correlated with the St. Daniel Formation by St. Julien and Hubert (1975). The calc-alkaline assemblage, or the Ascot and Weedon Formations, consists of felsic and intermediate metavolcanics, chloritic schists (metabasic volcanics), iron formation, cherts and metavolcaniclastics, and are interpreted as a Lower to Middle Ordovician island arc sequence (St. Julien and Hubert, 1975; de Romer, 1979; Doolan, et al., 1982).

SILURO-DEVONIAN METASEDIMENTS AND INTRUSIVES AND THE CRETACEOUS MONTEREGIAN HILLS

In southern Quebec, the Silurian metasedimentary rocks of the Gaspe-Connecticut Valley synclinorium (the Glenbrooke Group) lie in two narrow infolds parallel to the axis of Lake Memphremagog and in a third belt (The St. Francis Group). According to the SOQUIP line, St. Julien claims that the St. Francis Group is thrust over the metasedimentary rocks of the Ascot and Weedon Formations along the Bunker Hill thrust (Personal communication to B. Doolan, 1980). The Glenbrooke Group, which contains the Peasley Pond Conglomerate, the Glenbrooke Slate, and the Sargent Bay limestone, overlies the St. Daniel Formation and the Magog Group with angular unconformity (Doolan, et al., 1982). The St. Francis Group, which lies to the east of the Glenbrooke Group, is characterized by calcareous slates and limestones. Late Devonian granites, related to the Acadian orogeny, cut the Silurian strata of the Gaspe-Connecticut Valley synclinorium. These intrusive bodies appear epizonal, have contact aureoles, and contain xenoliths of the Silurian metasedimentary country rocks (Doolan, et al., 1982). Finally, Cretaceous alkaline, syenitic, and gabbroic intrusive rocks of the Monteregian Hills cut indiscriminantly, albeit in a west-northwest trend, through rocks of the autochthonous, external, and internal domains, and through the Siluro-Devonian metasediments of the Gaspe-Connecticut Valley synclinorium (St. Julien and Hubert, 1975).

TECTONIC MODELS

With the advent of plate tectonic theory in the late 1960's, an abundance of literature speculating on possible tectonic models for the Quebec ophiolites arose. St. Julien and Hubert (1975) proposed a model for the tectonic emplacement of southern Quebec ophiolites (Figure 4). Their model envisions sediments of the Caldwell Group deposited on the continental rise. These sediments, along with Cambrian-aged ocean crust of the marginal basin, were emplaced onto the continental margin in early Middle Ordovician time and were imbricated and folded by the end of the Middle Ordovician. These events would coincide with the Taconian

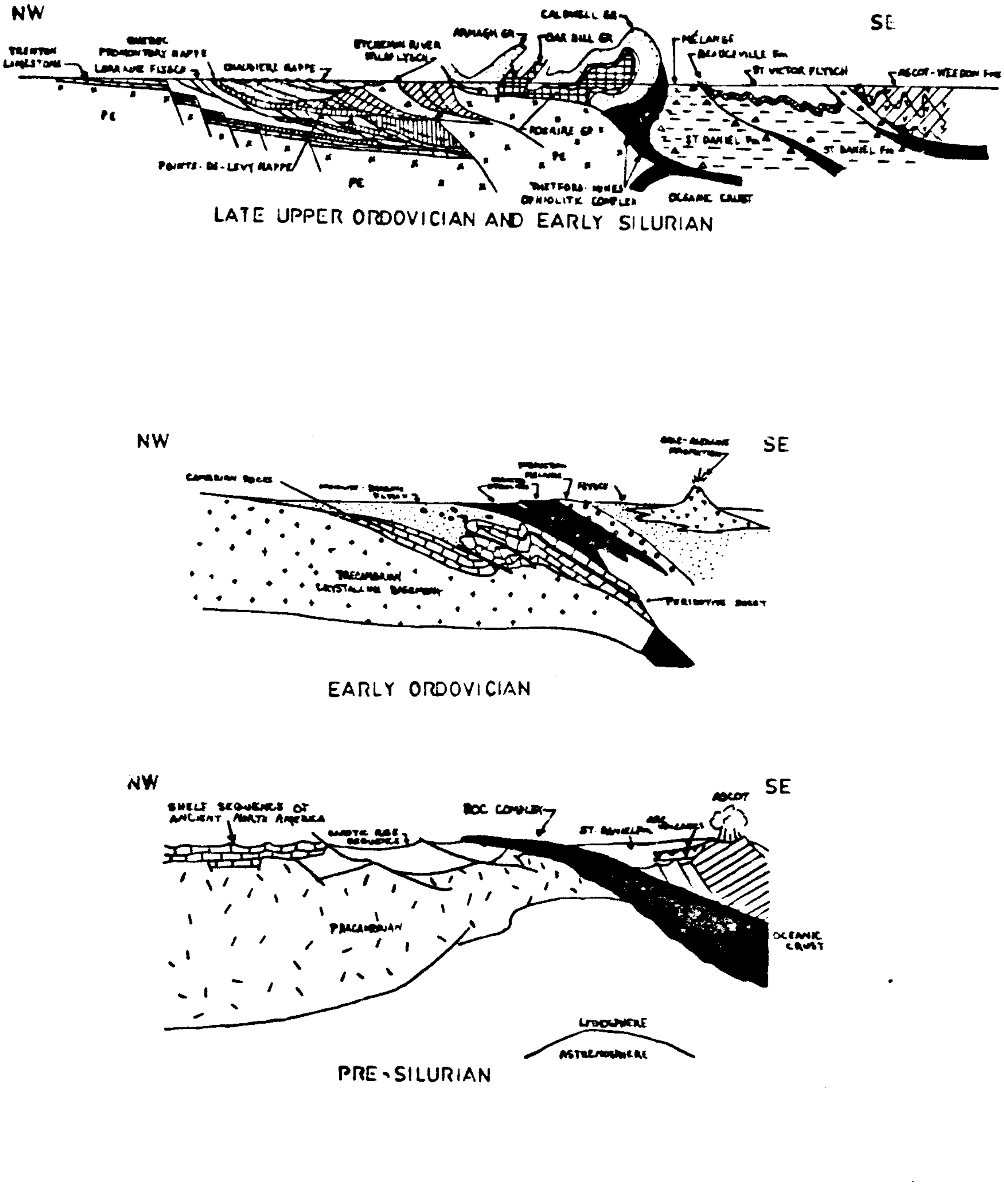

Figure 4: Tectonic models for southern Quebec. 4A, after St. Julien and Hubert, 1975; 4B, after Laurent, 1975; and 4C, after Doolan, et al., 1982.

orogeny in the New England Appalachians. The presence of calc-alkaline volcanic rocks of the Ascot and Weedon Formations to the southeast of the Thetford Mines, Asbestos, and Orford complexes led St. Julien and Hubert to conclude they represented an island arc system related to a westerly dipping subduction zone. By lithologic correlation with the Tetagouche Group of New Brunswick, they inferred a Middle Ordovician age for the calc-alkaline volcanics.

In 1978, Osberg looked at the regional geology in the New England and Quebec Appalachians. He presented a plate tectonic model based on his division of four basement domains. He envisioned a westward dipping subduction zone under northeastern North America eventually failing with obduction of oceanic crust in the lower Ordovician. At the same time, he explains the formation of the Ascot-Weedon volcanics by a eastward dipping subduction zone.

Unlike Osberg (1978), Laurent and others (1979) and Laurent (1980) did not use a westward dipping subduction zone under northeastern North America as no intrusive and extrusive calc-alkaline rocks of late Cambrian and early Ordovician age are present on the Canadian continental margin. Since Ordovician island arc volcanics of the Ascot-Weedon lie to the southeast of the ophiolite complexes, a southeastward dipping subduction zone was assumed. Seguin's work (1979) based on gravimetric, aeromagnetic, and magnetotelluric surveys, supports the obduction rather than intrusion hypothesis of origin for these ophiolites.

Doolan and others (1982) also derived a plate tectonic model for southern Quebec which attempts to explain the present distribution of rock units as resulting from a diachronous collision of volcanic arcs against an irregular continental margin. They envision a shallow eastward dipping subduction zone under the Ascot and Weedon volcanic arcs with closure of the ocean basin marked by ophiolite obduction onto the ancient North American continental margin (Figure 4c). Subsequent collision of the Ascot-Weedon arc with the ophiolite imbricated margin changed the plate interaction from subduction to left lateral transform tectonics thus producing the sideways-driven transform splinters of Dewey and Burke (1974) and further dismemberment of the ophiolitic sequences (Figure 5).

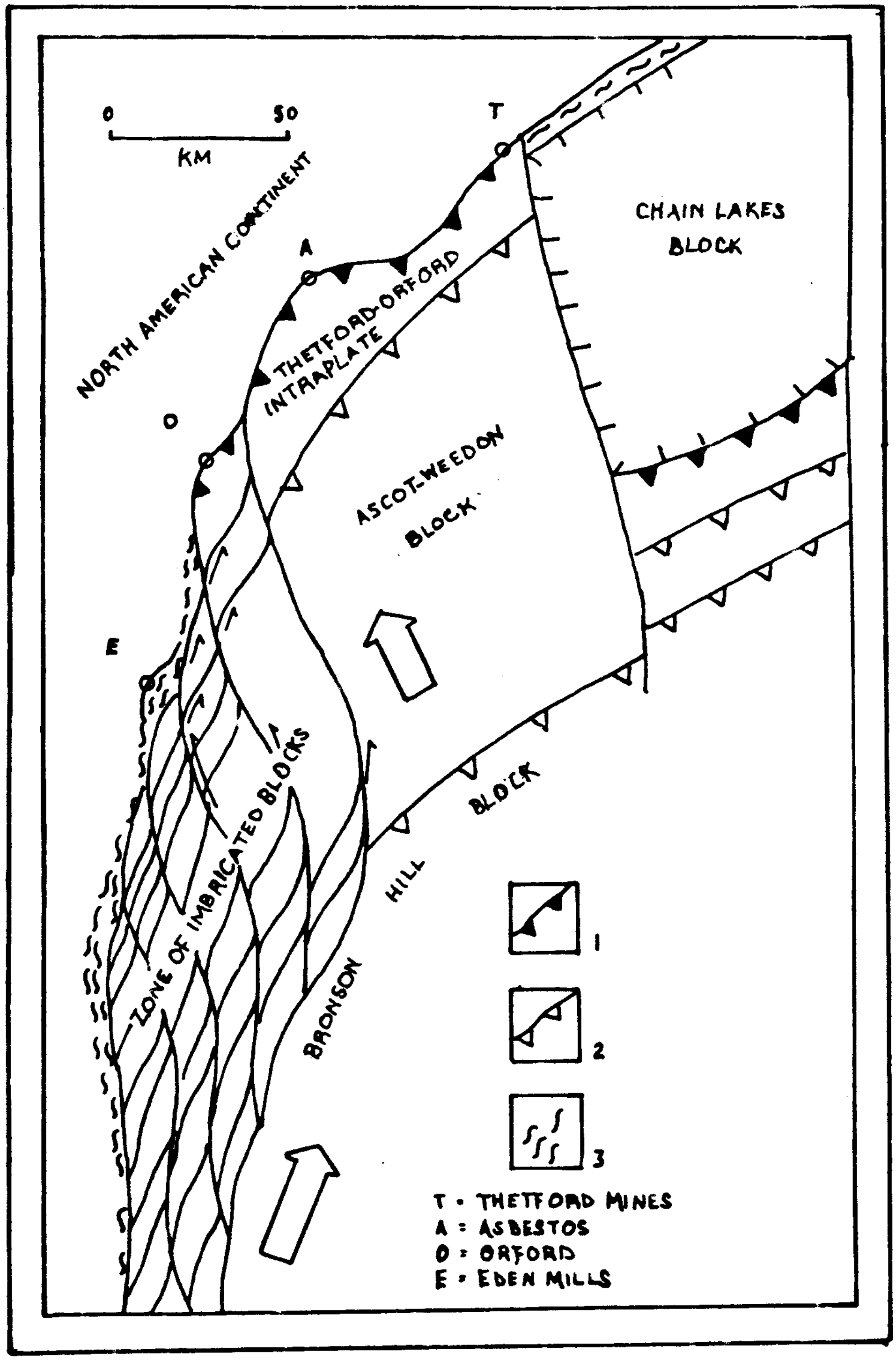

Figure 5: Plate tectonic inspired model for the Eastern Township-Vermont ultramafic belt depicting diachronous island arc-continental margin collision (from Doolan, et al., 1982).

CHAPTER II

FIELD RELATIONS, PETROGRAPHY AND STRUCTURAL GEOLOGY OF THE CHAGNON AREA

INTRODUCTION

The Chagnon Mountain area was mapped on aerial photographs during the summers of 1980 and 1981. The northern third of the area was mapped at a scale of 1:10,000 and the southern two thirds was mapped at a scale of 1:20,000. The map areas were then fitted together at a scale of 1:20,000 and placed on a topographic base enlarged two and one-half times from its original scale of 1:50,000 (plate A). Continuity at the adjoining boundary was checked in the field.

The rocks in the area of study include, from west to east, an igneous complex: consisting of massive gabbros, quartz-diorites, diabase, and volcanics; and the overlying metasediments: consisting of the St. Daniel Formation and the Glenbrooke Group. In general, contacts are not exposed and overall outcrop abundance is less than 10-15 percent.

FIELD RELATIONS AND PETROGRAPHY

The igneous complex is discussed first and the overlying metasediments subsequently, which is in order from west to east and also up structure. For the sake of consistency with ongoing research in the area (Winner, 1981; Doolan, et al., 1982), rock names will generally be that of their protoliths. Reference to samples identified in the text by numbers can be located on the outcrop map (plate A).

IGNEOUS COMPLEX

Rocks contained in the igneous complex at Chagnon Mountain, from west to east, are sheared ultramafics (serpentinite), massive ultramafics, massive gabbros, quartz-diorite and trondhjemites, diabase, and mafic volcanics. The sheared ultramafics and serpentinite, massive ultramafics, and massive gabbros are found west of the area studied in this report. Further information on these units can be found in Winner (1981).

MASSIVE GABBROS

Gabbroic rocks are the least abundant rock type in the area of study. They appear massive in outcrop, are bluish-green on a fresh surface and weather gray. The gabbro is reported to be a moderately east dipping fault bounded unit which narrows to the north as imbrication becomes more severe (Winner, 1981). This unit is northeast trending, is in fault contact with the underlying ultramafic units, and has a variable contact with structurally higher units. In the area Winner (1981) mapped to the north of this study's area, the upper contact is thought to be structural on the basis of observed faults and truncation of gradational gabbro/trondjhemite bodies by upper units. In the field area of this report, the gabbro/quartz-diorite contact is indeterminate due to the paucity in the volume of gabbro. Gabbro is believed to lie largely to the west-northwest of the quartz-diorite forming as a late-stage magmatic differentiate, or the quartz-diorite is intrusive into the gabbro and diabase units of the Chagnon massif. As the quartz-diorites are not known to be intrusive in any of the lower units (ultramafics), and as the gabbros that are present in the field area appear gradational to the quartz-diorites, it is likely they formed as late-stage magmatic differentiates of the gabbro.

Petrographically, the gabbros appear medium grained hypidiomorphic granular and show ophitic texture. Cataclastic zones containing chlorite, clinozoisite, and carbonate are often present. These gabbros characteristically contain plagioclase, clinopyroxene, and ilmenite with varying amounts of quartz. The plagioclase is lath shaped, has relict albite twinning, rare deformation twinning, and is strained. It has undergone saussauritization by chlorite, clinozoisite, $\pm$ sericite, $\pm$ carbonate. Clinopyroxene occurs as subhedral to anhedral grains and is augite in composition. Actinolite is sometimes found altering the clinopyroxene at the edges. Rarely, subhedral to anhedral chloritized olivine is found. When present, these grains are partially enclosed by the clinopyroxene.

Quartz is present in increasing abundance with proximity to the quartz diorite body. It occurs as anhedral grains showing undulose extinction. Accessory minerals include: skeletal ilmenite partially altered to leucoxene, opaques (probably magnetite) and sphene(?). The order of crystallization of the gabbro is plagioclase-olivine-ilmenite-clinopyroxene $\pm$ magnetite- $\pm$ quartz. Metamorphic minerals include fibrous actinolite altering clinopyroxene, chlorite after olivine, clinozoisite, chlorite, carbonate and some haematite stain in cracks and cataclastic zones. Modal estimates are given in Table 1.

QUARTZ-DIORITE AND TRONDHJEMITE

Quartz-diorites make up the volumetrically most important rock type in the northern portion of the field area but are absent in the southern portion. They are presumed to have a gradational contact with the underlying massive gabbros; however, this was not observed in continuous outcrop in the field area. It is reported that they do not intrude the metasediments (Miller Pond Formation) underlying the Chagnon massif (de Romer, 1960). Therefore, they cannot post-date emplacement, and are probably genetically related to the Chagnon complex through differentiation processes. Field observations reveal the irregular quartz-diorite/diabase boundary to have an intrusive rather than faulted or thrust imbricated contact with a few screens of diabase in its upper portions. In some areas near the contact, blocks of diabase 0.3 - 0.6 m in length are seen in the quartz-diorite (location A, location B, and location C; plate A). In these places, the quartz-diorite has a 2 mm chill margin against the diabase blocks. These blocks could represent stoping of a diabase roof into the felsic or upper portion of a differentiated magma chamber. The quartz-diorite generally is exposed where the terrain becomes steeper. It gives a knobby appearance to outcrops due to the abundance of medium to coarse grained (up to 6 mm) quartz grains. Fresh surfaces are a grayish blue color while weathered surfaces are a milky white.

Texturally, the quartz-diorites are xenomorphic granular with quartz and plagioclase feldspar the predominant minerals. These rocks appear compositionally gradational to trondhjemites as defined by Strekeisen (1976), where a trondhjemite is defined as having oligoclase or andesine plagioclase, quartz present as 20 percent or more, alkali feldspar as 10 percent or less, and color index of 10 or less. Barker (1979) defines trondhjemitic rocks chemically giving the following six criteria:

1. SiO_2 ca. 68 percent, usually 75 percent;
2. Al_2O_3 typically 15 percent at 70 percent SiO_2 and 14 percent at 75 percent SiO_2;
3. (FeO^* + MgO) 3.4 percent, and FeO^* : MgO commonly is 2-3 percent;
4. CaO ranges from 4.4 - 4.5 percent in calcic trondjhemite to typical values of 1.5 - 3.0 percent;

5. Na_2O typically is 4.0 - 5.5 percent; and

6. K_2O ca. 2.5 percent, and typically 2 percent.

The rocks mapped as quartz-diorites in this report contain no orthoclase feldspar (electron microprobe analyses yield an average chemical composition of An_2), but do have a variable amount of mafic constituents (0-35% Cpx, 0 - 5% chloritized Olivine, 0 - 20% actinolized hornblende), and thus can be seen as gradational. However, these two rocks types are indistinguishable in the field and show no consistent pattern of outcrop for a boundary between them to be drawn. It appears probable that the differences between the "quartz-diorites" and the "trondhjemites" reflects local variations of mafic mineral content in the magma chamber and are not the result of two separate magmatic differentiates. Hence, they are both labeled quartz-diorite for the remainder of this report and are described as a single rock type below.

Plagioclase occurs as subhedral to anhedral lath-shaped grains. It is severely altered to and overgrown by chlorite, clinozoisite, zoisite, carbonate, and actinolite. Relict albite and carlsbad twinning are visible and occasionally the albite twinning is seen kinked. A combined albite-carlsbad twin gave an An content of 43 indicating the plagioclase was originally andesine. However, measurements on a number of albite twins gave results around An 0-5, indicating albitization. Saussauritization is slightly more intense toward the core and in some cases a clear albite rim encloses the altered feldspar. This indicates the core may be calcic and the plagioclase might be slightly normal-zoned. The albite rim is probably a secondary overgrowth due to spilitization. The quartz in the quartz-diorite is anhedral in shape, strained, and exhibits deformation bands and subgrain development. Rare clinopyroxene inclusions are enclosed by quartz indicating quartz crystallized after clinopyroxene. It is overgrown slightly by actinolite, clinozoisite, and chlorite. Both the quartz and feldspar usually have a brecciated or shattered appearance with chlorite, clinozoisite, zoisite, and haematite filling the cracks and bordering the grains.

Clinopyroxene (augite) is rarely observed although it may locally be abundant (up to 35 estimated modal percent). When it occurs, it is strained, shows simple twinning, is marginally altered to actinolite, carbonate, zoisite, and chlorite, and in places is cored by chlorite. Primary amphibole, where observed, shows good prismatic shape and cleavage. It is less commonly present than the clinopyroxene and is probably hornblende (pleochroism ranges from green to yellow green to bluish-green and extinction angle ranges from 31 - 40°. Actinolite is common as an alteration mineral and occurs in fibrous masses. It rims the primary amphibole and has overgrown much of the original pyroxene. Pleochroism of the actinolite is α = light green, β = olivine green, γ = blue green, and extinction is less than 20°. Accessory minerals in the quartz-diorite include sphene, carbonate, opaques, and rare apatite. These rocks crystallized according to the sequence: plagioclase-augite-hornblende-quartz. Modal estimates are given in Table 1.

DIABASE

In the Chagnon area, diabase appears structurally up section or east of the quartz-diorite with the quartz-diorite apparently intrusive into it. The diabase appears homogeneous in outcrop, is bluish-green on fresh surfaces, weathers greenish-gray to tan, and sometimes gives a vague dike-like appearance. A few recognizable dikes can be found intruding the overlying volcanics and a few are also observed in the gabbro and quartz-diorite within the field area. H. de Romer (1960) mentions the presence of some discontinuous diabase dikes a few inches to three feet in width filling steep north or south dipping longitudinal and cross joints in the upper portion of the gabbroic unit. Although the diabase lacks sheeted structure now, it may originally have been sheeted and this structure obscured by subsequent metamorphism and dismemberment of the Chagnon complex.

