Structural Studies in the Mafic and Ultramafic Rocks of the Lewis Hills, Western Newfoundland

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Jeffrey A. Karson
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"Life's rough you got to be tough..."

-Gilbert Hash-

Graffito from Hines Pond Cabin

Frontispiece: The north shore of Hines Pond in the Lewis Hills. The hill on the skyline to the extreme right is the highest point on the Island of Newfoundland (2673 ft.), ten miles to the west.

(photograph by J.K., July 1974)

ACKNOWLEDGEMENTS

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CHAPTER I - INTRODUCTION

A. PURPOSE

The Lewis Hills is the southernmost of a series of three klippen that constitute the Bay of Islands Ophiolite Complex* of western Newfoundland, Canada. These masses are 15 to 25 kilometers across and extend for more than 100 kilometers along the western coast of the Island of Newfoundland from Bluff Head to Bonne Bay (see figure 1). They are composed chiefly of altered mafic and ultramafic rocks and lesser amounts of high grade metamorphic rocks. These klippen are considered to be the dissected remnants of a once continuous high level thrust sheet of oceanic crust and upper mantle (Dewey and Bird, 1971, Church and Stevens, 1971). As such, they must have been formed at an accreting plate margin of some type prior to their tectonic emplacement over an autochthonous Cambro-Ordovician carbonate platform in the lower Middle Ordovician.

Regional geology shows that these klippen lie upon a sequence of allochthonous sedimentary and volcanic assemblages and allochthonous masses of highly deformed metamorphic rocks whose deformation is pre-Ordovician. The zones of deformation, along the basal overthrusts separating these allochthonous masses, are quite narrow suggesting that there was no internal penetrative deformation of the allochthon during their transportation. These observations allow for the intriguing possibility that oceanic crust and upper mantle mineralogy, fabrics, igneous structures and metamorphic relations are preserved, and can be

*"Ophiolite Complex" as used in this thesis refers to a distinctive assemblage of mafic and ultramafic rocks in a definite layered sequence including from structural base to top: ultramafics, gabbros, diabase dyke complex, mafic extrusives and marine sediments (Dewey and Bird, 1971, Church, 1971, Conference participants, 1972).

Fig. 1 Location Map for Western Newfoundland

studied in outcrop. Marine geology and geophysics (e.g., Le Pichon et al., 1958), experimental work (e.g., Fox et al., 1973), and inferences (e.g., Dewey and Bird, 1971) concerning the composition of oceanic crust and processes at accreting plate boundaries have provided many hypotheses to be tested.

Previous workers, prior to 1970, considered the Bay of Islands Complex to be a large stratiform intrusion such as Skaergaard or the Bushveld. Mapping has been done only on a regional scale and most areas have not yet been described beyond the identification of the dominant rock type present. Igneous structures and petrography have been described from various parts of the complex (e.g., Williams and Malpas, 1972), but the development of foliations, lineations, high strain zones and the detailed distribution of rock types has yet to be studied in detail.

The Lewis Hills is the best exposed of the Bay of Islands masses and, therefore, allows the detailed study of its interior. The gabbro-ultramafic 'transition zone' ('critical zone' of Smith, 1958), which represents the oceanic Moho (Dewey and Bird, 1971; Moores, 1970; Church and Stevens, 1971; Coleman, 1971), is particularly well exposed here, especially in the vicinity of Hines Pond. A relatively small area was chosen here for a detailed study of the structure, petrography, and petrofabrics of the banded gabbroic and ultramafic rocks of this zone. This thesis reports the results of this study.

B. PREVIOUS WORK

Field work in the Bay of Islands area has been concentrated near population centers, roads and the shoreline where extensive coastal exposures exist. Mapping has been done only on a regional scale and many inland areas are very poorly known at present due to their inaccessibility. The Lewis Hills is such an area.

Only two previous workers have studied the Lewis Hills. The first of these was J. R. Cooper, who completed his Ph.D. thesis in 1936 on the geology of the southern half of the Bay of Islands area. His work included reconnaissance mapping, descriptions of igneous banding in various outcrop areas, petrography and petrology. Cooper made several important contributions to the understanding of the geology of the Bay of Islands area. He suggested a crystal setting model for the origin of the igneous banding in the plutonic mafic and ultramafic rocks. He was also the first to consider the three plutonic massifs to be dissected remnants of a once continuous body of lopolithic form. Most importantly, he showed that these rocks in the Lewis Hills were in thrust fault contact with the underlying sedimentary rocks, indicating that they had been transported from their site of intrusion.

Cooper's mapping was quite general. He used pace and compass as well as plane table traverses with the aid of British Admiralty Charts. He also used a rough base map made from vertical air photographs at a scale of 1:12,000. He assigned six major divisions to rocks of the Lewis Hills area: 1) gabbro, ultramafic rocks and/or troctolite; 2) serpentinized dunite and peridotite; 3) banded intrusives; 4) gabbroic rocks; 5) volcanic complex; and 6) amphibolite. He made further subdivisions which were referred to in the text of his thesis. Until the present study, this was the most detailed work done in the Lewis Hills.

In 1958, C. H. Smith published a study of the same problems that Cooper had worked on, but included observations on all three of the Bay of Islands masses. His Geological Survey of Canada Memoir included a map of the areas studied at a scale of 1;126,720. He concluded that the igneous rocks of the complex were a huge sill in which the magma was emplaced as a 'crystal mush' formed by gravitational segregation of early-formed crystals. He also proposed a hypothesis involving faulting, glaciation and erosion to produce the present outcrop pattern of plutonic rocks.

The maps of Cooper and Smith are the only ones showing geology in the interior of the Lewis Hills. The southern edge of the mass appears on a map of the Stephenville area by Riley (1962). Williams and Malpas (1972) have described some coastal exposures near Bluff Head (see figure 1).

The ophiolites to the north and the surrounding sediments have been studied much more extensively, but still only on a regional scale. These studies (for example, Stevens, 1965, 1970; Williams, 1970, 1973; Bruckner, 1966) have led to our present understanding of the regional geology (Rodgers and Neale, 1963; Kay, 1969; Bird and Dewey, 1970; Dewey and Bird, 1971) and evolution of the western Newfoundland Appalachians (see Chapter 2).

At present the only other worker who is mapping in the interior of the Lewis Hills is Dr. A. R. Berger of Memorial University of Newfoundland. Dr. Berger is studying structural problems near Carol Mountain in the southern Lewis Hills (see figure 2).

The present study is part of a larger project involving the study of gabbro-ultramafic transition zones throughout the Bay of Islands Ophiolite Complex with Dr. J. F. Dewey of the State University of New York at Albany.

C. FIELD WORK

Field work consisted of 12 weeks of detailed lithologic and structural outcrop mapping. The total area covered was approximately 20 square kilometers (see figure 2 and enclosed maps). Air photographs enlarged to

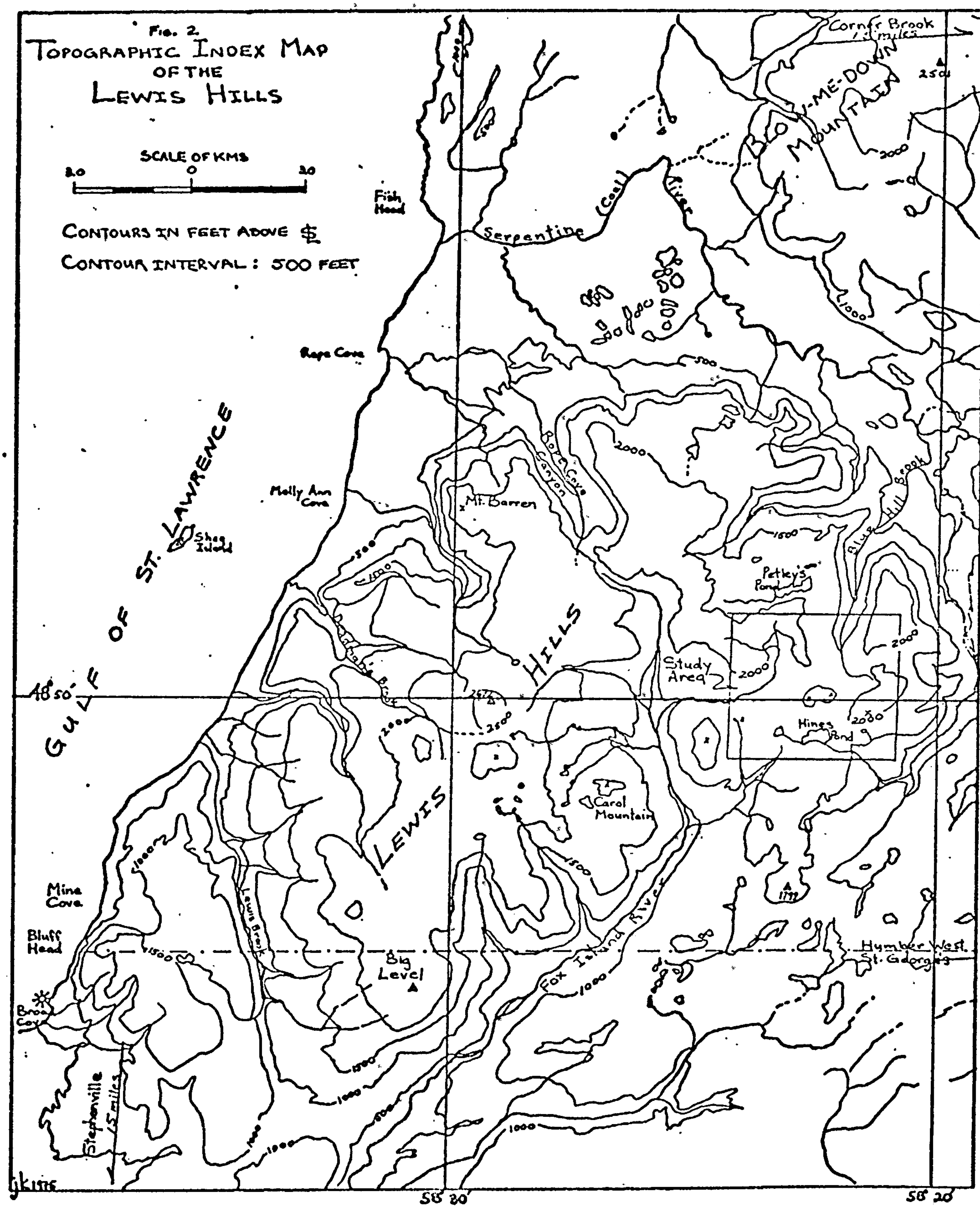


Fig. 2
Topographic Index Map
of the
Lewis Hills
Scale of Kms
Contours in feet above SL
Contour interval: 500 feet
Gulf of St. Lawrence
Lewis Hills
Corner Brook
Blow-Me-Down Mountain
Serpentine (Coal) River
Fish Head
Rope Cove
Molly Ann Cove
Shag Island
Mt. Barren
Study Area
Petley's Pond
Hines Pond
Carol Mountain
Fox Island River
Big Level
Lewis Brook
Mine Cove
Bluff Head
Stephenville
Humber West
St. Georges
48°50'
58°30'
58°20'

a scale of 1:15,000, were used as a base map. Sketch maps at a scale of 1:3,200 were made for most of the areas where gabbroic rocks outcrop.