Veins of quartz and quartz-diorite are observed cutting the diabase in a few places, especially in proximity to the quartz-diorite contact. For example, in one outcrop (location D, plate A) volcanic, diabase, and quartz-diorite units are all present. Where the volcanic and diabase units are in contact, the volcanics show a 15 cm thick chill zone and the diabase a 2mm alteration zone. The quartz-diorite is present, for the most part, as veins trending approximately N45W and dipping 70°S. Additionally, it shows a 2mm alteration zone against both the volcanic and diabase. Finally, minor right lateral faults offset contacts of all of the rock types by a few centimeters (Figure 6).

Petrographically, the diabase is fine to medium grained and displays an intergranular to subophitic texture. Often, granulated zones are observed with a nematoblastic texture developing adjacent to them. The diabase is composed primarily of plagioclase (saussaurite), clinopyroxene, actinolite, and quartz; quartz becoming more abundant as the quartz-diorite body is approached (see Table 1 for modal estimates).

Plagioclase, for the most part, is saussauritized, overgrown by chlorite, clinozoisite, zoisite, actinolite, sphene, and sericite. Saussauritization is relatively uniform and of moderate intensity although relict carlsbad and albite twins are still visible. Albite is observed rimming some of the lath-shaped feldspar and may result from

Figure 6: Outcrop of northwest trending quartz-diorite veins cutting diabase and volcanic (diabase and volcanic are not distinguishable in the photograph). Also note the presence of minor faulting. Silva [compass] for scale.

recrystallization.

The clinopyroxene in the diabase is augite and occurs as sub- to anhedral grains of brownish red color. Some simple twins and slight zoning may be seen; however, much of the augite is overgrown by actinolite, clinozoisite, and sphene. Amphibole alteration around the edges of grains is especially common. Actinolite shows a fibrous to acicular crystal form with infrequent simple twins. It is found rimming primary hornblende, rimming to replacing clinopyroxene, and as fibrous bundles in the groundmass. Extinction is from 15 - 20° and its pleochroic formula is α = green, β = olive, γ = bluish green. Quartz, when present, is subhedral to anhedral in shape, is partially resorbed, exhibits undulose extinction, and is slightly overgrown by actinolite and chlorite. Quartz overgrowths on resorbed quartz are not uncommon and are detectable where slightly dirty quartz is surrounded by clear quartz. Myrmekitic relationships of quartz with plagioclase are also observed. Accessory phases in the diabase include sphene, opaques (pyrite), chloritized olivine, apatite, and ilmenite altered to leucoxene. Chlorite, clinozoisite, haematite, and carbonate are often found filling microscopic fractures. The order of crystallization is augite-hornblende-plagioclase-quartz.

MAFIC VOLCANICS

Mafic volcanic rocks comprise the single most abundant rock type in the area studied. Uncommon diabase dikes in the volcanics indicate the dikes acted as feeders to the overlying volcanics. In addition, screens of mafic volcanics are seen in the diabase near the volcanic/diabase contact. In the field, the volcanics are most commonly massive, homogeneous units. However, basalt breccia and pillow lavas are common.

The pillow structure of some of these volcanics attests to a submarine extrusive origin. In addition, mafic volcaniclastic sediments are present in the southern portion of the map area. All of these volcanics are bluish-green on fresh surface and weather grayish green to black. An increase in the amount of disseminated and vein-filling carbonate is noted as the contact with the overlying St. Daniel Formation is approached.

In thin section, the volcanic rocks are more severely altered than any of the structurally underlying rocks. Much of the minerals present are secondary, suggesting, as de Romer (1960) notes, that the volcanics were subjected to strong deuteric action or were permeated by hydrothermal solutions. Despite this fact, primary igneous features are preserved in nearly all of the thin sections studied. Winner (1981) notes the presence of two petrographically and geochemically distinct volcanic groups on the north side of Chagnon Mountain. One he calls an olivine metatholeiite characterized by chloritized olivine phenocrysts, and the other is termed a metatholeiite characterized by phenocrysts of plagioclase and amphibole/chlorite pseudomorphs after clinopyroxene. The volcanics on the southern slopes in this study area appear to be of only one variety. They are often hiatal equigranular in texture and are plagiocase ± clinopyroxene ± chloritized olivine phenocrystic.

The massive mafic oceanic rock type is characterized by plagioclase phenocrysts with a lesser amount of clinopyroxene phenocrysts set in a fine-grained chloritized groundmass containing some plagioclase, clinopyroxene, and rare olivine pseudomorphed by chlorite microlites. Basaltic breccia, which is found only north of Trouserleg Pond, appears texturally fine grained with numerous cataclastic zones. Plagioclase and clinopyroxene are both present as phenocrysts, and with olivine in the chloritized groundmass. Calcite, clinozoisite, and haematite stain are also present in the groundmass. Pillow lavas on Chagnon's southern slopes are ellipsoidal in shape measuring 0.3 - 0.5 meters in length by 0.2 - 0.3 meters in width with 7.5 - 10 mm thick chill margins. They are deformed and attenuated in outcrops on the west side of Trouserleg Pond. This is possibly related to their proximity to an east-west trending fault. The pillow lavas are characterized by phenocrysts of olivine pseudomorphed by randomly orientated chlorite, by plagioclase laths set in chloritized groundmass of plagioclase and chloritized olivine microlites, and they exhibit good basaltic textures (Figure 7).

As mentioned above, mafic volcaniclastic sediments are found only south of Trouserleg Pond. They occur in low abundance (less than 10 percent) and appear interbedded with the massive volcanics. Previous workers in the area (e.g., Cooke, de Romer, Lamothe) have failed to recognize them possibly because they appear similar in outcrop to the massive volcanic unit which is so abundant in the area. Texturally, the plagioclase, clinopyroxene, and chlorite pseudomorphs after olivine and pyroxene mineral grains are broken to somewhat rounded with plagioclase in sub-parallel alignment. In addition, cataclastic zones are locally common. The mineral fragments are set in a very fine grained matrix which consists largely of chlorite, feldspar, and quartz. Many of the volcaniclastics show, by grain size distribution and degree of roundness, some degree of sorting by weathering and water processes. The volcaniclastics are made up not only of mineral grains but also of rock fragments. The mineral grains appear similar to those found in the other volcanic units in the field area. Hence, individual mineral descriptions for the different volcanic subtypes are grouped together

Figure 7: Top is a photomicrograph of a typical massive volcanic from the Chagnon area (crossed polars). Note the plagioclase microlites and clinopyroxene phenocrysts.

Bottom photograph shows elongated pillow basalts located approximately 0.25 kilometers west of Webster Pond. Silva for scale.

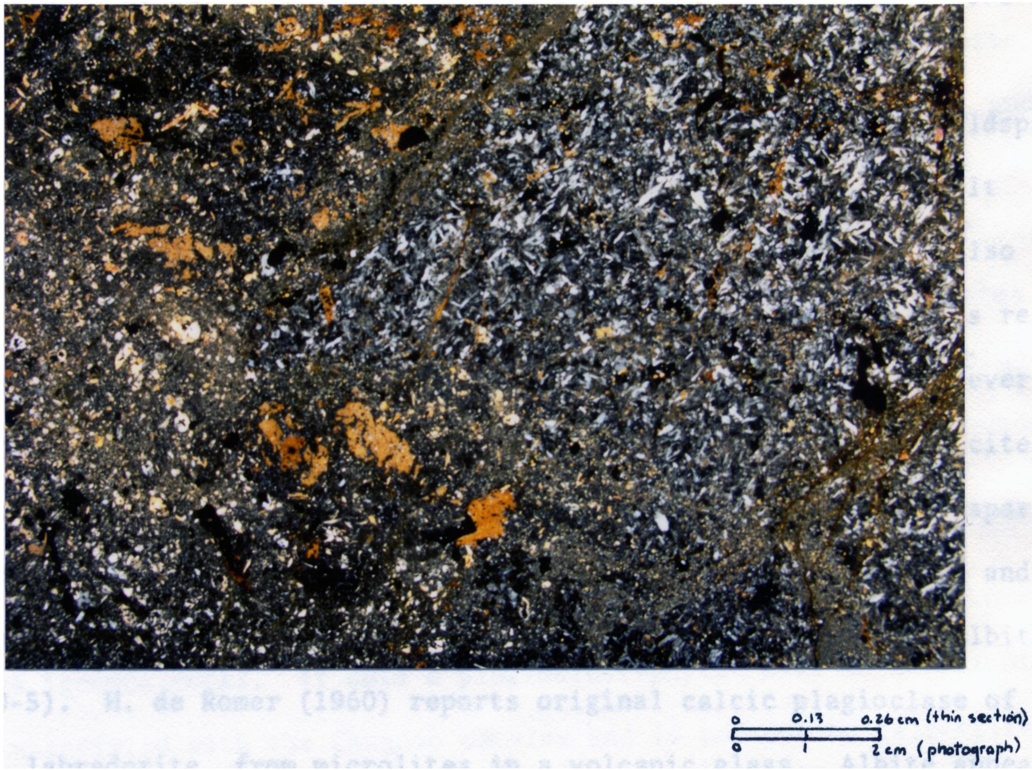

Figure 7: Photomicrograph of a typical massive volcanic from the Chagnon area (crossed polars). Note the plagioclase microlites and clinopyroxene phenocrysts.

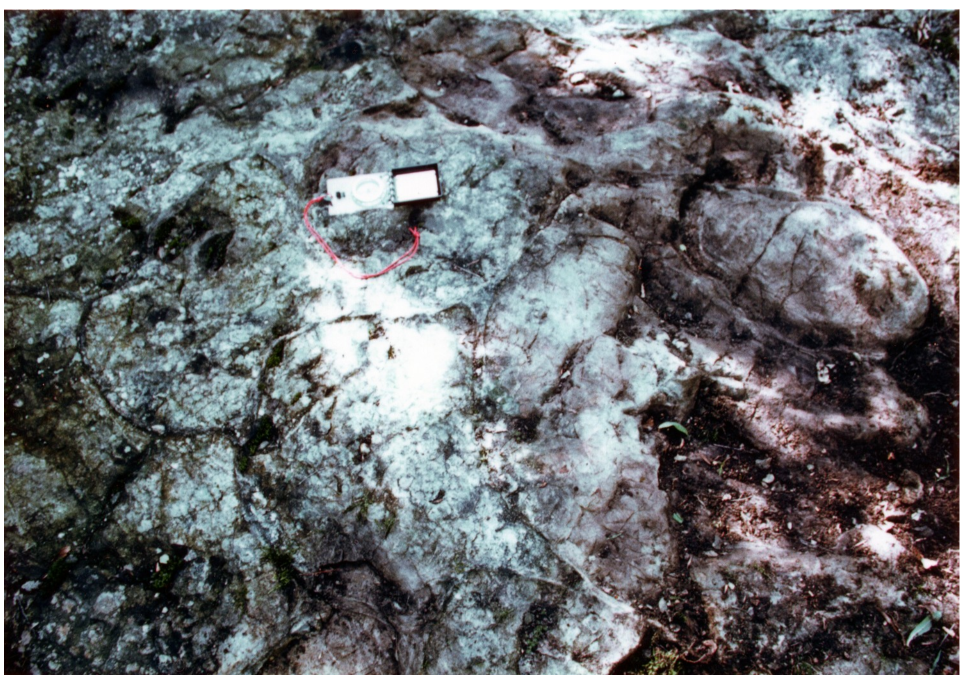

Figure 7b: Photograph shows elongated pillow basalts located approximately 0.25 kilometers west of Webster Pond. Silva [compass] for scale.

and given below. The rock fragments appear, for the most part, compositionally like the nearby massive and pillowed volcanics. However, rare clasts of dacite (ts. 81-19-P), and polycrystalline quartz also occur.

In all of the volcanics in the area of study, plagioclase feldspar is present as lath-shaped and moderately saussauritized grains. It occurs both as phenocrysts which are in some cases strained and also as a groundmass phase. In some rare instances, the plagioclase is replaced by prehnite (ts. 80-04-0, 80-06-0, 80-11-0, 81-20-P). However, chlorite, clinozoisite, actinolite, and, to a lesser extent, sericite, tremolite, cummingtonite, and carbonate commonly replace the feldspar. Relict albite, carlsbad, and pericline twinning may still be seen and measurements on relict albite twins indicate the plagioclase is albite (An 0-5). H. de Romer (1960) reports original calcic plagioclase of An_{60}, labradorite, from microlites in a volcanic glass. Albite appears as a thin clear zone rimming many of the plagioclase laths and is probably a result of spilitization. When quartz is present in the volcanic unit, myrmekitic texture is seen with the plagioclase. In places it occurs in polycrystalline mosaic patches but is most commonly seen as a groundmass phase. The quartz is anhedral in shape, exhibits undulose extinction, and is slightly overgrown by chlorite and actinolite.

Clinopyroxene occurs as euhedral to subhedral crystals often mantled by secondary actinolite and chlorite. Well-developed twins are common in these faintly reddish brown grains. The clinopyroxene is augite (2V = 70°, optic sign positive) and is subophitic with plagioclase. By virtue of this relationship and the fact that in a few instances plagioclase is found contained within the augite, the clinopyroxene must have crystallized after plagioclase feldspar. Olivine pseudomorphed by chlorite is rare as a phenocrystic phase, occurring as such only in the pillowed volcanics. Generally, it is present in accessory amounts in the ground mass. Rare apatite is also sometimes present. Alteration minerals include chlorite, clinozoisite, zoisite, actinolite, tremolite, cummingtonite, carbonate, quartz, prehnite, and haematite stain along fractures and cataclastic zones. Good euhedral crystals of chlorite, zoisite, and clinozoisite are seen as vein-filling minerals along with the massive variety of chlorite. Modal estimates are presented in Table 1. The mafic volcanics crystallized according to the sequence plagioclase ± olivine ± clinopyroxene ± quartz-groundmass.

LATE DIKE

One dike (81-06-C) in the area is apparently distinct from the rest of the igneous rocks. It cuts a plagioclase-phyric dike in quartz diorite associated with the Chagnon complex and is not cut by calc-silicate alteration stringers as is the earlier dike. The later dike appears black on both fresh and weathered surfaces and consists of medium-grained plagioclase phenocrysts set in an equigranular aphanitic groundmass. The subhedral to euhedral plagioclase is lath-shaped and is diverse in crystal orientation. It is slightly overgrown by chlorite, clinozoisite, and hornblende. Baveno, albite, and carlsbad twinning are still recognizable. Plagioclase also occurs in the groundmass as fine laths. Here it is severely altered by carbonate and chlorite. Other groundmass phases include subhedral to anhedral clinopyroxene, subhedral to anhedral chloritized olivine, subhedral to anhedral opaques, and subhedral sphene. The dike crystallized according to the sequence: plagioclase-groundmass (plagioclase-clinopyroxene-olivine-opaques). Later metamorphic minerals include amphibole, chlorite, clinozoisite, zoisite, sphene, and quartz. Table 1 gives estimated modal percentages of the various mineral constituents.

OVERLYING METASEDIMENTS

Metasediments of the St. Daniel Formation and the Glenbrooke Group are found structurally above the Chagnon igneous complex. One of the aims of this thesis is to determine the nature of such contacts, especially that of the St. Daniel to the volcanics. In general, rocks of these units are found in low-lying and often swampy areas. Outcrop is poor and less than five percent is exposed. In addition, glacial debris is most abundant in these low-lying areas and further obscures field relationships.

ST. DANIEL FORMATION

In the Eastern Townships of Southern Quebec, the St. Daniel Formation lies to the east and south of the BOC (Baldface-Orford-Chagnon) complex. Doolan and others (1982) have divided it into three lithotectonic subunits: 1) chaotic black and gray slate; 2) serpentinite-black slate-tectonic melange, and 3) black and gray slates interbedded with volcanogenic metasedimentary rocks and volcanic flows. The St. Daniel in the area studied in this report is of the first subtype. It consists of gray to black slates with a well developed cleavage. The rock is much fractured, making samples difficult to obtain. In places, the slates appear laminated with alternating carbonaceous and silty horizons.

Thin sections from various locations in the field area reveal consistent petrographic features. These rocks have very fine-grained equigranular matrix and exhibit lepidoblastic texture due to the subparallel alignment of various minerals and lithic clasts. Quartz, muscovite, sericite, opaques, plagioclase, and chlorite are the main components of the matrix. Accessory amounts of zircon and sphene are also present. The chlorite appears to be a metamorphic or secondary mineral as does actinolite, and the epidote and clinozoisite are found overgrowing the otherwise clear quartz. Haematite often accompanies chlorite as a stain in anastomosing fractures found in the thin sections.

Lithic clasts found in the St. Daniel black slates usually are graywackes, although quartzites, argillites, and shale fragments are also common. No ophiolitic detritus was found in the map area. However, to the south of Place Mountain, clasts of mafic metavolcanics, metagabbro, and serpentinite believed to be ophiolite-derived are reportedly contained in the St. Daniel. Doolan and others (1982) propose that these changes denote a "pre- to syn-ophiolite emplacement character north of Chagnon Mountain to a syn- to post-ophiolite emplacement age south of Chagnon Mountain."

Local folds are also sometimes present, ranging from approximately 10 mm to 0.45 m in half wavelength. Folds of similar dimensions have been reported in the area by de Romer (1960). Although de Romer describes the slates as interbedded with gray quartzites of uniform grain size, he reports only one area where this may be seen. This area is the swampy region between Trouserleg Pond and Malaga Pond, adjacent to the north end of the map area. In the map area, on trend to the south, an arenaceous subunit of the St. Daniel was found. In outcrop, it appears gray and exhibits a moderately good slaty cleavage. Petrographically it consists of angular quartz and plagioclase grains in a fine grained matrix (Figure 8). Quartz occurs in mosaic clots and much shows deformation bands and wavy extinction. The plagioclase grains are usually smaller and anhedral in shape. White mica (sericite and

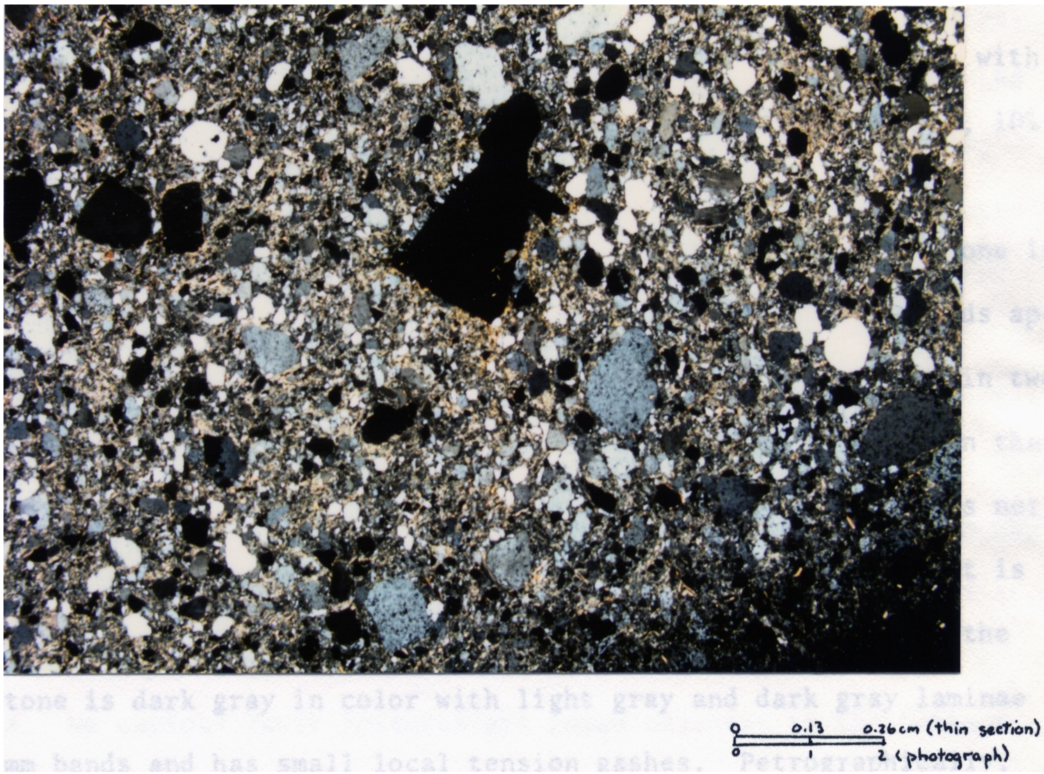

Figure 8: Photomicrograph of the arenaceous submember of the St. Daniel Formation (crossed polars). Large black triangular clast is pyrite.

muscovite) is the predominant mineral in the matrix. Other matrix constituents include quartz, plagioclase, zircon, and rare pyrite. Chlorite and clinozoisite are found as secondary minerals. This mineralogy is similar to that reported by de Romer (1960) for the St. Daniel quartzites with one exception; the quartzites he reports to the north appear to be relatively pure (quartz approximately 85%) whereas the arenites (strictly wackes) south of Trouserleg Pond are found with a substantial amount of matrix material (quartz approximately 35%, 10% plagioclase, 55% matrix).

South of Trouserleg Pond, a finely recrystallized lime mudstone is found interbedded with slates in the St. Daniel. It occurs in beds approximately 0.3 m in thickness with thinner dark slate interbeds in two adjacent outcrops (locality E). This occurrence is significant in that it has never before been reported in the Eastern Townships. It is not clear whether the limestone is present in continuous beds or if it is a large block emplaced by olistostromic mechanisms. In outcrop, the limestone is dark gray in color with light gray and dark gray laminae in 5 mm bands and has small local tension gashes. Petrographically, this unit contains predominantly subhedral shaped carbonate grains, with lesser amounts of subhedral to anhedral quartz, opaque, and sericite. A sample of this rock was given to New York State Paleontologist Ed Landing to be chemically disaggregated for insoluble microfossils in the hope of accurately dating the limestone. In his report, no macrofossils were recovered in hand cracking prior to processing in acid, none were observed on sawed surfaces, and no conodonts were found in the insoluble residue (Ed Landing, written communication, 1982).

The contact of the St. Daniel Formation to the structurally lower volcanics of the Chagnon area appears to be tectonic or unconformable.

Observations on the nature of the contact show the following characteristics:

1. The St. Daniel overlies mafic volcanics in the northern portion and volcanics and volcaniclastics in the southern portion of the study area, indicating a period of faulting and/or erosion before its deposition or structural juxtaposition. On a regional scale, the St. Daniel lies above various units of the serpentinite belt (e.g. volcaniclastic, volcanic, diabase, gabbro, pyroxenite, peridotite) where present, and above the Sutton-Notre Dame schist belt where the "ophiolitic" rocks are not present.
2. This contact is not straight in map pattern, therefore several generations of faulting may be involved in its formation.
3. Ophiolitic detritus is not found in the St. Daniel in the map area except for locally large blocks of volcanics present south of Mont Place outside this study area.
4. No obvious fault features are found adjacent to the contact in either the volcanics or the St. Daniel, However, the smallest gap between outcrops was approximately 4 meters and the actual contact in outcrop was never observed.
5. No basal conglomerate is developed in the map area or anywhere else in the St. Daniel (this does not include the Coleraine breccia at Thetford Mines which is probably not equivalent to the St. Daniel Formation).

The immediate implications of the above points are:

1. The contact is either an angular unconformity, a fault, or perhaps both. If partly or wholly faulted, the jagged nature might suggest several episodes, although normal faults often have a jagged outline.

2. It is unlikely to be an ordinary erosional angular unconformity because no typical basal conglomerate is seen and volumetrically little detritus from the ophiolite is seen in the St. Daniel.
3. It is unlikely to be a thrust as this should bring structurally lower material above originally higher material. This is obviously not the case with sediments over ophiolitic volcanics.
4. It could be a submarine normal fault, or more likely a set of faults, whereby sedimentation of muds occurred onto the surface existing before faulting in some places, but onto degrading fault scarps in others. Therefore, the sediment deposited on top of the blocks would appear locally conformable while that which draped the fault scarps would be unconformable. On this hypothesis the large igneous blocks in the St. Daniel represent pieces spalled off the upper steep parts of the scarps onto the lower parts accumulating muds (see Figure 9). Throw on the fault can be increased to expose deeper levels of the ophiolite, but most blocks in the St. Daniel appear to be high level, at least in this area. Also, the fault or faults are not necessarily downthrown to the east, the important point is deposition on a degrading submarine scarp.

GLENBROOKE GROUP

Near Peasley Pond, two members of the Peasley Pond Conglomerate of the Silurian-age Glenbrooke Group are found. The lower member is a conglomerate, and the upper one an equigranular sandstone. As no mention of a sandstone member could be found in the literature, it is hereafter referred to as the upper sandstone member. In the field area, these rocks

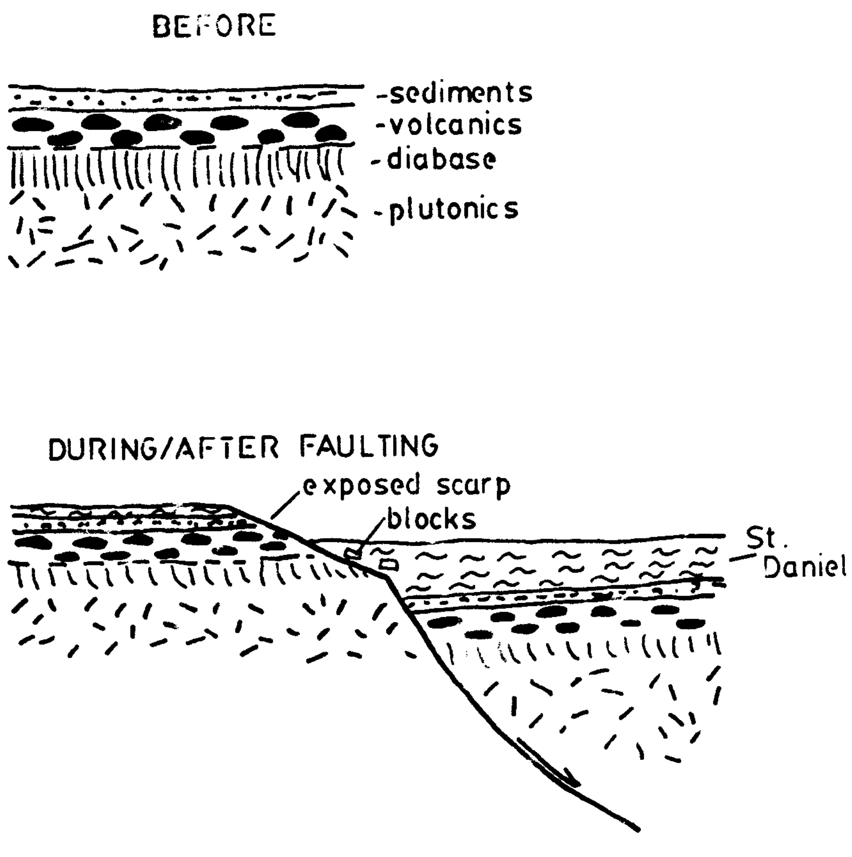

Figure 9: A schematic diagram depicting the St. Daniel-volcanic contact as resulting from deposition of muds onto a submarine normal fault.

are well exposed (approximately 15 percent outcrop) just northeast of Peasley Pond; exposure decreases (less than two percent outcrop) eastward as the terrain becomes low-lying and swampy. The contact between rocks of the Glenbrooke Group and those of the St. Daniel Formation is an angular unconformity; elsewhere (to the north) the Glenbrooke Group also overlies the volcanics of the Chagnon massif on the same angular unconformity (see Plate 1).

The Peasley Pond Conglomerate is a basal conglomerate unit. Pebble conglomerate contains angular to subangular clasts of quartz, chert, black shale, and some argillite set in a matrix of gray grit. This lithology fines upward into a quartz pebble sandstone and then into a relatively pure sandstone. This sequence is found repreated throughout the area approximately every three meters and is especially noteworthy on a long ridge just north of Peasley Pond (Plate A, location F; and Figure 10).

In thin section, the lithic clasts of the Peasley Pond Conglomerate are set in a predominantly micaceous matrix with some chloritic and haematitic components (Figure 11). The clasts themselves are more diverse than outcrop appearance indicates. In addition to chert, shale, argillite, and graywacke, clasts of feldspathic diabase and silicic volcanic rocks (equant potassium feldspar in a chloritic quartzofeldspathic matrix), though rare, are present. Mineral grains of quartz and chromite also occur. The presence of chromite indicates erosion of the ophiolitic masses was occurring during the deposition of the Peasley Pond Conglomerate and indicates some sedimentation was coming from the northwest. Silicic volcanics, however, are not known to the northwest but are present to the southeast (Ascot-Weedon Belt). Therefore, sediment was also being fed from the southeast.

Figure 10: Schematic drawing of repeated sequence (conglomerate, gradational sandstone, sandstone) of the Peasley Pond Conglomerate at location 12-P on plate A. Beds trend 290° and dip 63° SW.

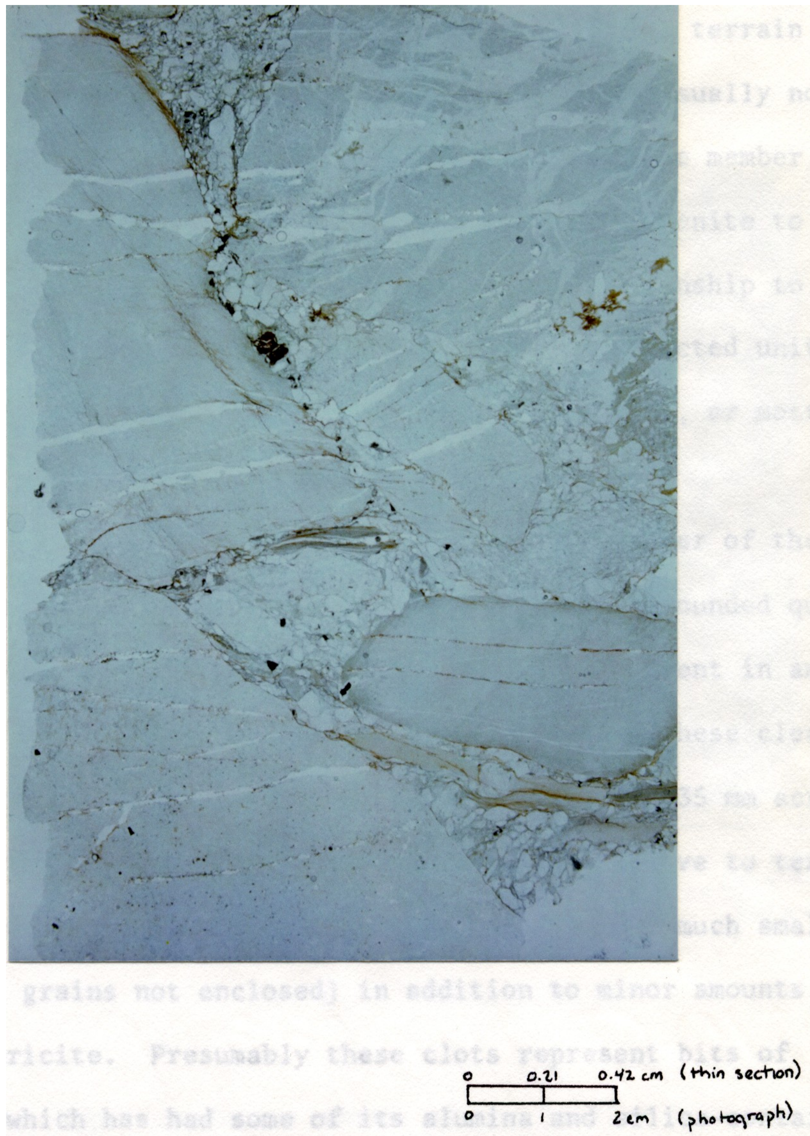

Figure 11: Photomicrograph of the Peasley Pond Conglomerate. Note the small red chromite grains between the lithic clasts of chert (plnae polarized light).

The upper sandstone member is found east of the Peasley Pond Conglomerate and continues to the northeast where it comes in contact with the St. Daniel Formation in the low-lying areas south of Trouser-leg Pond (see Plate A). Outcrop is poor with much of the terrain covered by swamps and glacial debris. The outcrops are usually no more than 1.5 m in length by 1 m in width. The upper sandstone member ranges in appearance from a gray relatively pure equigranular arenite to an extremely weathered reddish brown sandstone. Its relationship to the conglomerate appears to be either a depositionally restricted unit (i.e. by transgression, paleotopography, etc.), a fault contact, or most likely, a facies change of the conglomerate into the sandstone.

In thin section, samples of the upper sandstone member of the Peasley Pond Conglomerate are composed of subangular to rounded quartz in a fine grained matrix (Figure 12). The quartz is present in amounts ranging from 40 - 90 percent and the boundaries between these clear quartz grains are sutured. Haematitic clots typically 0.35 mm across are characteristically present in amounts varying from five to ten percent and contain corroded grains of quartz (which are much smaller than the quartz grains not enclosed) in addition to minor amounts of chlorite and sericite. Presumably these clots represent bits of lateritic soil which has had some of its alumina and silica-containing minerals leached out. The upper sandstone member also contains accessory opaques:magnetite (less than one percent) and rare detrital zircons (less than one percent). The micaceous matrix makes up 2 - 50 percent of the sandstone and consists predominantly of muscovite and sericite with minor amounts of chlorite and haematite.

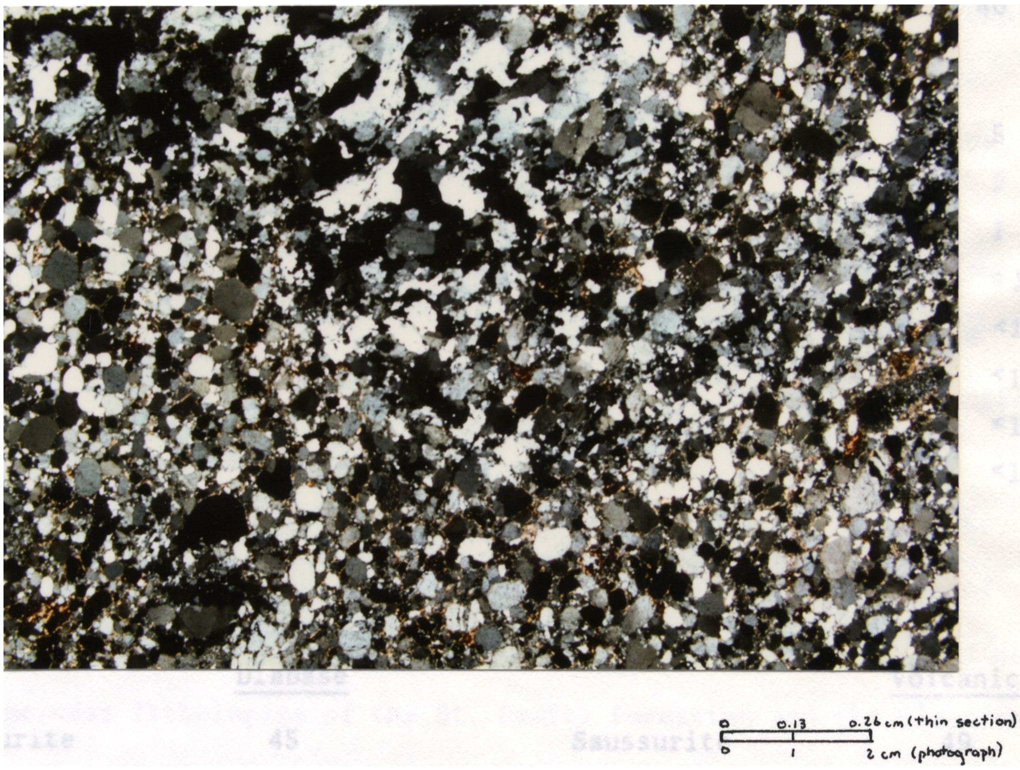

Figure 12: Upper sandstone member of the Peasley Pond Conglomerate. Note the sutured quartz grain boundaries and lateritic soil.

TABLE 1: AVERAGE ESTIMATED MODAL PERCENTAGES OF THE IGNEOUS ROCKS FROM THE CHAGNON AREA

	Gabbro
Saussurite	45
Augite	12
Tremolite-Actinolite	11
Quartz	7
Hornblende	5
Chlorite	5
Ilmenite	5
Clinozosite/ Epidote	3
Chloritized Olivine	2
Calcite	2
Sphene	1
Albite	1
Apatite	<1

	Quartz-Diorite
Quartz	44
Saussuritized Plagioclase Saussuritized Orthoclase	46
Clinozosite/ Epidote	5
Chlorite	[illegible]
Haematite	1
Augite	<1
Apatite	<1
Sphene	<1
Actinolite	<1
Opaque (magnetite)	<1

	Diabase
Saussurite	45
Actinolite	22
Quartz	17
Chlorite	6
Augite	2
Clinozoisite/ Epidote	2
Opaque (pyrite)	2
Opaque (ilmenite)	2
Calcite	1
Haematite	1
Sphene	<1
Albite	<1

	Volcanic
Saussurite	49
Actinolite	8
Clinozosite/ Epidote	6
Chlorite	5
Calcite	5
Augite	5
Chloritized Olivine	4
Opaque (pyrite)	4
Quartz	3
Tremolite	3
Haematite	3
Sphene	2
Opaque (ilmenite)	1
Albite	1
Sericite	<1

STRUCTURAL GEOLOGY

The Chagnon Mountain area has a northeast trending structural grain. This is consistent with Winner's (1981) findings for an area northwest of the field area studied in this report. He notes the metasedimentary rocks of the Miller Pond Formation, the serpentinite separating these rocks from the igneous complex, and the igneous complex itself all have a north-northeast trending dominant foliation. The same is true near Trouserleg Pond where rocks of the igneous complex, the St. Daniel Formation, and the Glenbrooke Group occur.

In the field cataclastic foliation, slaty cleavage, pillow structure, bedding, joints, and faults are the major structural features found. Most of these structures are restricted to specific lithologies; however, trends are consistent across lithologic units.

Two structural domains are recognized in the Chagnon area. The first includes the gabbro, quartz-diorite, diabase, and volcanics of Chagnon Mountain and will be called the igneous domain. The second domain includes lithologies of the St. Daniel Formation and the Glenbrooke Group. This domain is referred to as the metasediment domain. The igneous domain occurs west of the metasediment domain, is structurally lower, and is characteristically massive. Rocks of the metasediment domain show good foliation.

Structural features in the igneous domain include cataclastic foliation, pillow facing, bedding, joints and faults. Cataclastic foliation is found in two locations where the diabase and quartz-diorite are in contact. The boundary between these two units is irregular with the foliation developing in the diabase adjacent to the contact and trending N46°E, 55°S. A two mm thick alteration zone was noted in the quartz-diorite, none was observed in the diabase. This indicates the diabase was still warm when the quartz-diorite was intruded into its basal portions and that the diabase "flowed" around the hot acidic magma. Another structure commonly observed is the presence of silicic veins apparently of the same composition as the quartz-diorite body. These veins are observed cutting diabase and volcanic rocks in the northern portion of the study area, and in close proximity to the quartz-diorite body. They generally trend northwest-southeast and are frequently offset in a east-west direction by right lateral offsets. Left lateral offsets of these veins are less prominent. It is probable that these silicic veins are genetically related to the quartz-diorite body and, as such, probably formed from late stage magmatic fluids.

Cataclastic foliation is also observed within the massive volcanics and volcaniclastics, where it trends north-northeast, changing to east-northeast as the contact of the volcanic unit with the overlying meta-sediments is approached (see Plate A). This foliation is apparently due to deformation (see Figure 13). Bedding is also found in the volcaniclastics south of Trouserleg Pond, but is often poorly developed. Three measurements were taken and give an average of 35-40° and dip moderately to steeply southeast. The volcanics in the Chagnon area in places show pillow structure. Orientation determinations of the pillowed volcanics were made in seven locations and in all places way up is to the east-southeast.

Joints are found throughout the map area but only in the northern portion do they form a consistent joint set (Figure 14). Minor changes in their orientation may be observed in rocks of different lithology. In addition, two faults were recognized in the field. One is a minor fault trending 290° with left-lateral offset as determined by slickenslides. The second fault is more extensive, again left lateral with a small amount of dip slip motion. Slickenslides give the direction of movement as 130°, 12°W. In addition, minor right lateral offsets of diabase dikes and silicic veins which trend 280° are common in the area. A lesser amount of minor left-lateral offsets (also approximately east-west) of the diabase dikes and felsic veins are present. It seems likely, based on the similar trend of the joints and faults that they are genetically related and possibly the result of obduction processes.

Structural features in the metasediment domain include bedding, minor folding, and slaty cleavage. Bedding is discernable in a few places in the St. Daniel Formation, and is rarely clearly indicated in the Glenbrooke Group. Slaty cleavage in the St. Daniel slates and spaced cleavage in the Peasley Pond Conglomerate generally trend northeast with vertical to steep east or west dips. The poles to these foliations are plotted in Figure 15, and, although somewhat scattered, tend to cluster. This indicates that these units have undergone one deformational event and the bedding is broadly warped. Minor folding in the St. Daniel rarely occurs in the map area. These folds are steeply plunging open folds of the parallel class of Ramsey (1967), and possess a poorly developed axial plane cleavage.

The rocks of the Chagnon area may be divided into two structural domains, both of which display a dominant northeast trending foliation and steep to vertical dips. The igneous domain includes the gabbro, quartz-diorite, diabase, and volcanic rocks. Its structural features include cataclastic folaition, silicic veining, pillow facing, bedding, joints, and faults. The metasediment domain shows bedding, slaty cleavage, and minor folding. From pillow structure and bedding relationships in both domains, the units young to the southeast. A stereo-

Figure 13: Poles to foliation in the igneous domain (upper left stereonet).

Figure 14: Poles to joints in the igneous domain (lower stereonet).

Figure 15: Poles to cleavage and bedding in the metasediment domain (upper right stereonet).