Mapping was carried out an mylar overlays fixed to each photograph. A large amount of time in the field was devoted to sketching outcrop relations in the banded mafic and ultramafic rocks. Oriented samples were systematically collected across critical zones of layering for later laboratory study.

Field work was carried out from a base camp at Hines Pond. Supplies were brought in by seaplane at approximately 10-day intervals. This was necessary due to the complete lack of roads of any kind within 10 kilometers of the study area. The nearest roads are logging roads which wind for approximately 20 kilometers to paved roads near Corner Brook. A hunters' shack was occupied for most of the field season. This proved to have great advantage over a tent in the hostile climate of the area. Blizzards, torrential rains and thick coastal fog along with continual strong west winds keep the area very damp and hinder field work. This high plateau may be entirely enclosed by dense, low clouds even while the surrounding lowlands enjoy clear, warm weather.

The Lewis Hills have very little vegetation, especially where ultramafic rocks outcrop. Much of the area is a felsenmeer dotted with small ponds and bogs. Steep sided hills and roches moutonnées are mainly of more resistant gabbroic rocks. These provide the best outcrops for structural studies. The rugged relief of the area can be seen in the topographic index map (figure 2).

CHAPTER II - REGIONAL GEOLOGY

In 1966, J. T. Wilson pointed out that the sialic basement ages of the Canadian Shield decreased from province to province away from the Superior Province toward the east (Wilson, 1966). The youngest shield rocks to the east are of Grenville age (1100 my) and are exposed on the Island of Newfoundland in the Long Range and Indian Head Range of the Western Platform (figure 3).

The Avalon Peninsula of southeastern Newfoundland is also made up primarily of Precambrian rocks. Between the Western and Avalon Platforms lies the Central Mobile Belt of lower Paleozoic volcanic, plutonic and metamorphic rocks. Thus, there is a basement age reversal across Newfoundland.

Wilson (1966) suggested that an ocean basin (subsequently dubbed 'Iapetus' by Harland and Gayer, 1974) had opened and subsequently closed between the two old blocks of crust. Later, in the lower Jurassic, the present day central Atlantic Ocean opened to the east of the lower Paleozoic suture zone. The Central Mobile Belt must be regarded as the zone of deformation of two old continental margins and the site of destruction of an ocean basin (Dewey, 1969).

The Central Mobile Belt is made up of two large deformed clastic wedges, marginal to the platforms of the east and west, and masses of metamorphic, plutonic and volcanic rocks. It is cut by several major tectonic discontinuities marked by large fault zones, melange complexes and masses of ultramafic rocks (see figure 3). The complexity of this zone reflects the complex nature of the continental margins which collided here. These probably involved island arcs, remnant arcs and marginal basins (Dewey and Bird, 1971, Church and Stevens, 1971).