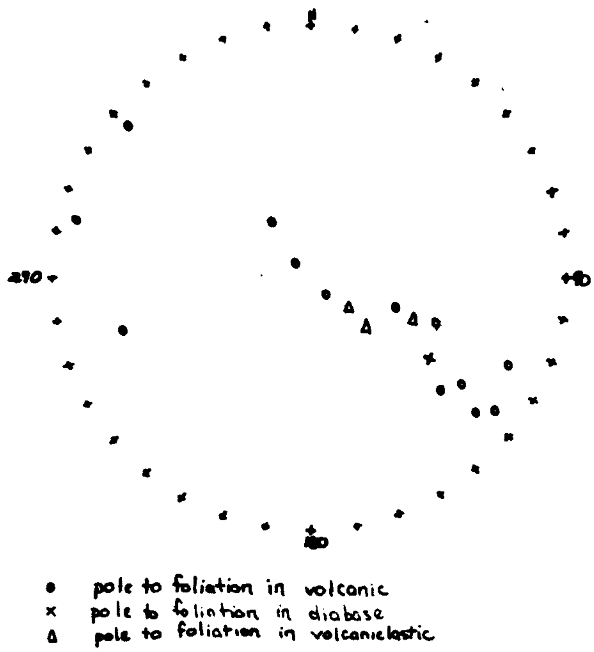

Figure 13

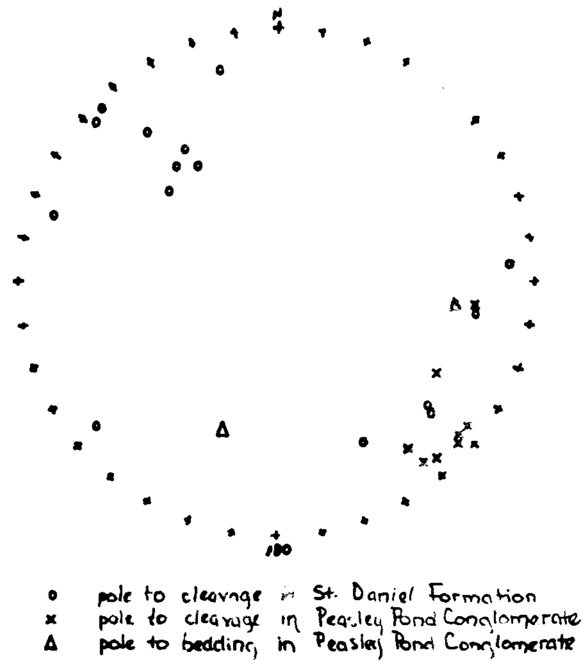

Figure 15

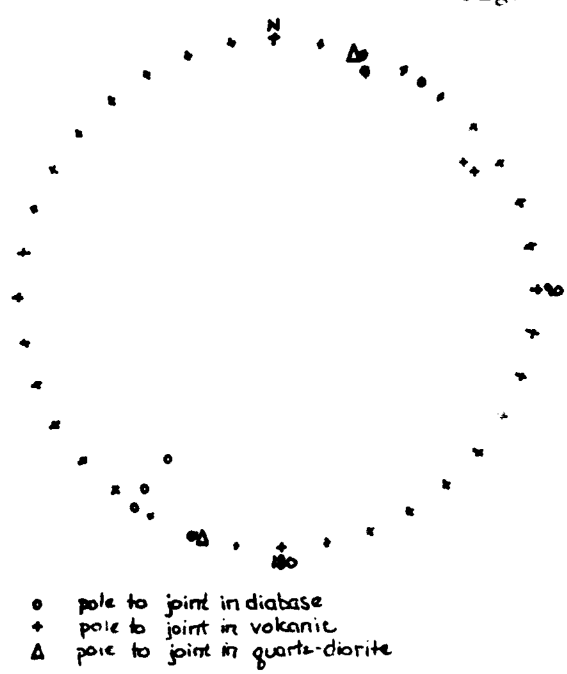

Figure 14

graphic projection of poles to foliation in both domains indicates the bedding in this area is broadly warped (Figures 13 and 15). In addition, the poles in the metasediment domain tend to cluster about a diffuse maximum while poles in the igneous domain seem to girdle along the same trend. Although the structural data is insufficient to be conclusive, this perhaps indicates the igneous domain has suffered two deformational events (Sn and Sn + 1) and the metasediment domain one (Sn +1). The first event in the igneous domain may have been related to its formation. The second event, which is common to both domains, apparently caused the dominant northeast trending structural grain of the area. It is interesting to note that a stereoprojection of poles to joint and fault surfaces shows them to be approximately 90 degrees to the foliation poles. Perhaps these brittle features formed at right angles to the foliation (or parallel to the approximate direction of compression) during the same deformational event.

CHAPTER III

METAMORPHISM

As mentioned in the preceding chapter, all rocks in the Chagnon area have been metamorphosed to the greenschist facies. Although a description of metamorphic recrystallization products has already been given, it is reiterated here in brief in order to relate metamorphic mineral growth to deformation. Textural criteria used for determination of pre-, syn- and post-kinematic (deformation) recrystallization follows that of Spry (1969).

IGNEOUS COMPLEX

The rocks in the igneous complex from west to east and up structure are gabbro, quartz-diorite, diabase, and mafic volcanics. These rocks are apparently genetically related to a single mafic magma chamber and are analogous to ocean floor lithologies. They have been metamorphosed to the chlorite zone of the greenschist facies and are characterized by the assemblage chlorite-clinozoisite-actinolite-albite- ± quartz ± sericite ± calcite ± sphene (mineral growth and deformation history are summarized in Figure 16). This assemblage is similar to that described by Miyashiro and others (1971) and Coleman (1977) for ocean floor (hydrothermal) metamorphism.

Few gabbroic rocks are found in the study area. However petrographic observations reveal syn- to post-kinematic growth with respect to the cataclastic foliation. Actinolite is clear to pale green in color and rarely present. It occurs as randomly orientated (post-kinematic) aggregates, as alteration of plagioclase feldspar (syn-kinematic) and as a reaction rim on clinopyroxene (syn-kinematic). Chlorite and

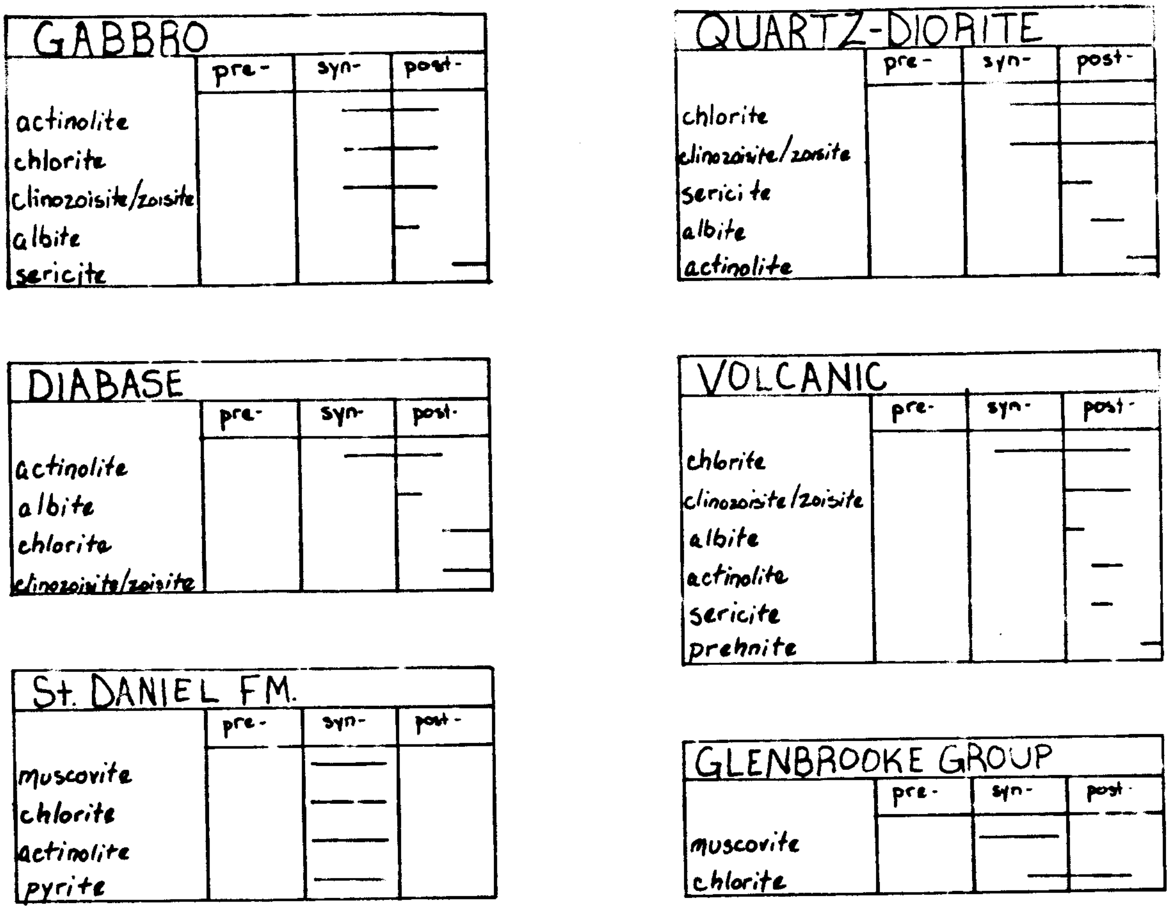

Figure 16: Mineral growth and deformation history of the various rock types in the Chagnon Mountain area.

clinozoisite/zoisite are usually intimately associated, and are also syn- to post-kinematic. Syn-kinematic chlorite is present in the form of parallel aligned olive green colored flakes. Clinozoisite/zoisite grains are randomly orientated and granular. Secondary albite is found as a very thin clear rim on altered feldspar. It possibly forms as a result of spilitization and is post-kinematic. Post-kinematic actinolite, chlorite, and clinozoisite all can be observed in these rims as well as in the feldspar cores. In addition, some syn- to post-kinematic sericite is observed overgrowing the feldspar in generally random although sometimes parallel aligned orientation.

The quartz-diorite bodies in the northern part of the Chagnon area, like the gabbros, have a syn- to post-kinematic metamorphic mineral assemblage with respect to the cataclastic foliation. Textural relationships allotriomorphic granular with sutured grain boundaries) demonstrate that the quartz is igneous not metamorphic. The subparallelism of subgrain boundaries and undulose extinction in the quartz, however, may have developed syn-kinematically. Chlorite and clinozoisite/zoisite are syn-kinematic with some of the flakes and prisms in parallel alignment while others are random in orientation and granular. Sericite, like chlorite and clinozoisite, is found overgrowing quartz and feldspar. In the feldspar, however, it is found only in the core and in random orientation. But, as plagioclase phenocrysts themselves resist deformation, the sericite is probably syn to post-kinematic. Albite occurs as clear narrow rims on some of the altered feldspar, and is post kinematic in the quartz-diorites (no sericite is seen in these rims). Rare actinolite forms as alteration of the feldspar (core and rim) and quartz. It occurs as randomly orientated clear to light green needles and is post-kinematic.

Diabase generally occurs as a massive homogenous unit in the study area. It is characterized by the assemblage actinolite-chlorite-clinozoisite/zoisite-albite. The actinolite occurs syn-kinematically, as parallel aligned fibrous overgrowths which rim to entirely pseudomorph pyroxene. It is also found in bundles bending around the plagioclase feldspar, and as randomly orientated, post-kinematic stubby crystals which alter the feldspar. Chlorite and clinozoisite both occur as post-kinematic minerals; chlorite as olive green granular masses and as randomly orientated with berlin blue birefringent crystals, and clinozoisite in random orientation associated with the chlorite. Very thin reaction rims of clear albite on altered plagioclase feldspar are sometimes present and have overgrowths of randomly orientated actinolite and chlorite indicating that the actinolite and chlorite are post-kinematic.

The structurally highest unit in the Chagnon massif is the mafic volcanic unit. It can be subdivided into massive flows, basalt breccias, pillow basalts, and volcaniclastics. All of these have been metamorphosed to the greenschist facies. Chlorite occurs syn- to post-kinematically where it has pseudomorphed olivine in parallel aligned flakes. Since both sericite and actinolite are found in random orientation, sericite overgrowing the core of the plagioclase and its albite rim and actinolite in the groundmass, both are considered post-kinematic. Rare prehnite crystals are found associated with the haematite stain and carbonate which fill cracks and they are, therefore, considered a very-late stage alteration feature.

ST. DANIEL FORMATION

The St. Daniel Formation is found structurally overlying the volcanics of Chagnon Mountain. Both the slate and the sandstone are characterized by the assemblage: muscovite-chlorite-actinolite. The dominant foliation (Sn + 1) is defined by these minerals in addition to black carbonaceous material in the matrix. Furthermore, these minerals also wrap around the graywacke, quartzite, and opaque porphyroclasts and are therefore pre- or syn-kinematic. The graywacke and quartzite porphyroclasts are elongate parallel to the foliation. However, sericite orientated at high angles to the foliation (Sn + 1) is observed in the graywacke. The Sn + 1 foliation is, in rare instances, folded (Sn + 2) but no new mineral growth was observed with this deformation. Pyrite has been found with the long dimension of its prism aligned parallel to the Sn + 1 foliation and is, therefore, also syn-kinematic.

GLENBROOKE GROUP

The two members of the Peasley Pond Conglomerate occur south of Trouserleg Pond in the Chagnon area. The foliation present in these units is a spaced cleavage and is not as well-developed as that of the St. Daniel but may be observed both in the field and on thin section scale. Petrographically, the foliation is defined by the elongate nature of quartz grains and by the alignment of muscovite and minor chlorite in the matrix. Post-kinematic chlorite is also found and has a granular texture. Later addition of carbonate and haematite between grains is evident.

DISCUSSION

In order to understand the metamorphism of the mafic rocks of the Chagnon area, an understanding of the metamorphic minerals themselves, is needed. These rocks are characterized by the following assemblage:

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DISCUSSION

In order to understand the metamorphism of the mafic rocks of the Chagnon area, an understanding of the metamorphic minerals themselves, is needed. These rocks are characterized by the following assemblage:

epidote group-actinolite-albite- ± sericite ± calcite ± sphene. The following discussion attempts to outline the necessary conditions (T, P) for this metamorphic grade to be reached and the resulting properties the characteristic minerals should exhibit.

Chlorite first appears in the prehnite-pumpellyite facies and persists into the lower epidote amphbolite facies (Figure 17). It is a magnesian-rich mineral, $Fe^{2+}/(Mg+Fe^{2+}) = 0.1$ to 0.5 and is usually green with low birefringence. In the Chagnon area, its birefringence is very low (generally around 0.0025). This clearly indicates that it is Mg-rich. (Miyashiro, personal communication, 1981).

Epidote, clinozoisite, and zoisite are all found in the Chagnon area. These minerals first appear in mafic rocks in the prehnite-pumpellyite facies and persist into the lower amphibolite facies. They are the predominant calcium-aluminum silicate in low temperature zones (Miyashiro, 1973). Epidote is usually higher in iron content than either zoisite or clinozoisite. In the study area, clinozoisite is the most common mineral of the epidote group, followed by zoisite and minor amounts of epidote. This seems to indicate a paucity of iron in the overall rock and, hence, the formation of clinozoisite/zoisite occurred in preference to epidote.

Calcic amphiboles may be divided into two groups: the actinolite group and the hornblende group. The actinolite group first appears in the upper prehnite-pumpellyite facies and contains a spectrum of compositions from tremolite through actinolite to ferroactinolite. This group persists into the lower epidote-amphibolite facies. Members of the hornblende group appear in epidote-amphibolite facies and persist into the lower granulite facies. Tremolite-Actinolite group amphiboles are relatively poor in aluminum and sodium compared to those of the hornblende group. In the Chagnon area, actinolite and minor amounts of tremolite are observed in the metabasic rocks; and hornblende, when present, occurs as a primary (igneous) phase. In addition, to the calcic amphiboles, rare occurences of cummingtonite $(Mg, Fe, Al)_7 (Si, Al)_8 O_{22}(OH)_2$, are observed with actinolite in diabase (81-08-P), volcanic (81-18-0), and volcaniclastic (81-04-C) rocks. Cummingtonite reportedly occurs from the upper epidote amhibolite facies to the lower granulite facies. It is also found, but in minor amounts, in many low pressure Ca-poor metabasites (Miyashiro, 1973). Its presence in some of the mafic rocks from Chagnon is problematic.

Metamorphic plagioclase first appears in the upper zeolite facies, is albitic in composition, and persists to the lower epidote-amphibolite facies. Slightly below the greenschist/epidote-amphibolite facies boundary, oligoclase crystallizes and continues to do so until the upper amphibolite facies where anorthite forms (see Figure 17). Miyashiro (1973) notes that albites in low-temperature metamorphic rocks are mostly water-clear, untwinned, and unzoned; and with rising temperature, twinning tends to increase. The mafic rocks in the Chagnon area characteristically have clear albite rims around moderately altered plagioclase feldspar. In one thin section (81-08-P, diabase) the secondary plagioclase is twinned, and has an anorthite content of An_5 (albite). This albite is found rimming opaques, sphene, and cummingtontie which themselves appear to be replacing pyroxene.

Sericite, biotite, sphene, ilmenite, magnetite, haematite, and pyrite are present in a few of the mafic rocks studied. Sericite is found altering feldspar and is known to form in greenschist facies metabasites and exist into the lower epidote-amphibolite facies. Biotite is observed in only one thin section (80-29-0, pillow basalt) overgrowing chloritized olivine. It reportedly occurs from middle greenschist to lower granulite facies. Calcite forms in the lower zeolite facies and continues to form into upper amphibolite facies metamorphism. Miyashiro (1973) notes haematite (Fe_2O_3) is stable at high PO_2 and, as PO_2 decreases, magnetite forms. In the mafic rocks from the Chagnon area no magnetite ($Fe^{2+}Fe_2^{3+}O_4$) is found except where enclosed in chloritized olivine (t.s. 80-29-0). However, ilmenite is found in the gabbro, diabase, and in some volcanics but only rarely in the diabase.

A typical tholeiitic basalt contains plagioclase with an anorthite content of An_{40-70}, clinopyroxene (usually augite), and may or may not contain olivine. The mafic rocks from Chagnon Mountain had an original mineralogy consisting of plagiocalse, clinopyroxene (augite), minor amounts of olivine, ± ilmenite. These mafic rocks have been matamorphosed to the greenschist facies as defined by the assemblage: chlorite-epidote group-actinolite-albite ± sericite ± calcite ± sphene. Upon metamorphism, the anorthite component in the plagioclase probably was taken up in the formation of clinozoisite/epidote thus lowering the An content of the plagioclase. Hence, a narrow rim of water-clear albite formed around the altered feldspar by postmagmatic replacement (spilitization). This view is supported by Gilluly (1935), Vallance (1969, 1974), Coombs (1974) and Turner (1981). Chlorite was probably formed by the hydrothermal alteration of pyroxene; and quartz, sericite, calcite, and pyrite were also probably derived by hydrothermal fluids circulating through the rocks at low metamorphic temperatures.

In general, the igneous complex contains no prehnite or pumpellyite and no metamorphic hornblende. Even though low pressure metamorphism is assumed, the temperature of this metamorphism can be crudely bracketed between approximately 350° and 500°C. The lower temperature is defined by the reaction: (pumpellyite + chlorite + quartz = clinozoisite + actinolite) at pressures above four kbars. This reaction defines the boundary between the prehnite-pumpellyite facies and the greenschist facies (Winkler, 1979). The upper temperature limit of 500°C is defined by the formation of hornblende. This temperature rises only slightly with increasing pressure (Winkler, 1979).

In some thin sections, rare overgrowths of prehnite on plagioclase feldspar are present and there is the association of prehnite with haematite and calcite in cataclastic zones. Although experimental work done by Hinrichsen and Schurmann (1969) and Nitsch (1971) show prehnite (with or without pumpellyite) existing at high and medium pressures, its formation is generally attributed to decreasing temperatures and may be represented by the reaction: (clinozoisite + actinolite + water = prehnite + chlorite + quartz at temperatures near 340 ± 20°C and 1 kbar water pressure (Winkler, 1979). Hence, the formation of prehnite in the mafic rocks at Chagnon likely occurred during the waning (retrogressive) stages of metamorphism.

As these rocks are similar in lithology to oceanic crust, a brief comparison of ocean floor metamorphism with that observed on Chagnon is made here. In general, previous studies indicate the metamorphism is static and caused by hydrothermal circulation of seawater within the spreading center (Miyashiro et al., 1971; Elthon and Stern, 1978; Stern and Elthon, 1979; Bonnati et al., 1975; Cann, 1979). Descriptions from dredge hauls reveal the rocks to be homogeneous with primary textures and phases preserved. Recrystallization is often incomplete and metamorphism is usually to the greenschist or amphibolite facies. This is, in texture and assemblages, similar to what is observed in the mafic

TABLE 2: ASSEMBLAGES OF OCEAN FLOOR METAMORPHISM COMPARED WITH ASSEMBLAGES OBSERVED AT CHAGNON MOUNTAIN (modified from Winner, 1981)

Facies	Assemblage	T°C	Reference
Greenschist	Chl.+Ab.+epi.+act.+sph.±qtz.	200-350	1
Greenschist	Chl.+Ab.+epi.+sph.	200-450	2
transitional between greenschist and amphibolite	Chl.+Ab.+epi.±act.+sph.	450	2
amphibolite	Chl.+Ab.+epi.+act.+sph.	350-400	1
lower actinolite	Ca Plag.(An 5o)+act. (fibrous & pale)+sph.±bio.+cc.	450	2
upper actinolite	Ca Plag.(An 5o)+act. (both fibrous, pale, and coarse colored)+mag./il.±bio.	450	2
transitional (gabbro)	Chl.+Ab.+Act.(pale, fibrous) +epi.+leucox./il. (+ mt?)	450	3, this study
Greenschist (volcanic)	Chl.+Ab.+Act. (pale, fibrous) +epi.±sphene±qtz.+cc	350	This study

1 - Bonnati and others, 1975; Cann, 1979; Coleman, 1977; Stern and others, 1976; Miyashiro, 1971.

2 - Elthon and Stern, 1978.

3 - Winner, 1981.

rocks of the Chagnon area. In addition, Winner (1981) compiled a table of metamorphic assemblages derived through ocean floor metamorphism (Table 2). When comparing these to the assemblages from Chagnon Mountain, strong similarities are noted. Furthermore, information in this table indicates the temperature of the metamorphism probably ranged from near 450°C for the gabbroic rocks decreasing to approximately 350°C for the volcanics. It is suggested here that the metamorphism of the mafic rocks from the Chagnon massif was an ocean floor event and that this metamorphism caused the spilitization and was associated with the development of the cataclastic zones (Sn in structure section) in the rocks. The second deformational event (Sn + 1), which gave rise to the northeast-trending foliation and metamorphic mineral growth in the St. Daniel is related to the emplacement of the ophiolite upon the ancient North American continental margin. This event (Sn + 1) had no apparent effect on the matamorphic mineral assemblages in the ophiolite, but did cause structural telescoping of the section (see Chapter V).

CHAPTER IV

GEOCHEMISTRY

METHODS

Geochemical analysis was done in order to establish whether there are more than one group of mafic volcanics in the Chagnon area. Rocks were selected that appeared homogeneous in the field, with special attention to select those with as little veining as possible (Figure 18). Since these rocks have been severely affected by spilitization, the selection process was often difficult. Moreover, in this section, hydrous minerals are abundant indicating the conditions were ideal for maximum mobility of many elements. Eight samples were chosen based on hand specimen and thin section appearance. These were prepared following procedures outlined by Bender (J.F. Bender, personal communication, 1981). To begin, rocks were broken down to 5 to 10 mm sized particles with a sledge hammer on a steel plate. Next, weathered surfaces and vein material were removed. The sample was then rolled back and forth on paper for approximately fifteen minutes and split into four equal fractions. At this point one fraction was taken and pounded with a steel mortar and pestle to a coarse powder. Another split was taken from this and put into the "shatter box" for ten minutes. This material was then removed from the "shatter box" and ground by use of an alumina mortar and pestle to 200 mesh size.

To guard against possible contamination, the steel mortar and pestle were cleaned between samples by first using compressed air to blow out any loose particles and then by grinding quartz (Ottawa sand) spiked with the next sample. The same cleaning procedure was also

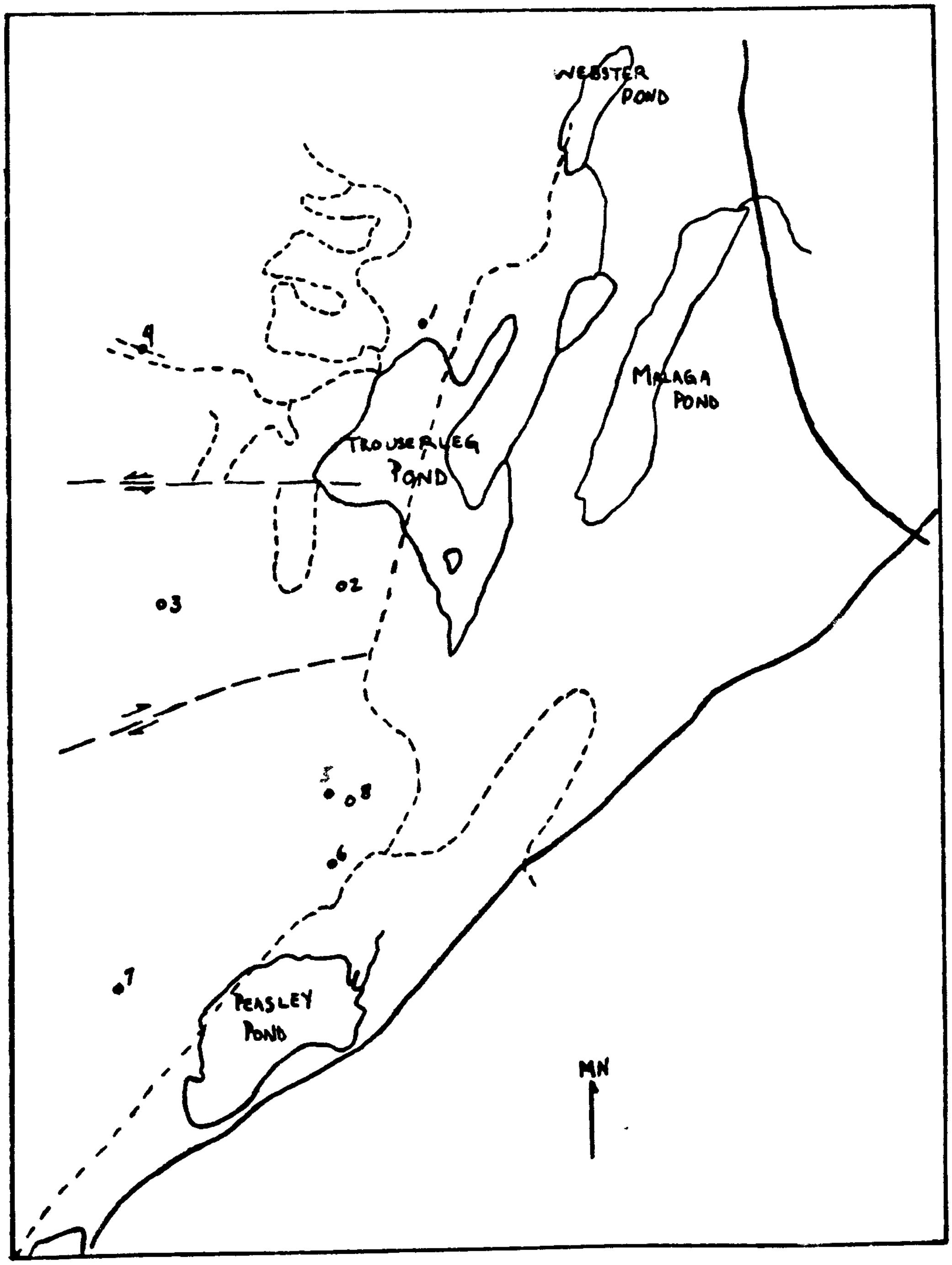


Figure 18: Location map of samples in the Chagnon Area analyzed geochemically. Numbers are reference numbers to the samples.

done with the alumina mortar and pestle. Here, however, an acetone rinse coupled with distilled water treatments was done. In addition, after every third sample, the alumina mortar, with pestle sitting inside, was filled with hydrofluoric acid and left to stand overnight. They were then rinsed with distilled water, then acetone, and distilled water again before being dried by heat lamp.

Sample preparation for major element analyzes began by placing a portion of powder in a platinum crucible at 1100°C for thirty-five minutes. 280 mg of anhydous sample was then combined with 1500 mg of "spex" brand flux and put into platinum crucibles for a six minute baking at 1020°C. Every two minutes the crucible was taken out and swirled to insure homogenity of the melt. At the end of the six minutes, the melt was poured out on a graphite disc and pressed with an alumina plunger. Two quenched discs were made for each sample and analyzed on a Siemens automated x-ray fluorescence (XRF) unit at the University of Massachusetts. For trace element analyses, 25 mg of sample backed with 50 mg of boric acid was pellitized under vacuum in a 31 mm evacuable die at 11 x 10^3 kg. Two pressed powder pellets were made of each sample and analyzed by XRF on a Philips AXS automated spectrometer at Woods Hole.

Analytical precision on the major elements was checked by running the BCR-1 standard in the last chamber. In addition, the duplicates for each sample were looked at for consistency. If the values obtained for BCR-1 were consistent with known values and if the values between duplicates were consistent, then machine error and error in sample preparation techniques were considered negligible. When the duplicates had SiO_2 values within one percent, they passed screening (the greatest difference in weight percent should be found here) and were averaged. According to Dr. J. Rhodes of the University of Massachusetts, their analyses have a relative error of one to two percent. Trace element values on the duplicates were averaged together and accepted. Precision here was again checked by running USGS standard BCR-1 and accuracy for the trace elements generally ranged from one to five percent. Analytical results and the results for the standard are given in Table 3.

ANALYTICAL RESULTS AND INTERPRETATIONS

Major and trace element chemistry of four volcanic rocks, one mafic breccia, one volcaniclastic arenite, one gabbro sill, and one late mafic dike are given in Table 3. These parameters were plotted in various combinations in order to see if one or more magma types are present. While a case can be made against the ability of a "discrimination" diagram to identify the correct tectonic environment of a sample (i.e. ocean floor, calc-alkaline, etc.) they have proved useful as a means for distinguishing different magma types in a single area (W.S.F. Kidd, personal communication, 1982). In general, the application of discrimination diagrams to igneous rocks of unknown tectonic environment is restricted to the volcanics as they are believed to be closer to true liquid compositions. The plutonic rocks are not used as they are often too strongly fractionated (Winner, 1981).

In this section various discrimination diagrams are used and some of these have been used by others to infer magma type and tectonic setting. The various samples discussed in the text will be referred to by reference number (see Table 3). The diagrams used to determine magma type are Na_2O+K_2O - FeO (total) - MgO (Figure 23), $(Na_2O + K_2O)$ - $[(\frac{K_2O}{Na_2O+K_2O}) \times 100]$ (Figure 24; Hughes, 1973), a simulated trace element

TABLE 3: CHEMICAL ANALYSES OF IGNEOUS ROCKS FROM THE CHAGNON MOUNTAIN AREA

Type of Rock:	volcanic	volcanic	volcanic	volcanic sill
Geochemical Sample No.:	2	7	8	6
Hand Specimen Sample No.:	81-01-C	81-11-D	81-15-P	81-08-P
Element weight%				
SiO_2	50.99	50.26	47.85	52.59
Al_2O_3	14.66	14.77	18.57	16.46
Fe_2O_3*	11.84	12.30	13.92	8.24
MgO	5.53	7.52	8.61	7.46
CaO	9.74	8.23	2.89	5.86
Na_2O	5.06	4.19	2.78	2.34
K_2O	0.07	0.27	2.37	4.14
TiO_2	1.78	1.71	2.30	1.63
MnO	0.17	0.19	0.24	0.09
P_2O_5	0.21	0.14	0.20	0.14
Mg#	0.49	0.55	0.55	0.64
ppm				
Sr	153.6	334.7	122.8	68.4
Rb	1.4	14.3	34.9	59.5
Y	40.8	39.3	27.4	31.6
Zr	106.8	118.2	143.7	105.4
Nb	3.4	3.2	7.9	1.7

TABLE 3: CHEMICAL ANALYSES. . .(cont'd)

Type of Rock:	flow breccia	volcaniclastic	gabbro sill	late dike
Geochemical Sample No.:	1	3	5	4
Hand Specimen Sample No.:	80-06-0	81-04-C	81-02-P	81-06-C
Element weight%				
SiO_2	46.34	55.07	48.87	48.75
Al_2O_3	15.10	18.59	18.46	17.30
Fe_2O_3*	14.44	7.96	8.98	10.27
MgO	7.05	4.73	7.71	6.90
CaO	9.77	6.45	9.82	10.74
Na_2O	3.94	6.08	4.13	4.13
K_2O	0.54	0.71	1.09	0.44
TiO_2	1.99	0.56	1.14	1.54
MnO	0.24	0.10	0.14	0.17
P_2O_5	0.19	0.09	0.10	0.17
Mg#	0.49	0.54	0.63	0.93
ppm				
Sr	156.7	327.4	454.0	115.2
Rb	13.0	14.2	18.9	10.7
Y	36.5	16.1	25.1	30.4
Zr	118.0	88.6	92.8	122.4
Nb	4.9	4.3	1.1	5.2

TABLE 3: CHEMICAL ANALYSES. . .(cont'd)

Type of Rock:	volcanic standard
Geochemical Sample No.:	--
Hand Specimen Sample No.:	--
Element weight%	BCR-1
SiO_2	54.64
Al_2O_3	13.59
$Fe_2^*O_3$	13.44
MgO	3.39
CaO	7.01
Na_2O	3.37
K_2O	1.69
TiO_2	2.25
MnO	0.18
P_2O_5	0.37
Mg#	--
ppm	
Sr	329.3
Rb	46.6
Y	37.3
Zr	181.0
Nb	--

plot (Figure 25; Sun et al., 1978), TiO_2 - Zr (Figure 26; Floyd and Winchester, 1975), TiO_2 - Y/Nb (Figure 27; Floyd and Winchester, 1975), and TiO_2 - FeO (total)/MgO (Figure 28; Miyashiro, 1975). Plots used to infer tectonic setting include: K_2O - TiO_2- P_2O_5 (Figure 29; Pearce et al., 1975), Zr - Nb (Figure 30; Bass et al., 1973), Zr/Y - Zr (Figure 31; Pearce and Norry, 1979), Zr - Ti/100 - Y x 3 (Figure 32, Pearce and Cann, 1973), and Zr - Ti/100 - Sr/2 (Figure 33; Pearce and Cann, 1973). First, however, four figures will be used to attempt to show the relative amounts of alteration, differentiation, and/or crystal accumulation as these parameters will affect where the samples plot in many of the various discrimination diagrams.

A plot of MgO vs Al_2O_3 (in wt %) indicates four things (Figure 19). First, it appears sample 2, which is a volcanic, is altered and thin section shows this sample has abundant (~ 10 percent) carbonate stringers and up to 10 modal percent clinopyroxene. Although care was taken in sample preparation to remove all secondary vein material, enough probably passed through to significantly affect the result. Second, sample 5 (a gabbro sill) shows slight crystal accumulation of plagioclase and clinopyroxene and 8 (a volcanic) of plagioclase and olivine affected their chemistry as can be seen in increasing content of both Al_2O_3 and MgO. This also is confirmed in thin section. Sample 3 (volcaniclastic) shows low MgO and high Al_2O_3 contents indicating large amounts of plagioclase are present. Petrographic examination of this sample reveals ~35 modal %. The remaining samples generally plot between 6.75 and 8.0 wt percent MgO indicating that differentiation by accumulation processes did not significantly affect the chemistry in any one sample more than the others.

On a plot of FeO/MgO vs Al_2O_3 (in wt percent), three of the samples

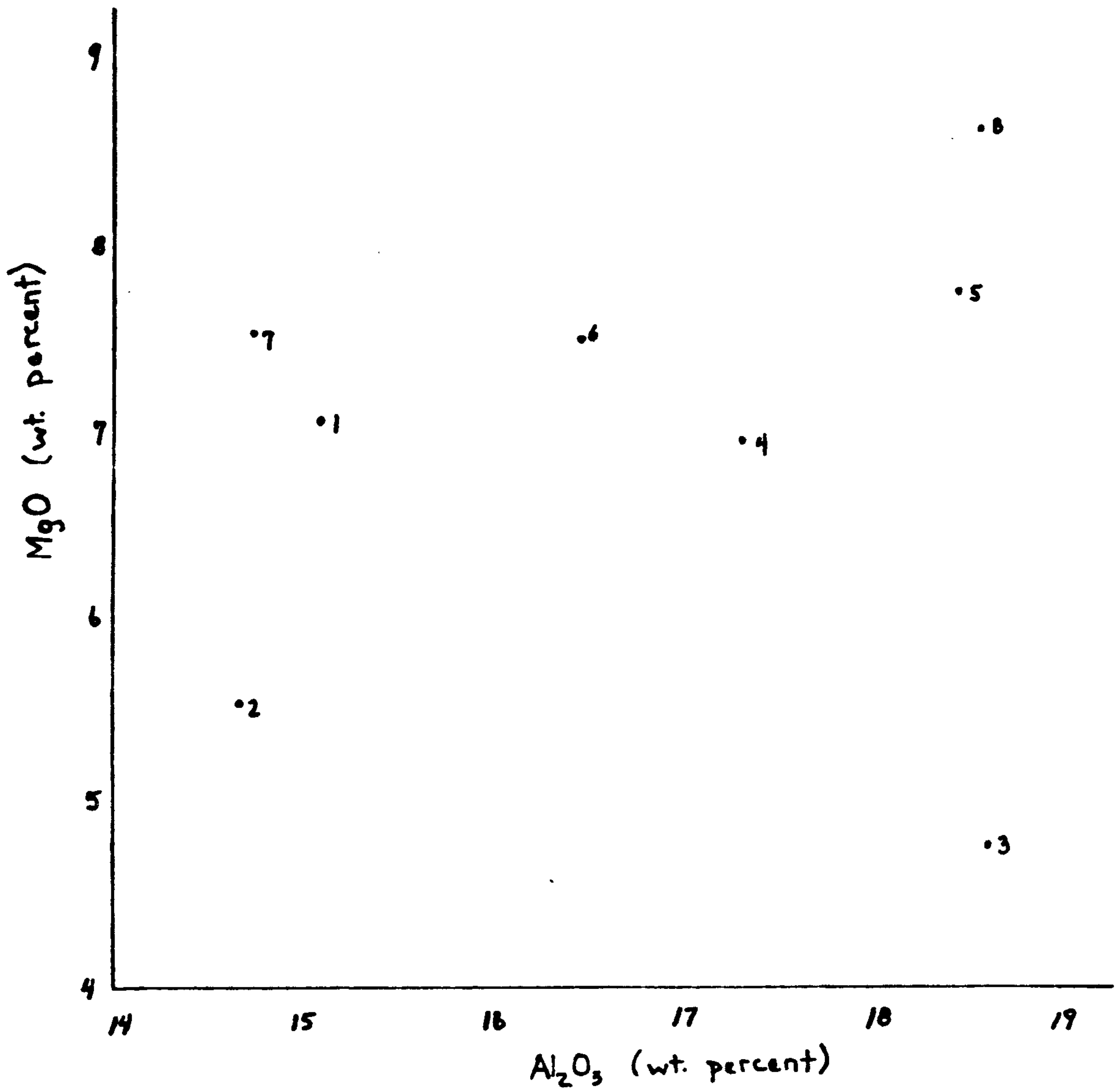


Figure 19: MgO (weight percent) versus Al_2O_3 (weight percent)

plot at a relatively higher Fe/MgO ratio and lower Al_2O_3 value and hence appear slightly more differentiated (Figure 20). These samples (1, 2, 7) are not the same samples that appear to be marginally differentiated in Figure 1. However, sample 2 (a volcanic) was shown to have abundant carbonate stringers and 10 modal percent clinopyroxene. Petrographic study of sample 1 (a flow breccia) shows 10 modal percent calcite in veins and finely disseminated in the groundmass. It also reveals up to 36 percent chlorite replacing mainly plagioclase feldspar and also totally pseudomorphing olivine and clinopyroxene. Thin section study of sample 7 (a volcanic) shows 27 modal percent clinopyroxene. A plot of Mg number versus strontium, a mobile element (Figure 21), and zirconium, an immobile element (Figure 22) reveals first, that with the exception of the late dike, the Mg numbers from the Chagnon massif have a limited range (.49 - .64); and second, strontium has a wide range in abundance (50 - 475 ppm, approximately a factor of ten) while zirconium is relatively consistent (85 - 145 ppm, approximately a factor of two). Differentiation of a mafic magma toward a more silicic magma should result in the depletion of strontium as plagioclase separates out (Carmichael, et al., 1974). In this study, strontium abundance is highest in the gabbro (sample 5), shows a decrease in the volcanic (sample 7) and volcaniclastic (sample 3) and is lowest in the remainder of the volcanics, in the flow breccia, and in the late basaltic dike (samples 1, 2, 4, 6, and 8). A consistency in Mg numbers and zirconium abundance would be expected in a massif of a single parent or related parent magmas.

The rocks from the Chagnon area generally appear tholeiitic. A

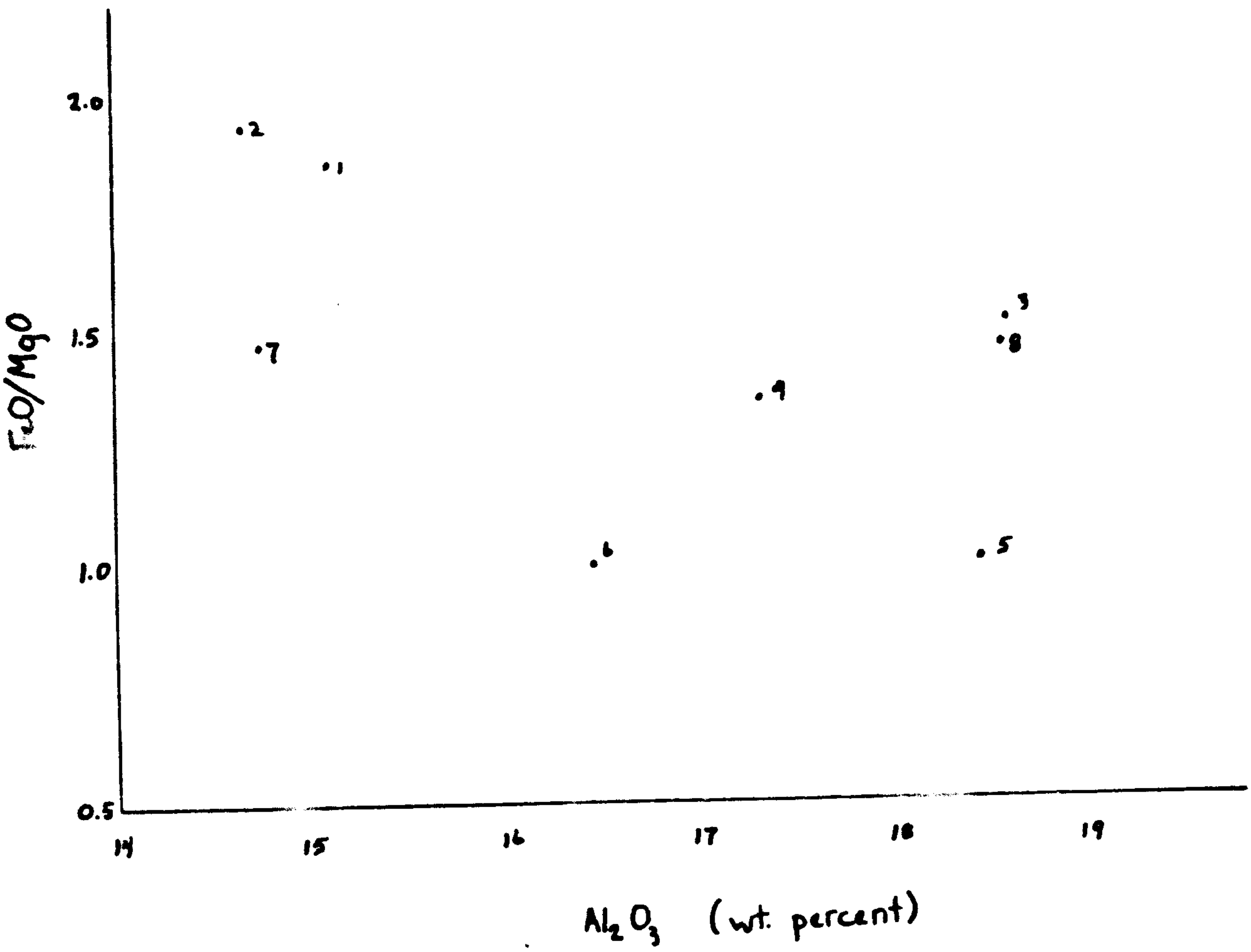


Figure 20: FeO/MgO versus Al_2O_3 (weight percent)