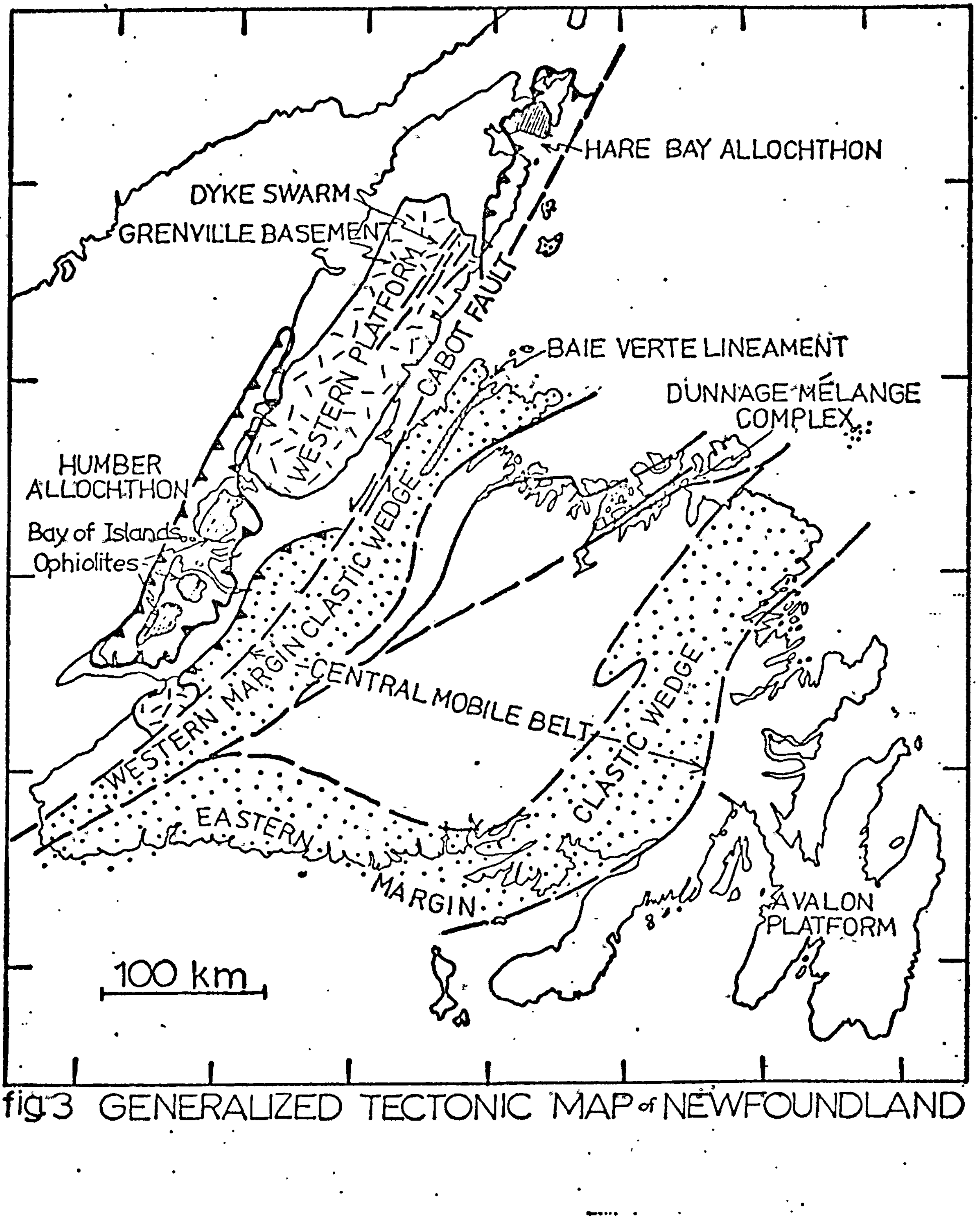


fig 3 GENERALIZED TECTONIC MAP of NEWFOUNDLAND

The Western Platform is better known than other regions of Newfoundland. West of the Cabot Fault (figure 3) an autochthonous carbonate terrane is overlain by huge allochthonous masses of clastic sedimentary rocks which are in turn overlain by allochthonous masses of igneous and metamorphic rocks, including ophiolites.

Earliest workers in the Bay of Islands area explored and described mineral prospects such as asbestos, chromite, and copper (Jukes, 1842; Willis, 1894; Brunton, 1922; Lippincott, 1931). In the period from 1930 to 1960 many workers, such as Snelgrove (1932), Cooper (1936), Buddington and Hess (1937), Ingerson (1935), Troelson (1947) and Smith (1958) worked on the ophiolites of the Bay of Islands. These workers considered the plutonic rocks to be intrusive into, although now mainly faulted against, the clastic sedimentary rocks of the area. Several important problems were recognized by these authors. They included: 1.) the temporal relations of the plutonic and sedimentary rocks; 2.) the origin of banding in the mafic and ultramafic plutonic rocks, and 3.) the origin of the cryptic layering in these bodies.

Meanwhile, workers in the sedimentary rocks had determined that the ophiolites lay structurally above the clastic sediments (Schuchert and Dunbar, 1934) and that these clastic sediments were allochthonous (Johnston, 1941; Kay, 1945). The available evidence for the allochthonous hypothesis was synthesized and interpreted by Rodgers and Neale (1963). At this time the ophiolites were believed to have been intruded into the clastic sediments before the westward transportation of that clastic terrane.

Subsequent work showed that the ophiolites formed a discrete allochthonous slice. They were then suggested to have been formed outside of the clastic terrane (Stevens, 1970). The thin basal contact metamorphic aureole, which had suggested an intrusive origin for these rocks, was found to be an integral part of the ophiolite allochthon (Williams, 1970).

This series of discoveries cleared the way for the interpretation of the Bay of Islands Ophiolite Complex as a slice of old oceanic crust and upper mantle (Moores, 1970; Stevens, 1970; Church and Stevens, 1970, 1971; Dewey and Bird, 1971). Ophiolites were first suggested to be remnants of ocean floor by de Roever (1955), Dietz (1963), and Gass (1967).

Continued mapping and other studies in the Bay of Islands area has resulted in the following regional geologic setting of the Western Platform (figure 4).

The oldest rocks in the area are the Precambrian gneiss complexes of exposed in the Indian Head and Long Ranges. These are cut by mafic dykes which trend northeast. Above a Lower Cambrian unconformity, westerly derived clastic sediments of the Bateau Formation are also cut by these dykes. These terminate in the Lighthouse Cove volcanics which are probably Lower Cambrian in age. Lower to Middle Cambrian dominantly clastic sediments with a westerly provenance overlie these. They include the Kippens and March Point Formations of the Port au Port Peninsula. These pass upward into conformably overlying carbonates of Upper Cambrian to Middle Ordovician age. These include the Petit Jardin, St. George and Table Head limestones. The last two of these are separated by a slight unconformity. A time transgressive shale and flysch facies covers this carbonate sequence. The deposition of these clastics marks a major sedimentary polarity reversal as these show an easterly provenance. This is the stratigraphically highest autochthonous unit. All structurally higher sediments are allochthonous, until the Upper Ordovician. The