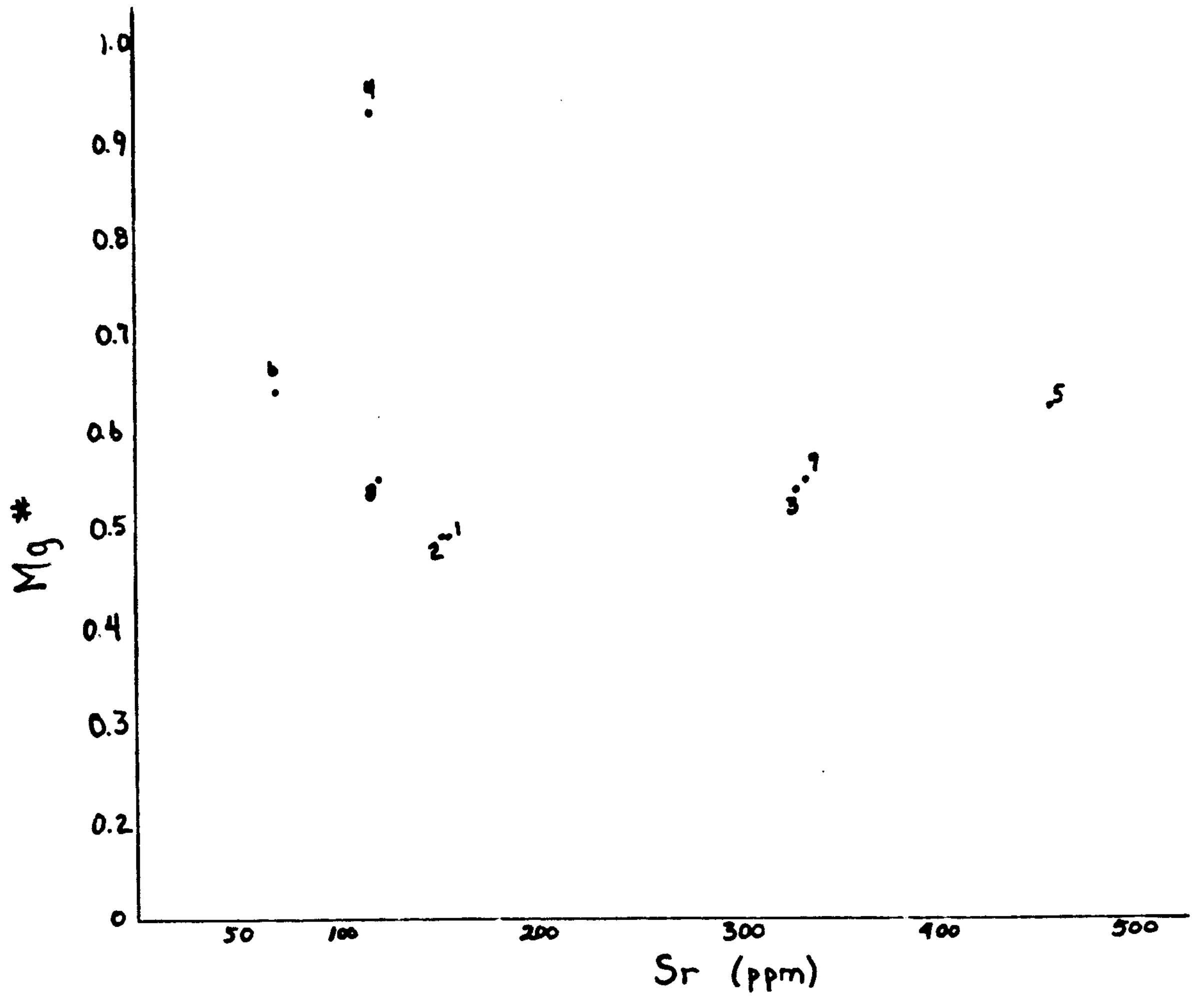


Figure 21: Mg number versus Sr (ppm)

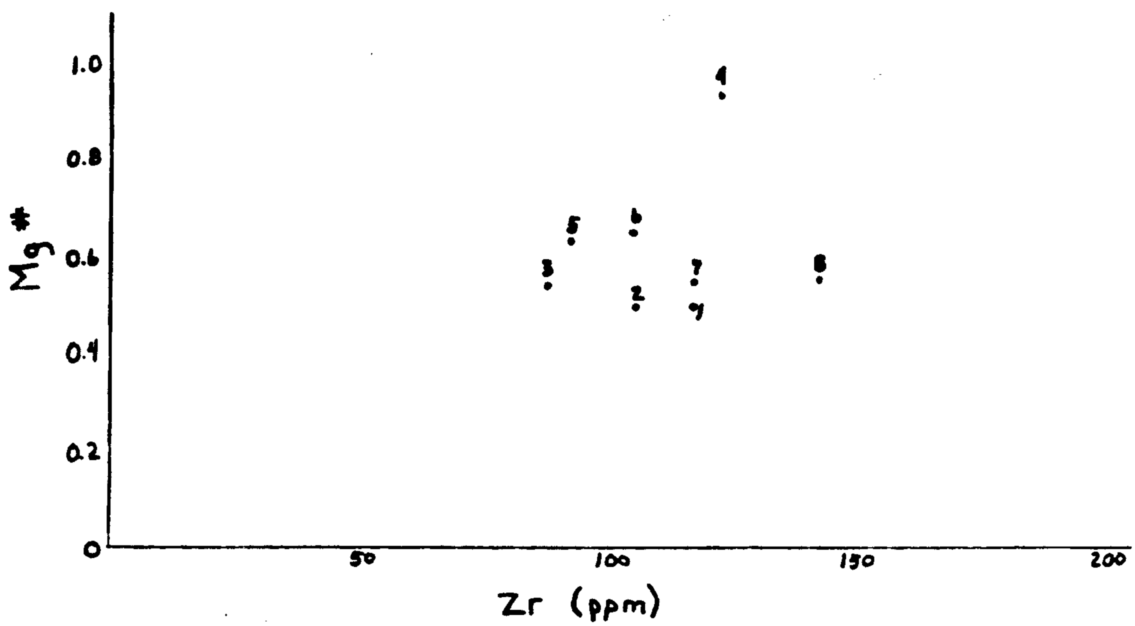


Figure 22: Mg number versus Zr (ppm)

moderate tendency toward iron enrichment in the volcanics as compared to the volcanic sill, gabbro sill, and the volcaniclastic is seen in Figure 23. Samples 3 (volcaniclastic) and 6 (volcanic sill) tend more towards the calc-alkaline field. This, however, is probably due to plagioclase accumulation and K_2O enrichment (see Table 3) in the volcanic sill and to sedimentation and weathering in the volcaniclastic (see Figures 19 and 20).

A plot of total alkalis versus alkali ratio of the mafic rocks from the Chagnon area shows a significant amount (~ 100-150%) of alkali enrichment has occurred (Figure 24). These samples, which petrographically are mafic (basaltic volcanics, plot either above the tholeiite field or in fields which the petrography and geochemistry do not support. Clearly, alkali metasomatism has affected the protolith of these samples. Furthermore, a trace element plot using normalized chondrite abundances from Sun and others (1979) and from Wanke and others (1974) shows K, Sr, and Rb have wide variability and appear enriched (Figure 25). This plot also suggests apart from these trace elements that the Chagnon mafic rocks have an ocean tholeiite trend. Floyd and Winchester (1975) discrimination diagrams utilizing trace elements rather than major elements were used to check the validity of the above assumption (Figures 26 and 27). In both cases, the rocks plotted in the tholeiitic rather than alkali basalt field. In addition, a plot of Ti vs Y/Nb (Figure 27) indicates they are largely ocean tholeiites rather than continental tholeiites.

The geochemical suggestion of only one basaltic magma is inferred in the discussion up to this point. Excluding the late dike (sample 4), the differences between the samples can be attributed to crystal accumulation via magmatic processes or via sedimentation processes

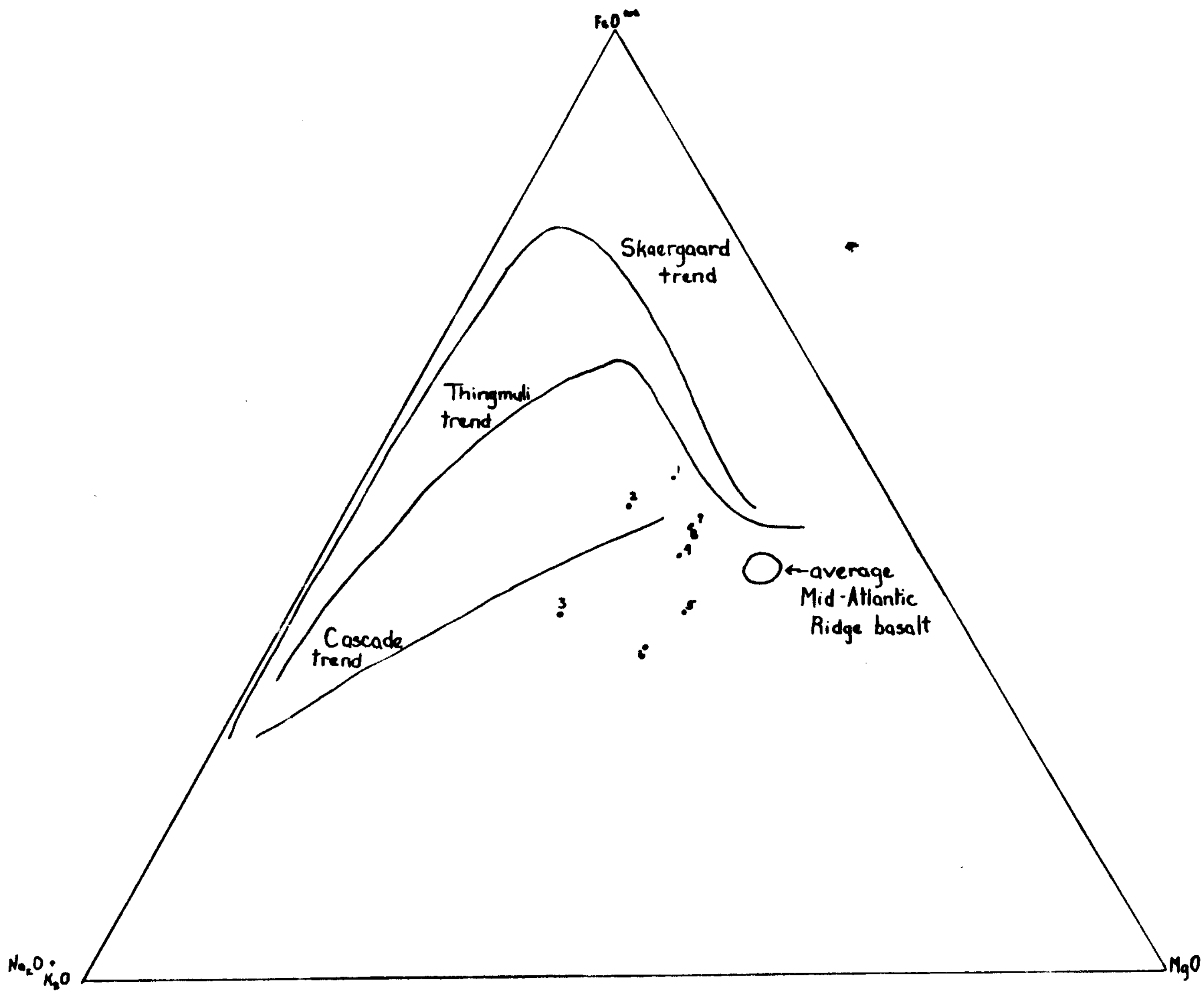


Figure 23: Samples from the Chagnon area plotted in the system FeO^{total} - Na_2O+K_2O - MgO with trends from Skaergaard, Thingmuli, and the Cascades included. Area encompassing position of average Mid-Atlantic Ridge basalt is circled.

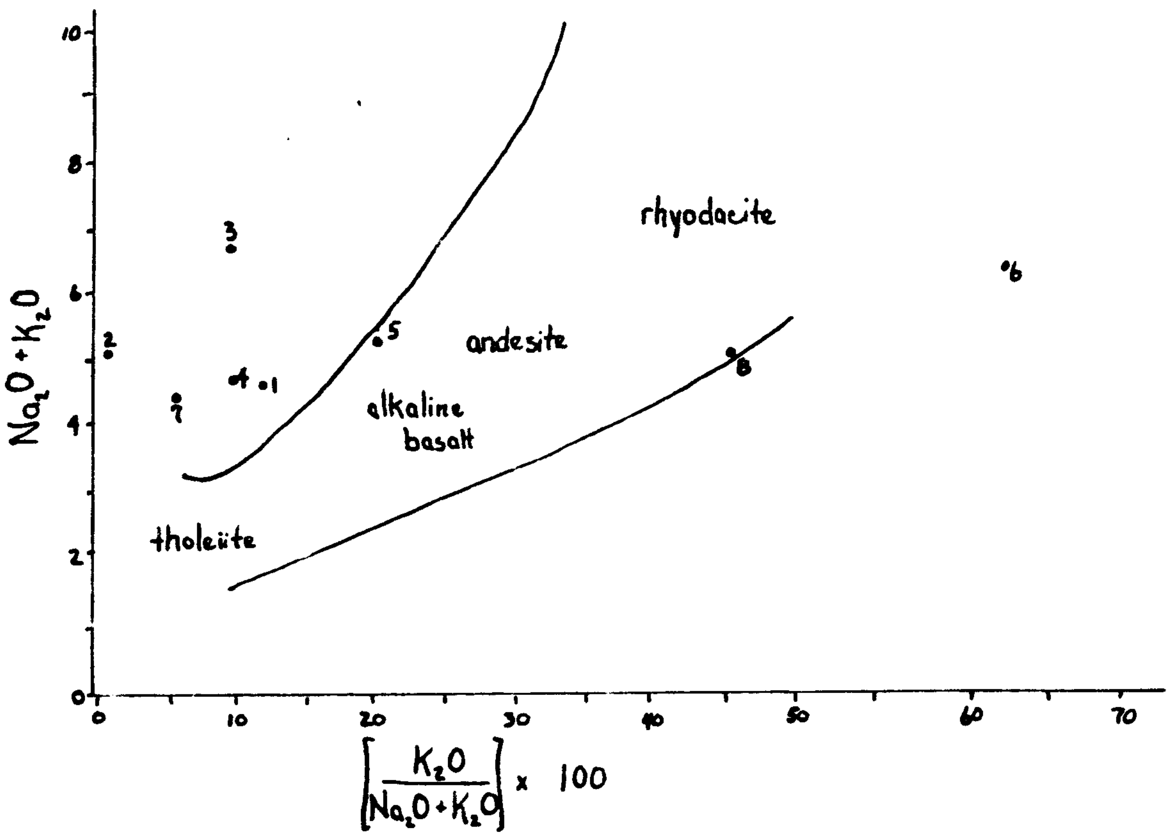
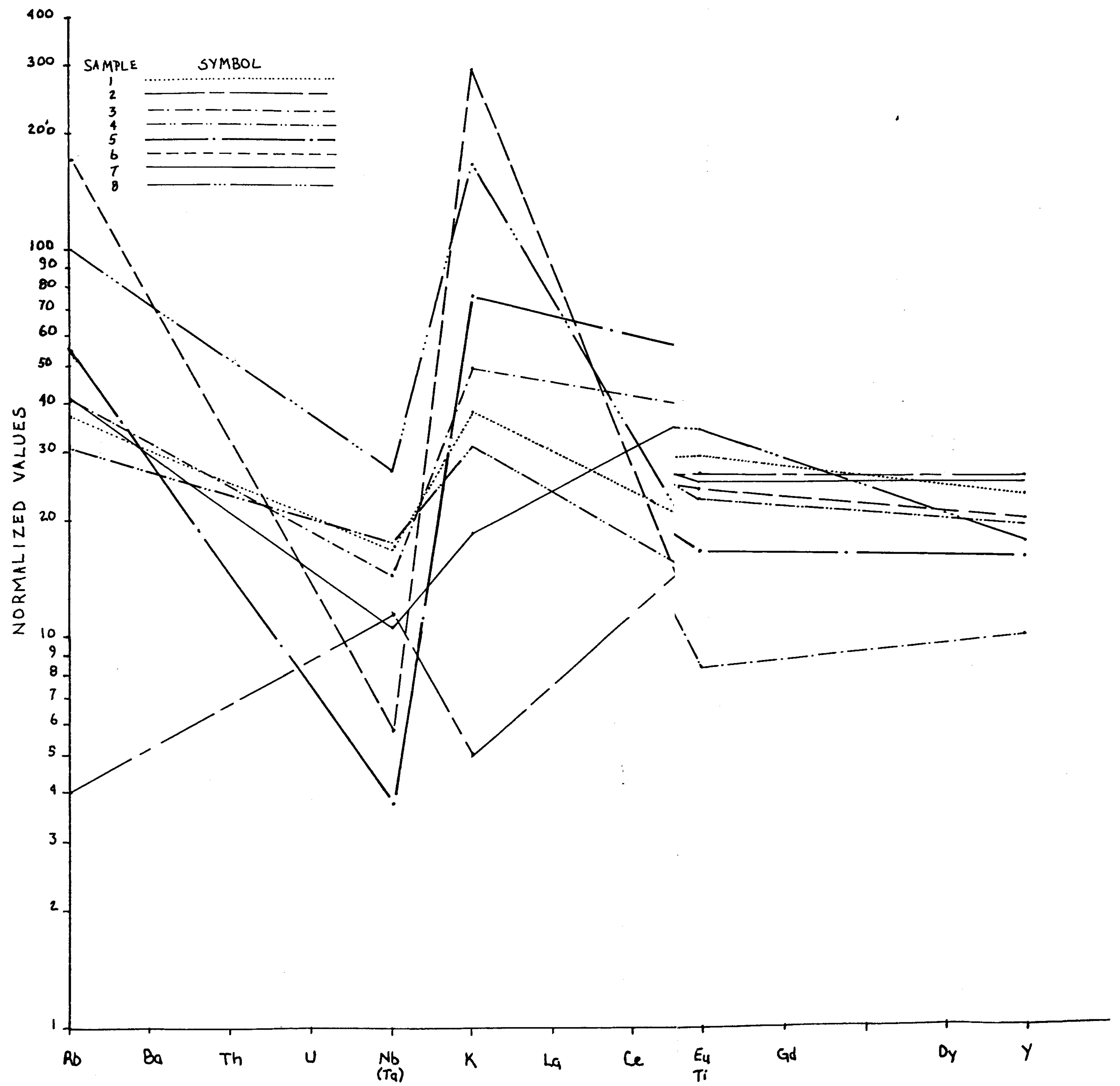


Figure 24: Total alkalis versus alkalic ratio of mafic rocks from the Chagnon area. Boundaries determined from fresh volcanic rocks from Hughes (1973).

Figure 25: Plot of normalized incompatible element abundance patterns for mafic rocks from the Chagnon area. Abundances of Ti, Sr, Y, Zr, Nb are normalized using condrite abundances from Wänke and others (1974). Abundances of Rb, K, P are normalized using condrite abundances from Sun and others (1978).



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NORMALIZED VALUES
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SYMBOL
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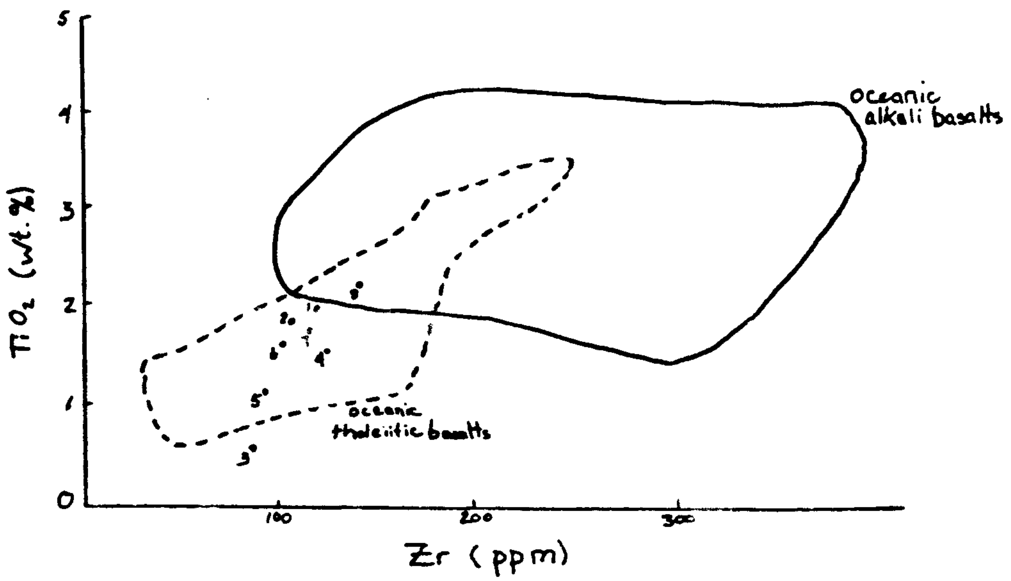

Figure 26: TiO_2 (weight percent versus Zr [ppm]) discrimination diagram of mafic rocks from Chagnon. Field boundaries from Floyd and Winchester (1975).

(sample 3). In addition, alkali metasomatism of the rocks gave rise to their high sodium and potassium contents. Furthermore, the trace element plot suggests an ocean tholeiite trend and this is supported by the trace element discrimination diagrams of Floyd and Winchester (1975). All of the samples in this study, with the exception of the volcaniclastic, have TiO_2 values greater than one weight percent (Figure 28), thus also suggesting only one parent magma. These samples plot in the range of Winner's (1981) tholeiites while the volcaniclastic in this study plots with his olivine tholeiites.