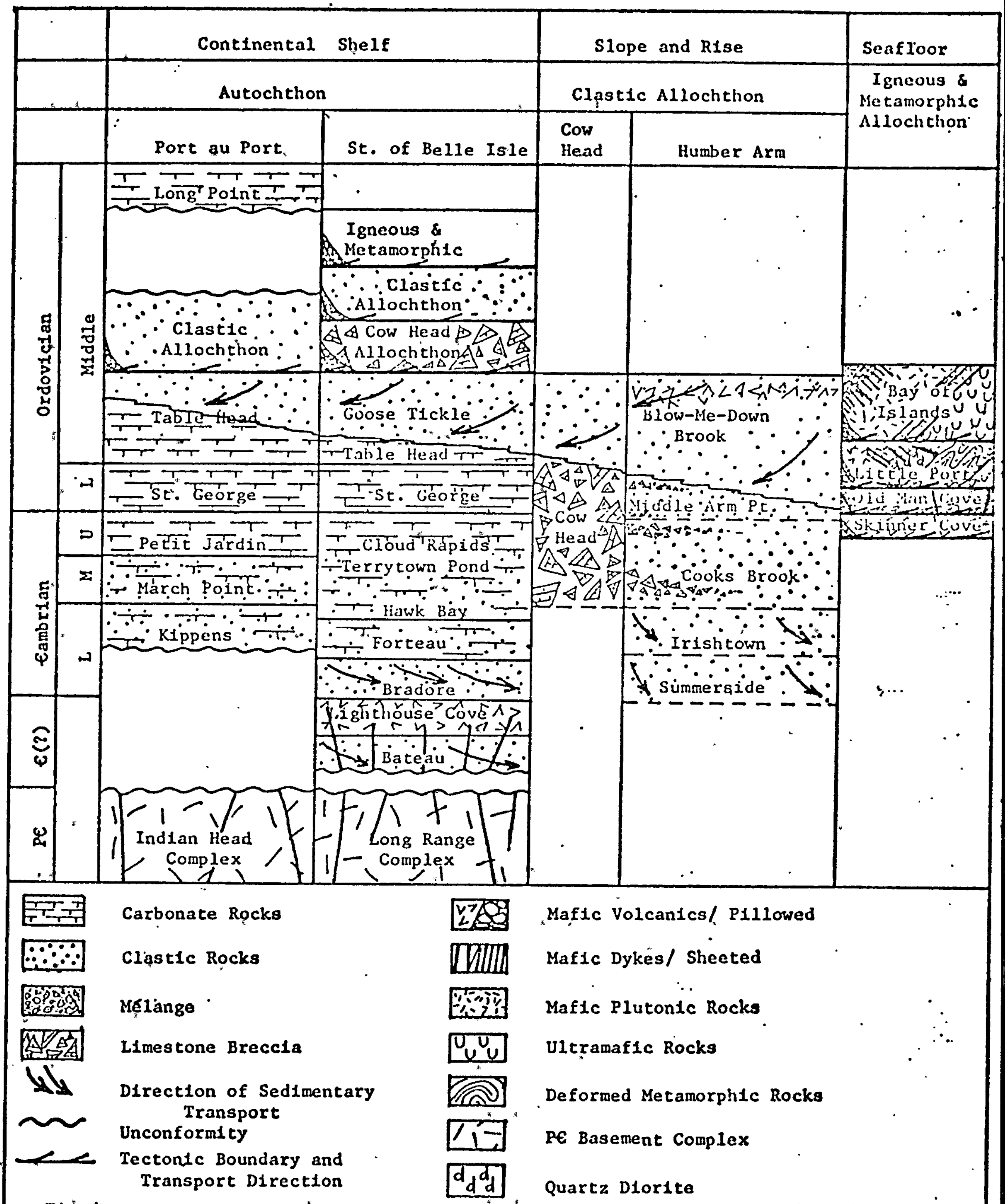


Fig.4 RESTORED STRATIGRAPHIC RELATIONSHIPS OF FACIES BELTS IN W. NEWFOUNDLAND

(after Williams, 1971)

jk 1175

allochthons have been transported from the east of the carbonate autochthon and are interpreted as the time synchronous distal facies of the autochthon (Stevens, 1970). The allochthonous slices are enclosed in easterly derived flysch of the Blow-me-down Brook formation (Stevens, 1970). These include ophiolite debris, implying that the ophiolites were structurally high enough by the Middle Ordovician to be a source terrane for these clastics. Graptolites in melange units marking the fronts of thrust slices indicate that these rocks were transported during the Middle Ordovician.

The structurally lowest allochthonous slice is the Cow Head Allochthon. This is composed the Middle Cambrian to Middle Ordovician Cow Head Breccia and overlying graywackes. These rocks are mainly very coarse carbonate breccias and shales. They are interpreted as a proximal off-shelf deposits formed near and just beyond the edge of the carbonate platform (Bird and Dewey, 1970).

This mass is overlain by a huge allochthonous mass of clastic sediments whose clastic components were derived mainly from the west. These transported clastic rocks are known as the Humber Arm Supergroup (Stevens, 1970). These consist of a conformable sequence of flyschoid sediments of Lower Cambrian to Middle Ordovician age. The lowest part of this section includes mainly westerly derived clastic sediments of the Summerside and Irishtown Formations. These are mainly shale, siltstone, and greywacke. They pass upward into Cooks Brook and Middle Arm Point shales, calcareous flysch and minor fine grained carbonate breccias. These are Middle Cambrian to Middle Ordovician in age and are overlain by Middle Ordovician easterly derived greywackes, shales and arkosic sandstones which locally contain a small amount of mafic agglomerate. These constitute the

the Blow-me-down Brook Formation. These rocks are overlain by a complex series of allochthonous igneous and metamorphic rocks.

These structurally higher allochthons of the Bay of Islands area consist of several thrust slices composed of four distinct lithologic assemblages. These are the Skinner Cove, Old Man Cove, Little Port and Bay of Islands Slice assemblages from structurally lowest to highest respectively.