Previous workers have claimed to be able to define tectonic environments using a large data base of fresh rocks from known tectonic settings (Pearce and Cann, 1973; Bass et al., 1973; Pearce et al., 1975; Pearce et al., 1977; Pearce and Norry, 1979). Use of diagrams derived from such studies allow the original tectonic setting to be inferred for rocks of the Chagnon area. Pearce and others (1975) plot K_2O - TiO_2 - P_2O_5 in order to distinguish oceanic basalts from continental basalts. This diagram has limited value, however, as these rocks have been shown to be alkali enriched. Rocks from the Chagnon area plot in both fieldson the K_2O-TiO_2 - P_2O_5 plot (Figure 29). It should be remembered from the discussion of magma type that samples 5 (gabbro sill) and 8 (volcanic) are affected by plagioclase and clinopyroxene/olivine accumulation, sample 6 (volcanic sill) by K_2O enrichment, and sample 3 (volcaniclastic) is affected by sedimentation and weathering processes. In addition, Pearce and others (1975) note metamorphism and weathering result in basalt compositions plotting outside the oceanic basalt field; those that remain undoubtedly are of oceanic origin. As trace elements are less mobile, Zr and Nb contents of samples from this study were plotted on a diagram following Bass

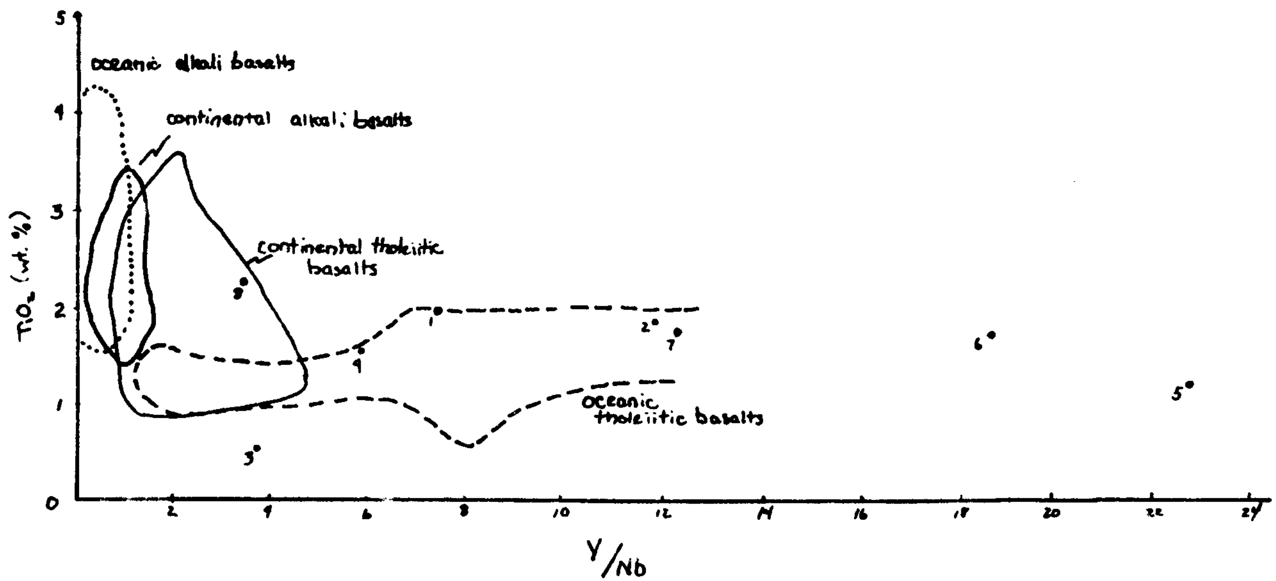

Figure 27: TiO_2 (weight percent) versus Y/Nb discrimincation diagram of mafic rocks from Chagnon. Field boundaries from Floyd and Winchester (1975).

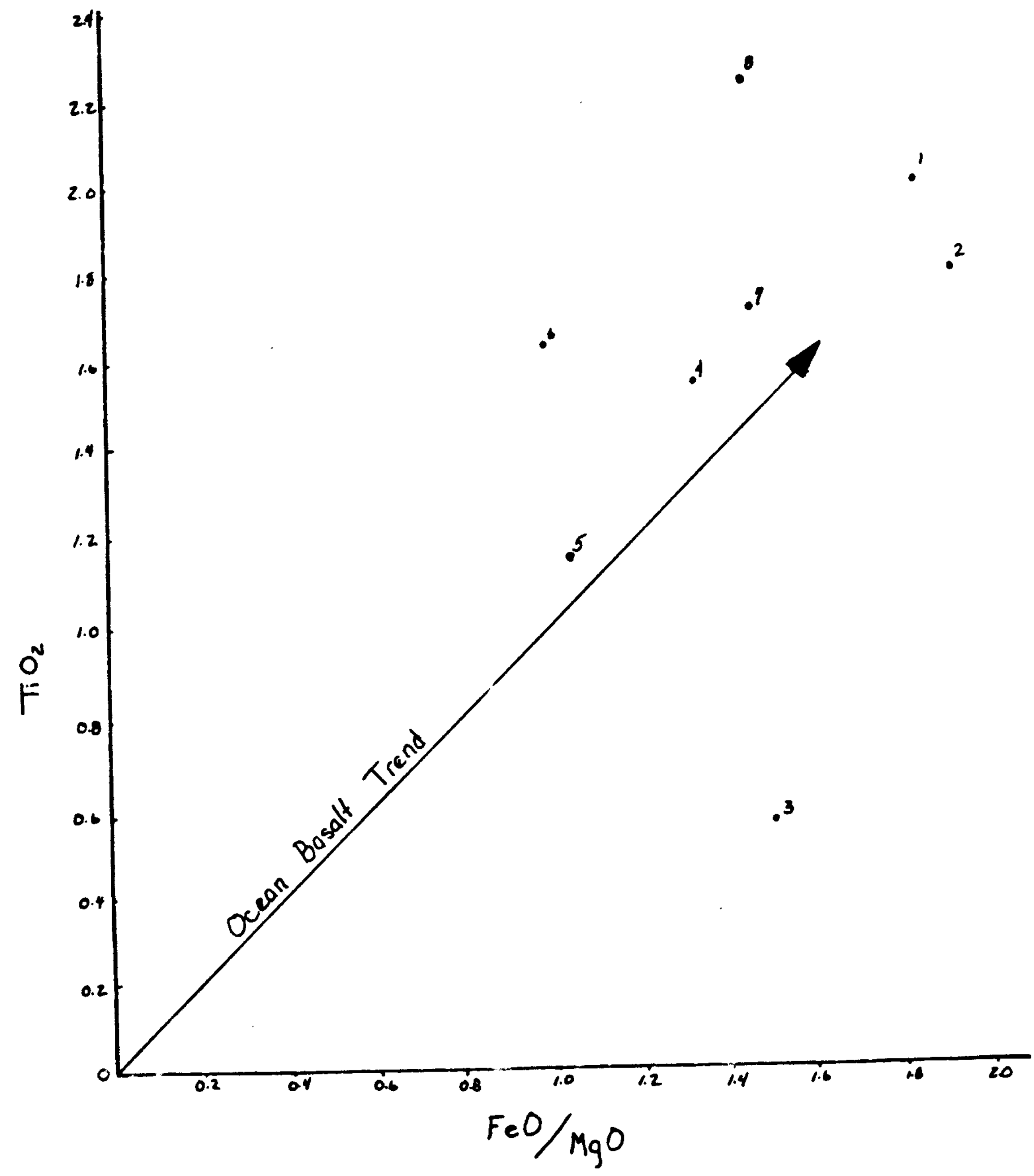

Figure 28: TiO_2 versus FeO (total)/MgO diagram.

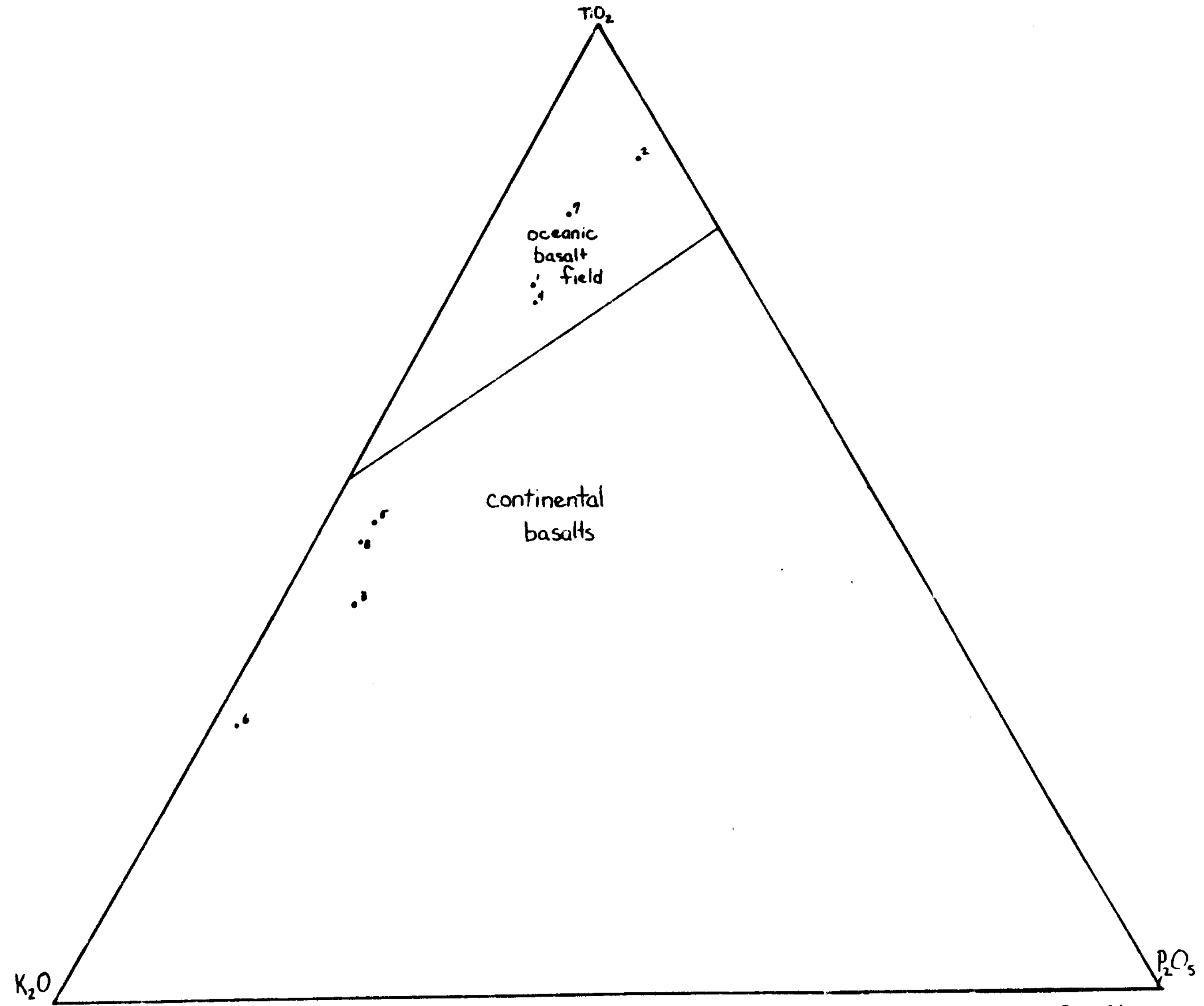

Figure 29: Mafic rocks from the Chagnon area plotted on the K_2O - TiO_2 - P_2O_5 diagram. Basalt field from Pearce and others (1975).

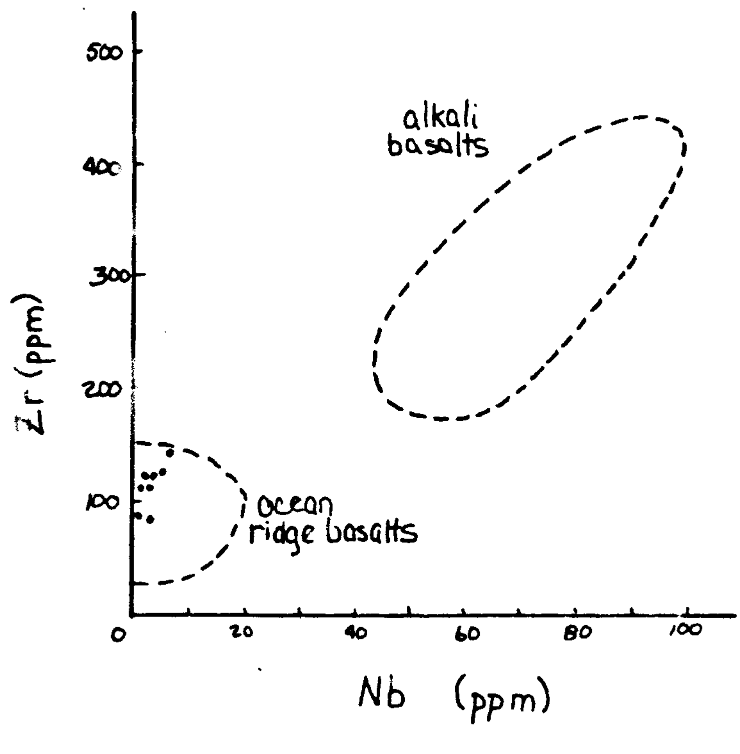

Figure 30: Zr-Nb plot of mafic rocks from the Chagnon area. Field boundaries are from Bass and others (1973).

and others (1973). All of the rocks in the Chagnon area plot completely within the ocean ridge basalt field (Figure 30).

A Pearce and Norry (1979) Zr/Y - Zr diagram was used to infer tectonic environment. Most of the samples, again, plot within the mid-ocean ridge field (Figure 31). Samples 4 and 8, however, plot just within the in-plate basalt field. Some overlap between the mid-ocean ridge basalts and within plate basalt fields does occur on Pearce and Norry's original diagrams. The samples from the Chagnon area were also plotted on two Pierce and Cann (1973) diagrams; Ti/100-Zr-Y·3 (Figure 32) and Ti/100-Zr-Sr/2 (Figure 33). Samples 3 and 5, the volcaniclastic and the gabbro respectively, plot in the calc-alkaline field in both figures although sample 5 in Figure 32 actually is within the area of overlap between ocean floor basalts and calc-alkaline basalts. The other samples generally plot as ocean floor basalts. From these figures it can be inferred that one basaltic magma type is present in the Chagnon massif, and it is very likely to have been ocean floor basalt.

DISCUSSION

Samples from five volcanics, one volcaniclastic, one gabbro sill, and one plagioclase phyric dike were analyzed and plotted on various discrimination diagrams in order to infer: 1) If one or more magma types is present in the Chagnon massif; 2) what was the nature of the magma(s); and 3) what was the original tectonic environment of the magma(s). Although the number of samples is small, some inferences can be made. First, a spatial separation of the volcaniclastic (3) and often the volcanic sill (6) from the other samples occurs on the various diagrams. This is attributed to sedimentation and weathering processes in the case of the volcaniclastic and to alkali

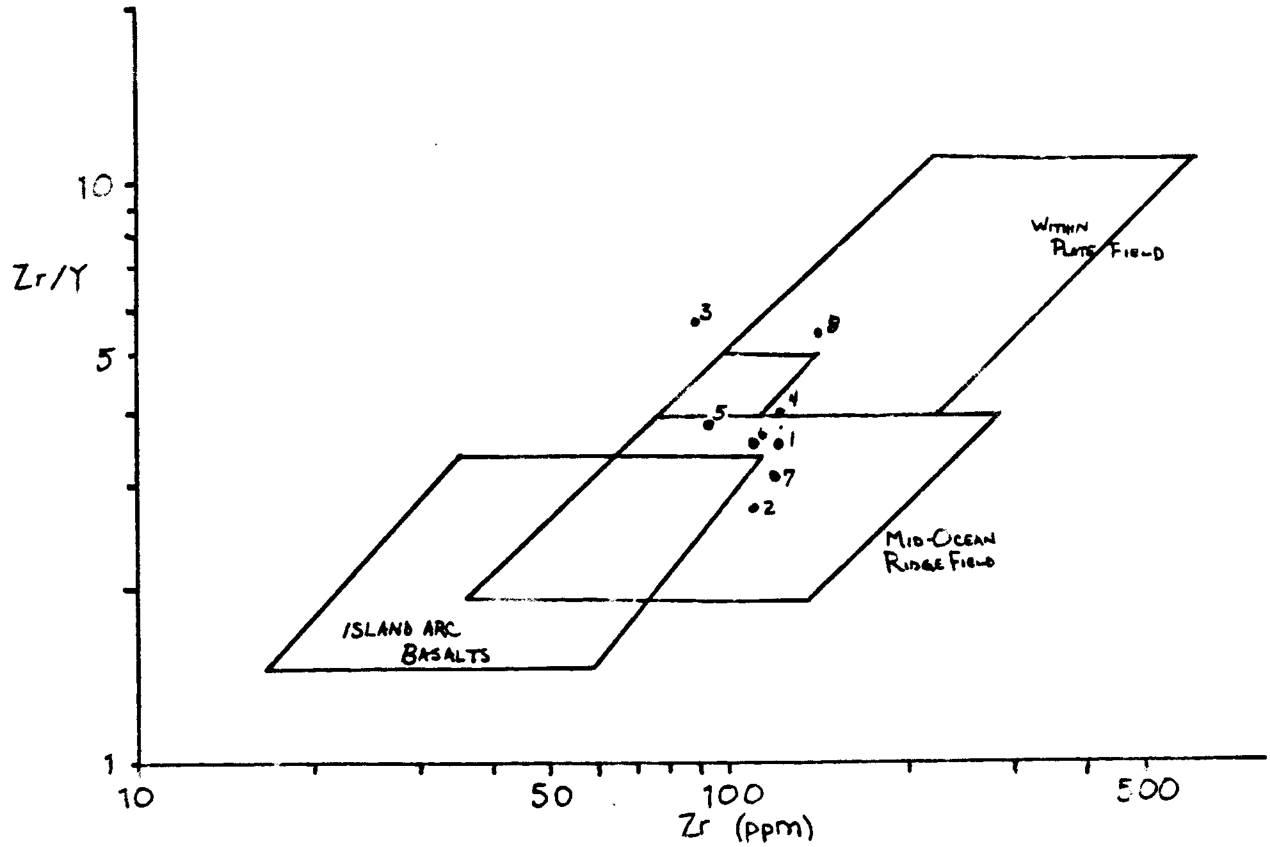

Figure 31: Plot of mafic rocks from the Chagnon area using Pearce and Norry's (1979) Zr/Y - Zr (ppm) discrimination diagram.

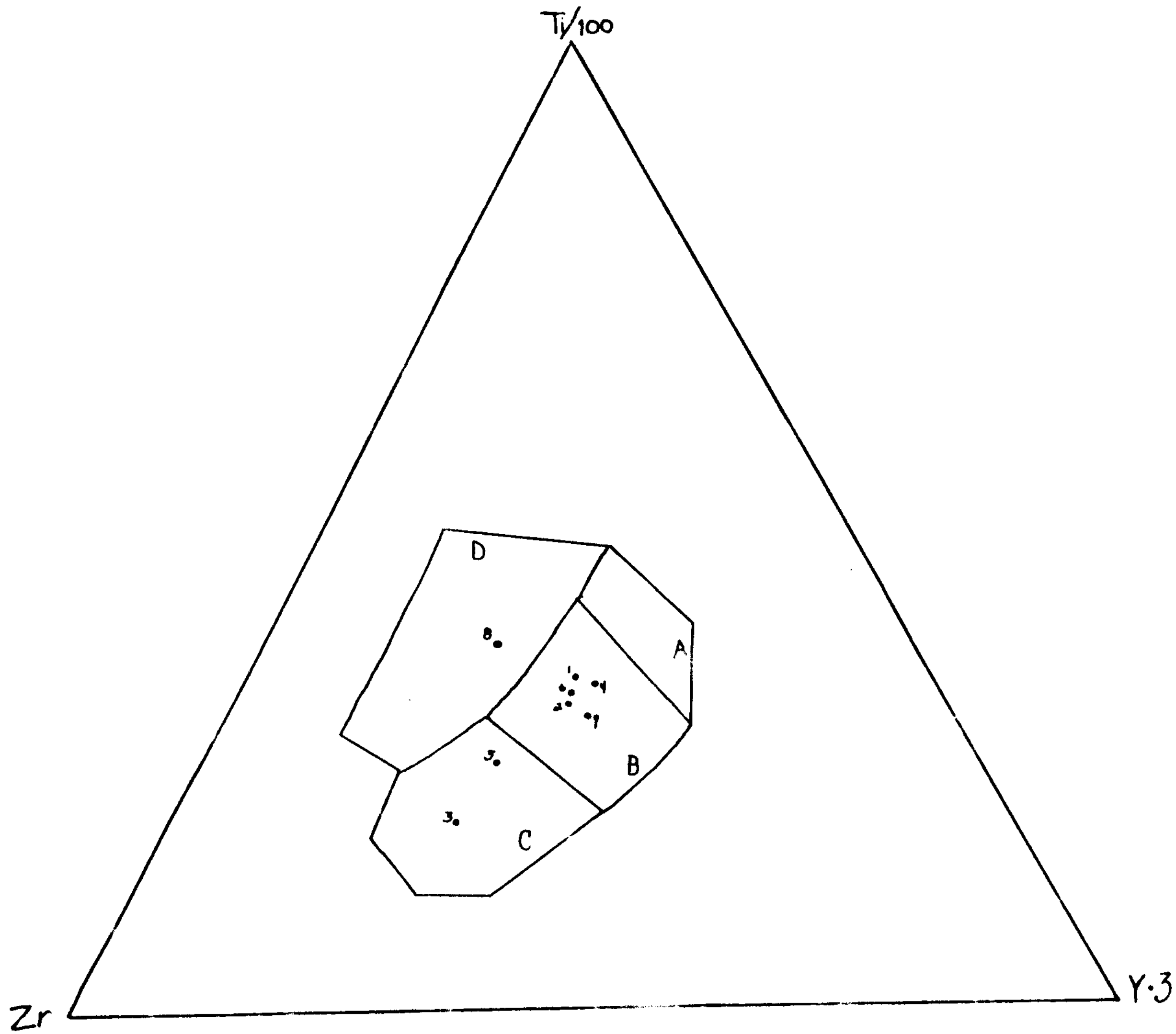

Figure 32: Mafic rocks from Chagnon plotted on the Ti - Zr - Y diagram of Pearce and Cann (1973). Ocean floor basalts plot in field B, island arc basalts in fields A and B, calc-alkali basalts in fields B and C, and within plate basalts in field D.

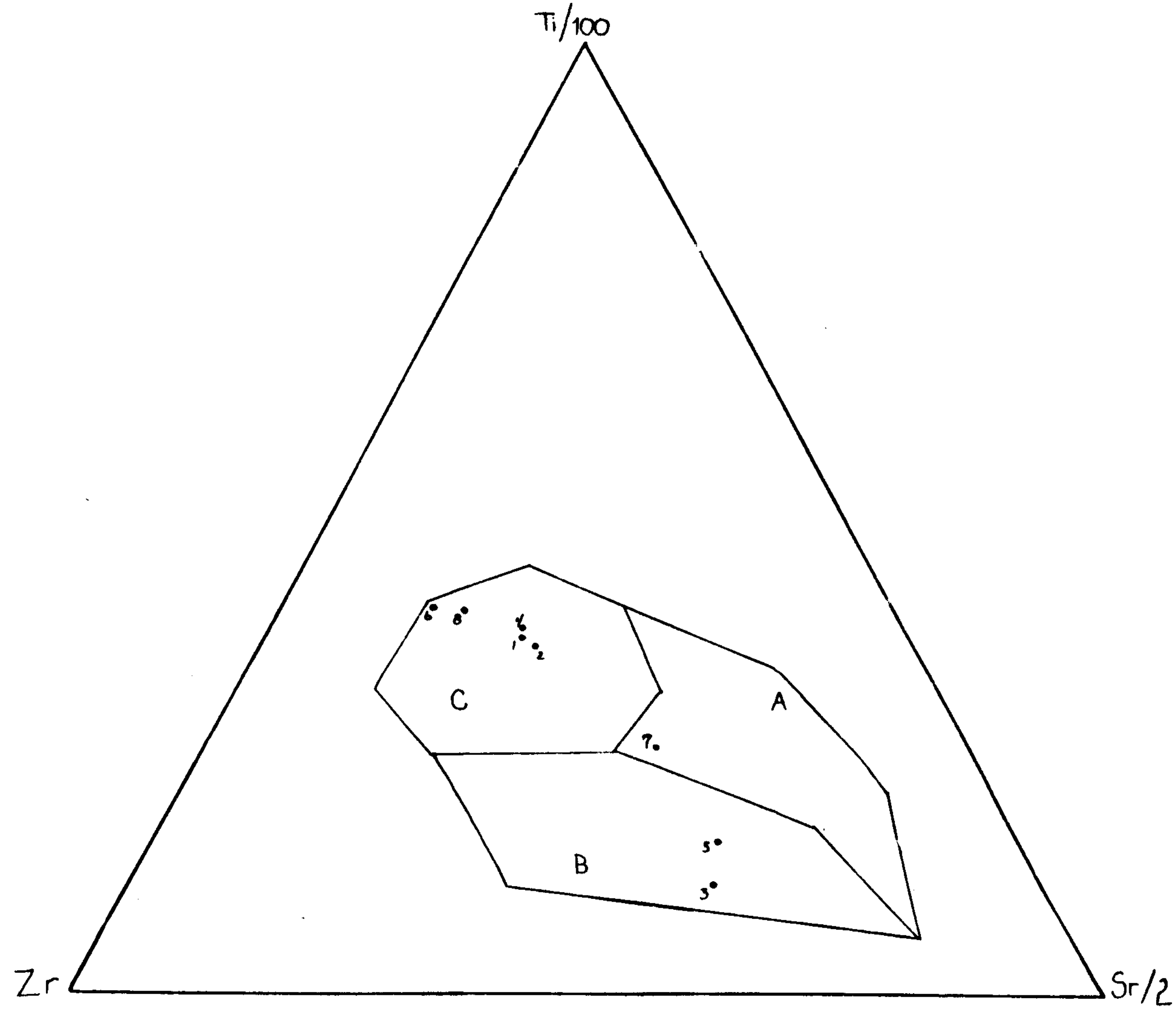

Figure 33: Ti - Zr - Sr diagram of Pearce and Cann (1973) with the mafic rocks from the Chagnon area plotted. Island arc baslats are in field A, calc-alkali basalts are in field B, and ocean floor basalts plot in field C.

enrichment in the volcanic sill. However, only one magma type is believed to be present. This appears to be an ocean floor tholeiite which has been enriched in alkalis as suggested by the anomalously high values for Na_2O, K_2O, Rb, and Sr (Figures 24 and 25). Finally, presence of tholeiitic magma suggests the Chagnon massif was formed at a oceanic spreading ridge.

CHAPTER V

EVALUATION OF THE CHAGNON AREA

SUMMARY

The Chagnon Mountain area consists of six major lithologic units which, from west to east and going up structure, are: gabbro, quartz-diorite, diabase, volcanics, the St. Daniel Formation and rocks of the Glenbrooke Group. All of the rocks have been metamorphosed to the greenschist facies; however, primary textures and minerals are often well preserved. Field relations between the gabbro and quartz-diorite indicate a gradational boundary. In addition, quartz-diorite has never been reported as intruding into the structurally lower units to the west (the peridotites of the igneous complex and the metasediments of the Miller Pond Formation). This suggests the quartz-diorite may be genetically related to the gabbro through the process of differentiation, or may represent a later partial melt.

Diabase lies structurally above the quartz-diorite and apparently formed the lid to the magma chamber as indicated by the irregular nature of the contact in map pattern. Additionally, diabase shows a well-developed cataclastic foliation where in contact with the quartz-diorite, and the quartz-diorite shows a thin alteration zone. Furthermore, blocks of diabase are present in the quartz-diorite near the contact, indicating stoping, and veins of silicic composition (probably quartz-diorite) intrude the diabase and volcanics near their contact with the quartz-diorite.

Some diabase dikes are unquestionably present in the diabase unit and also in the volcanics. This indicates that these dikes acted as feeders to the overlying volcanics. That more dikes are not clearly discernable in the field is not a major argument against the hypothesis that the diabase unit consisted entirely of dikes as this area has undergone deformation and related metamorphism and, in addition, presently has limited exposure. Thus, these features, if originally present, may easily have become obscured.

A mafic volcanic unit consisting of massive volcanics, breccias, pillow lavas, and arenaceous volcaniclastics caps the igneous sequence at Chagnon Mountain. Petrographically the volcanics are similar to each other and also the diabase and gabbro suggesting a common parent magma. The presence of pillow structure demonstrates the submarine extrusive origin of these volcanics. However, because of the occurrence of volcaniclastics, the mafic assemblage at Chagnon cannot be described as a "normal" (mid-ocean ridge) ophiolitic fragment. The arenacoeus volcaniclastics, which are found in the southern portion of the area, are interbedded with the massive volcanics, and their presence seems to suggest the existence of a nearby island arc.

Petrographically, the gabbros, diabases and volcanics appear similar. All have plagioclase, augite, and olivine with accessory amounts of magnetite, ilmenite, and apatite as primary phases. These mafic rocks have been metamorphosed to the chlorite zone of the greenschist facies and are characterized by the assemblage: chlorite-clinozoisite-albite ± quartz ± sericite ± calcite ± sphene. This metamorphic mineralogy is consistent with the interpretation of these mafic rocks as spilites formed by hydrothermal circulation of water through the rocks.

Although an original stratigraphy comparable to some kind of oceanic crust (inter- or intra-arc, or mid-ocean ridge) is preserved at Chagnon, the section has been apparently telescoped. Similar rocks (peridotites, gabbros, quartz-diorites/troundjhemite, diabase, and volcanics) at

Thetford Mines give a thickness of 5 km; at Asbestos, 2 km; at Orford, over 1 km; and at Chagnon, less than 1 km (Winner, 1981). Hence, a structural thinning to the south seems indicated.

Geochemical analysis of eight mafic rocks from the Chagnon area was done in order to determine if one or more parent magmas was responsible for the complex. Although the number of samples may be statistically too small for a comprehensive statement to be made; magma type and environment, however, still are indicated. Five of the eight samples are volcanic (four massive volcanics and one basalt breccia), one is a mafic volcaniclastic arenite, one is from a gabbro sill and the last is from a late plagioclase phyric dike. All but the volcaniclastic seem to be of tholeiitic affinity and from an ocean floor setting.

The St. Daniel Formation lies structurally on top of the volcanics in the study area. This formation is made up predominantly of gray to black olistostromal slates containing graywacke, quartzite, argillite, and shale fragments. Minor sandstone and unfossiliferous limestone are also present. Ophiolitic fragments are reported in the St. Daniel slates south of Place Mountain; and, in the map area, large blocks of massive volcanics locally occur. This could be explained by block faulting of ocean crust with ophiolitic fragments spalling off the scarps and into the olistostromic sediment. These sediments would be deposited draping the scarps and give rise to locally conformable but overall unconformable contact with the ophiolite.

The St. Daniel slates consist of predominantly angular quartz and plagioclase set in a micaceous matrix. Zircon is present in accessory amounts, and clinozoisite, chlorite, actinolite, and pyrite occur as alteration minerals.

The Peasley Pond Conglomerate is a common marker horizon for the base of the Glenbrooke Group throughout the Eastern Townships. It occurs in the Chagnon area as a basal conglomerate unconformably overlying the volcanics, volcaniclastics, and the St. Daniel Formation. Above the conglomerate is the upper sandstone member, a relatively pure, equigranular sandstone (see plate A). The conglomerate pinches out along strike in the map area and the sandstone directly overlies the St. Daniel Formation. It mainly contains quartz, chert, and shale fragments at the base to a nearly pure quartz sandstone at the top. Chromite is present in the Peasley Pond Conglomerate, as are clasts of silicic volcanics and clastic clots of probable lateritic soil. Metamorphism of this unit resulted in the growth of chlorite and sericite in the matrix.

The rocks in the map area can be divided into two structural domains: the igneous domain and the metasediment domain. Both have a dominant northeast trending foliation and young to the southeast. Poles to foliation in these domains indicate the bedding in the area is broadly warped. Furthermore, the poles to foliation in the igneous domain tend to girdle along the same trend as the poles in the metasediment domain cluster. Although the data is insufficient to be conclusive, there is indication that the igneous domain suffered two deformational events (Sn and Sn + 1) while the metasediment domain incurred only one (Sn + 1). The first event, Sn, in the igneous domain may have been related to its formation. The second event, Sn + 1, is common to both domains and caused the dominant northeast-trending structural grain of the area.

TECTONIC MODELS

A tectonic model of the Chagnon area must take into account the following critical pieces of evidence:

1) The igneous rocks of the Chagnon massif represent an ocean crustal fragment (ophiolite) that was obducted onto the ancient North American continental margin during the closing of the Iapetus Ocean. Petrologic features indicate this complex was formed by a single parent magma which evolved by the process of differentiation (crystallization of plagioclase, olivine, and clinopyroxene). The resulting mafic rocks are of tholeiitic ocean-floor affinity.

2) Mafic volcaniclastic arenites, which contain rare pieces of silicic volcanic rock, are found interstratified with the volcanics in the southern portion of the map area. They do not overlie all of the volcanics and they are not wholly separated from them. Several of the samples used for volcanic analyses are south of and presumably stratigraphically above the volcaniclastic sediments.

3) There is an abrupt discontinuity at the St. Daniel-ophiolite contact. In addition, the arenites in the St. Daniel are quartzose, unlike those in the volcanics.

4) The Magog flysch units are also quartzose and contain tuffs suggesting a connection with the Ascot-Weedon arc. Although St. Julien and Hubert (1975) interpret an unconformity between the St. Daniel and the overlying Magog Assemblage (which consists of graphitic slates, tuffaceous sandstones and chert at the base, overlain by a sequence of well graded sandy turbidites, black slates, and silicic tuffs), examination of the contact (Castle Brook locality) revealed no evidence of an erosional surface between the two (Personal communication,

W.S.F. Kidd and Barry Doolan, 1981). Fossils found in the basal Magog at this locality, Nemagraptus gracilis, and Diplograptus multidens, date the underlying St. Daniel Formation as early-Caradocian in age. According to Casey (1980, p. 130): "The contact appears gradational, and at best, represents a disconformity resulting simply from changes in sedimentation processes rather than a long period of non-deposition or erosion. The top of the St. Daniel Formation is, therefore, regarded [here] as only slightly older than the Llandeilian-Caradocian Magog Flysch."

5) The presence of quartz in the St. Daniel and Magog arenites requires a continental source (perhaps recycled deep sea sediments in an accretionary prism, but ultimately eroded from a continent) be feeding the Magog depositional basin.

From the foregoing discussion, two models appear feasible (Figures 34 and 35): The first model envisions subduction of the ocean floor under the Ascot-Weedon arc. The Magog flysch was deposited in the fore-arc basin, with basement to this basin not now exposed. The St. Daniel was deposited as subduction melange generated from the same kind of sediments as the Magog flysch. The BOC ophiolite was then accreted to the base of the St. Daniel melange and the main thrust zone moved to the west of it with Brompton/Ottaqueche sedimentation and disruption being a later melange representing thrusting below the BOC ophiolite slice. This implies a thrust-type tectonic contact between the St. Daniel and the ophiolite, which is entirely possible; its nature may have been obscured by later faulting. In this model, the mafic volcaniclastic arenites in the ophiolite are explained by erosion from a tholeiitic "intra-plate" type volcanic accumulation on or very near a main ocean

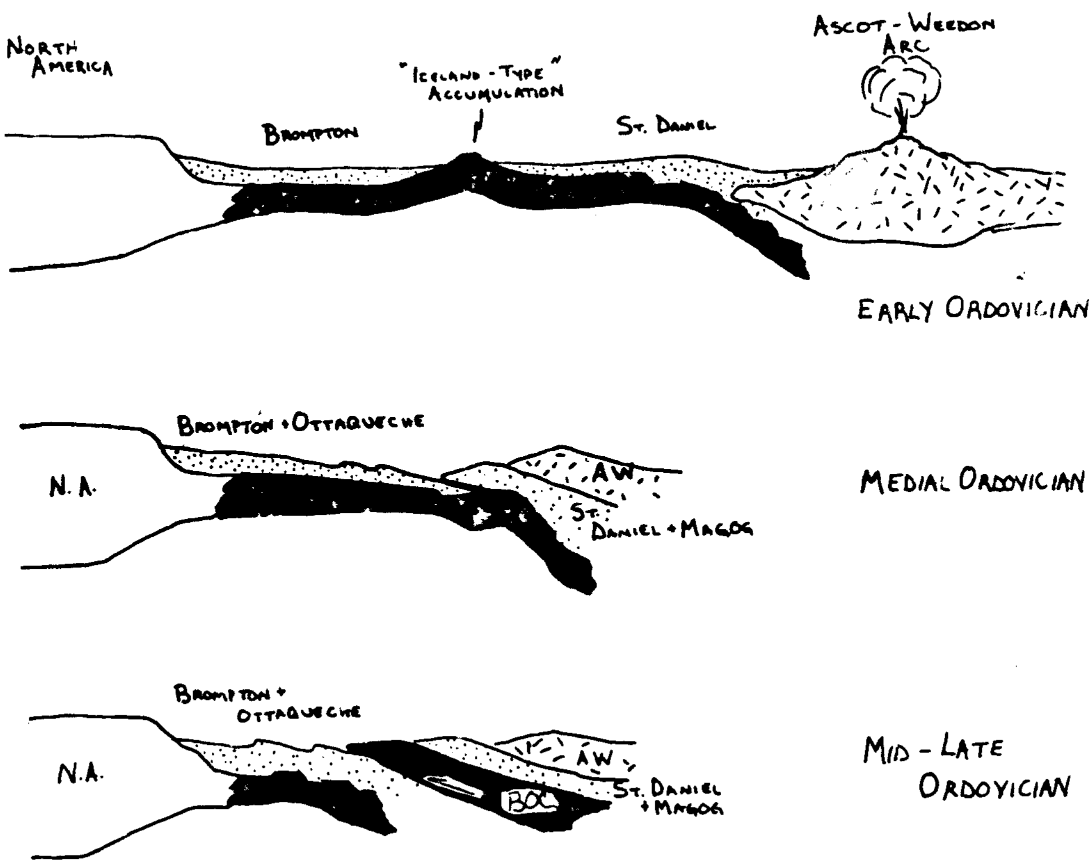

Figure 34: Plate tectonic model of the BOC ophiolite including "intra-plate" type volcanism.

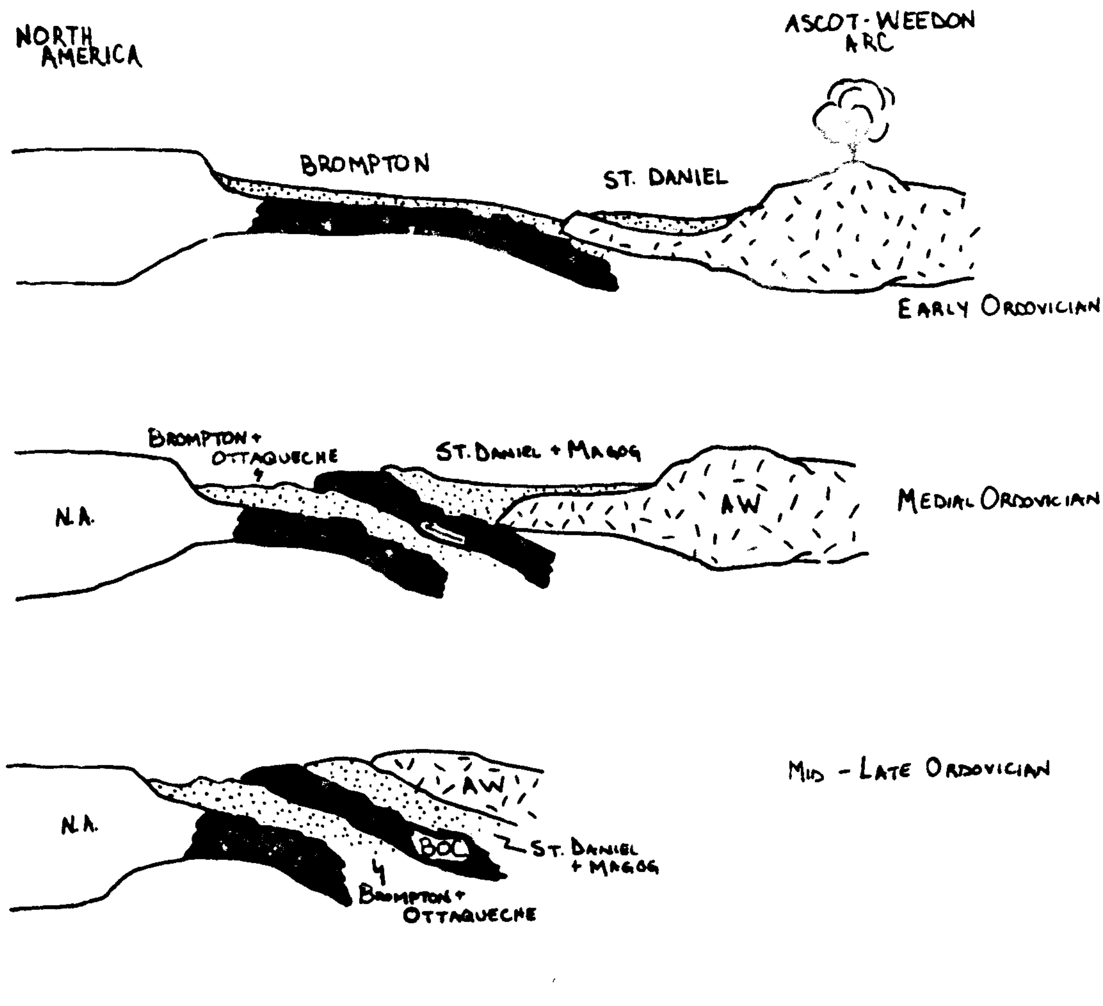

Figure 35: Plate tectonic model of the formation of the BOC ophiolite by intra-arc spreading.

spreading axis (Iceland-type model).

The second model sees the formation of the BOC ophiolite by intra-arc spreading, perhaps in the fore-arc region of the dominantly mafic Ascot-Weedon arc. The arenaceous mafic volcaniclastics are interpreted here as resulting from erosion from the arc volcanoes synchronous with the formation of the ophiolite. Subsequent sedimentation of quartzose flysch adjacent to the arc would have covered the fore-arc region, including the BOC ophiolite. Then extension and block-faulting of the fore-arc region (possibly by dominantly strike-slip faulting), olistostromic disruption of the St. Daniel and deposition of it, in part, over degraded fault-scarp generated surfaces in the ophiolite occurred. This was followed by further sedimentation, without disruption, of the Magog flysch over the St. Daniel and the subsequent obduction of the whole package over the Brompton slates.

Finally, the deposition of the Peasley Pond Conglomerate of the Glenbrooke Group occurred in the Silurian (see discussion of fossil control in Chapter one) after the emplacement of both the Chagnon ophiolite and Ascot-Weedon arc, and after a period of erosion. Further, the sediments of this unit were apparently fed along strike and had source terrains both to the northeast and southwest as is evidenced by the presence of chromite grains (Thetford-Chagnon source) and clasts of silicic volcanics (Ascot-Weedon source).

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