The Skinner Cove rocks are largely unaltered mafic alkalic pillow lavas and interbedded argillites containing Tremadocian fossils (Strong, 1973). These are the freshest volcanics in the Bay of Islands area.

Skinner Cove rocks locally overlie the Old Man Cove slice. This unit is composed of 'polydeformed' greenschists and amphibolites cut by mafic dykes post-dating the penetrative deformation.

The Little Port assemblage structurally overlies the Old Man Cove or lower slices. It is a complex assemblage consisting mainly of highly deformed gabbros with multiple foliations intruded prior to deformation by large bodies of variably foliated coarse grained leucocratic quartz diorite. Minor amounts of ultramafic rocks are also known. All of these are cut by post-kinematic mafic dykes often brecciated and locally sheeted (Williams and Malpas, 1972). Mafic pillow lavas and agglomerate have also been mapped as part of this slice and are considered to be related to the dyke rocks (Williams, 1973). Mattinson (1975) has published a zircon radiometric age for a quartz diorite body in the Little Port Slice at Trout River. This yielded a date of 508±5 my (about Tremadocian) which is older than much of the clastic sedimentary allochthons that it overlies.

By extension of the thrust fault beneath the Bay of Islands Slice the latter may be inferred to have originally overlain the Little Port Slice, It does not now actually overlie this assemblage anywhere. The Bay of Islands Slice has an unusually well exposed, complete ophiolite 'stratigraphy.' From the base to the top this includes the following units (descriptions are based on Williams, 1973; Dewey, 1975 and the present author's personal observations): A narrow (100 to 300 meters) contact metamorphic aureole of garnetiferous amphibolites and clinopyroxene amphibolites nearest the base of the ophiolite grading downward into dark green phyllites. The metamorphic grade, therefore, is highest adjacent to the ophiolite and decreases rapidly downward away from it. These rocks are locally altered by intense calcium metasomatism. The ultramafics adjacent to these metamorphic rocks have a narrow zone, several meters wide, of 'ultramafic mylonites' which grade into a zone of layered harzburgite and dunite tectonites. This zone is usually 3 to 4 kilometers thick, but up to 7 kilometers thick in Table Mountain. Lherzolites and rarely ariegites occur at the base of this sequence and are apparently associated with the basal metamorphic aureole and high strain zone. This passes upward into a 1 kilometer thick interbanded ultramafic and gabbroic zone. This is known as the 'transition zone.' Rocks of these zones are rich in clinopyroxene and have dominantly tectonite fabrics but cumulate textures are also reported. These grade upward into a 3 to 4 kilometer thick mass of gabbros which show layering, probably of cumulate origin, near the base and variable alteration and very low greenschist facies metamorphism. Minor bodies of hornblende gabbro and quartz diorite are found in the upper part of the gabbro unit. A few diabase dykes are also present here. They increase upward to form a layer of 100% ('sheeted') dykes. These have variable alteration and low greenschist facies metamorphism and are sometimes brecciated. Some of these extend into the overlying altered mafic pillow lavas. These form a layer approximately 1 kilometer thick and are overlain by a thinner layer of volcanogenic clastic sediments.

The age of formation of the Bay of Islands Ophiolite Complex is uncertain, but the age of tectonic emplacement is fairly well known. Llanvirnian to Caradocian graptolites have been found in the shaley matrix of melange units at the front of the ophiolite slice. Also, recent $^{40}Ar/^{39}Ar$ release spectra work on amphiboles in the basal contact aureole of the ophiolite gives a date of 460±5 my for their obduction (Dallmeyer, 1975). The restricted narrow zone of deformation at the basal thrust contact shows that the rest of the ophiolite complex was not penetratively deformed during their obduction and transportation.

The allochthonous sedimentary rocks are unconformably overlain by neoautochthonous upper Middle Ordovician nodular limestones and green shales of the Long Point Formation (Bird and Dewey, 1970). Red and green shales and sandstones of the Clam Bank Formation of Lower Devonian age are homoclinally tilted reflecting the gentle deformation of the Acadian event in western Newfoundland.

In summary the Bay of Islands Ophiolite Complex is a dissected allochthonous mass of plutonic and extrusive rocks with metamorphic and deformation features predating its Arenigian obduction. This was the first slice of the western Newfoundland allochthon to move. The allochthon grew with each slice overriding the one beneath it until the whole assemblage was transported over the autochthon. Each slice in the lower allochthon has traveled further, relative to the autochthon, than the slice below it, so that the already assembled allochthon was emplaced as a single mass (Stevens, 1970; Dewey, 1975). Thus, the ophiolite complexes traveled the farthest with respect to the allochthon, but need only have moved its own width relative to the slice underlying it. There is a definite stacking order of slices in the allochthon and there are no known reversals of this order (Williams, 1973). Neither the obduction nor the later Acadian event produced internal penetrative deformation of the ophiolite complex. This means that igneous, metamorphic, and structural relations in the ophiolite complex must reflect the conditions at their point of formation. The current working hypothesis for this point of formation is an accreting plate margin.

CHAPTER III - THE LEWIS HILLS COMPARED TO THE NORTHERN AREAS OF THE BAY OF ISLANDS OPHIOLITE COMPLEX

The Bay of Islands Ophiolite Complex consists of three flat topped massifs located along the western coast of Newfoundland (figures 1 and 2). These rugged windswept plateaux are apparently the dissected remnants of a once continuous allochthonous mass. They have an average elevation of approximately 2,000 feet and stand high above the surrounding coastal lowlands which are mainly underlain by clastic allochthonous sediments of the Humber Arm Supergroup (Williams, 1973).

Wide outcrop areas make the Bay of Islands Complex one of the world's best exposed, complete ophiolite suites. It includes the layered sequence mentioned above and overlies weakly deformed, virtually unmetamorphosed sediments across a narrow overthrust fault zone.

The complete ophiolite 'stratigraphy' is developed only in the Blow-me-down Mountain and North Arm Mountain areas. The Table Mountain area to the north has no dykes or higher units and the Lewis Hills seem to lack the main gabbro and all higher units. The layered sequence faces westward and is illustrated in figure 6.

Besides lacking most of the upper units of the ophiolite stratigraphy, the Lewis Hills differs significantly in other respects from the massifs to the north.

The Lewis Hills has large exposures of metamorphic rocks that are not found elsewhere in the Bay of Islands Ophiolite Complex. In the western areas and to the south of Hines Pond, amphibolites and metagabbros have been mapped by both previous workers. Those south of Hines Pond have been considered to be part of the basal contact metamorphic aureole exposed by low dips in this area. Those of the west, including the Mount

Barren Gneisses, are of unknown origin and only briefly described at present.

The trend of the narrow 'transition' zone between the ultramafic and gabbroic rocks of the massifs north of the Lewis Hills is quite regular and curves smoothly with an overall northeast trend. In the Lewis Hills, however, layered ultramafic and gabbroic rocks occur as apparent inclusions with irregular outlines within a very thick (5 kilometer) layer of massive dunite. Attitudes of foliations including large scale layering are also irregular here in contrast to the other massifs. Large areas in the Lewis Hills have foliations with north-south or northwest trend. Williams and Malpas (1972) noted dykes with northwest trends in coastal exposures near Bluff Head. They suggest that the Lewis Hills have been rotated 90^{o} with respect to the rest of the Bay of Islands Ophiolite Complex.

The present study focuses on the gabbro-ultramafic transition zones exposed near Hines Pond in the eastern Lewis Hills. The area mapped also includes a portion of the anomalously wide metamorphic aureole to the south (figure 5).

The Lewis Hills has an average elevation of approximately 2,000 feet and up to 800 feet of relief. The terrane rises to the west to an elevation of 2,673 feet, the highest point on the Island of Newfoundland. Barren areas of ultramafic rocks surround dark steep-sided hills of gabbroic rocks. This rugged plateau has a steep marginal escarpment cut by steep-sided stream valleys. The surrounding areas are covered by a dense pine forest with numerous lakes, swamps, and meandering streams.

The Hines Pond area is situated on the edge of the marginal escarpment. It is very well exposed except for the areas of metamorphic rocks,

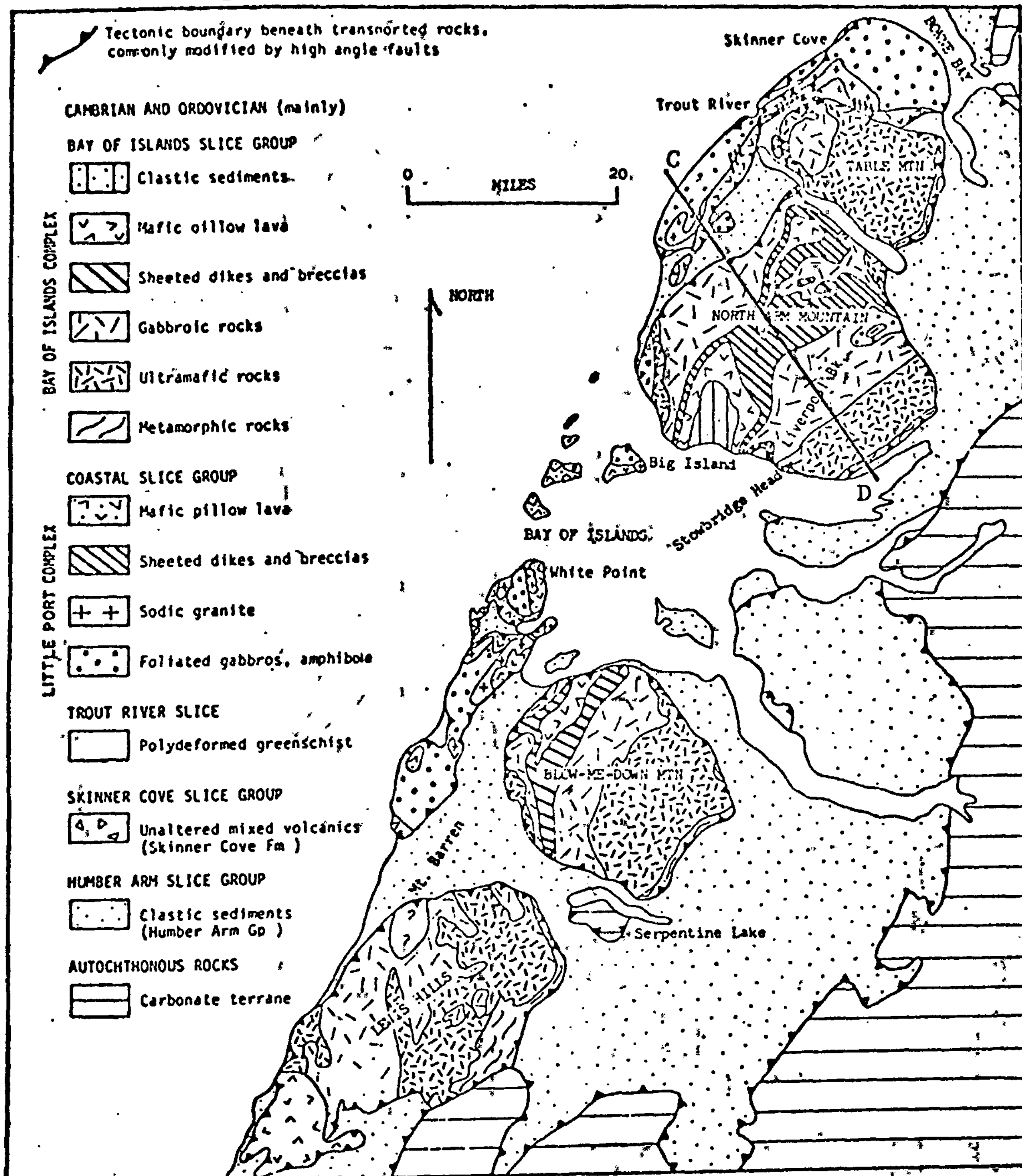
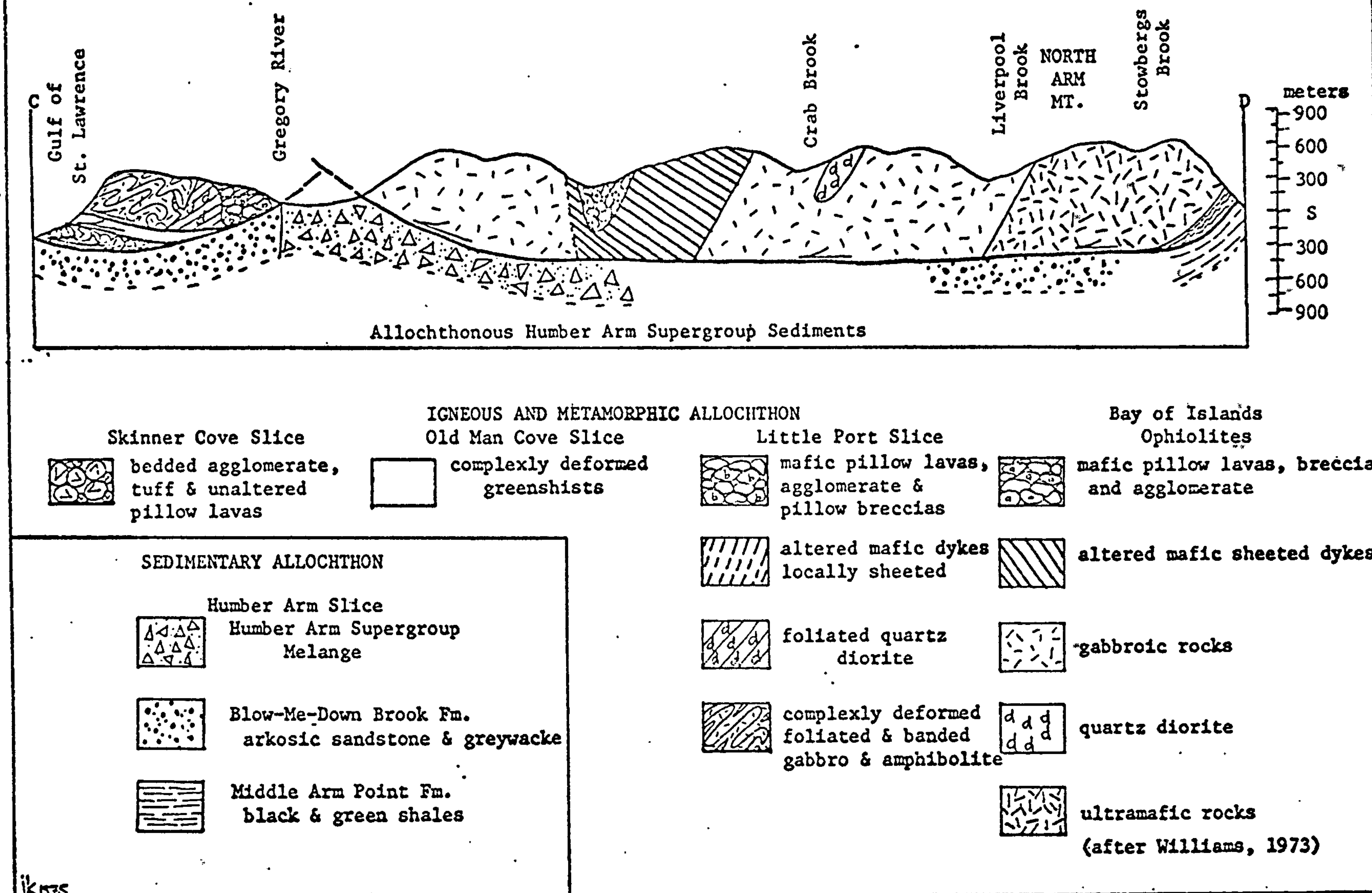


Fig. 5 General Geology of the Bay of Islands Area (from Williams and Malpas, 1972)

Fig. 6 Cross Section of North Arm Mt.
(after Williams, 1973)



where low shrubs and stunted pine trees make travel on foot very difficult. The gross lithologies are easily mapped but details of igneous banding are difficult to follow in the discontinuous outcrops. These are separated by gravel and displaced boulders formed by spheroidal weathering and frost action along joints. There seems to be very little transport of the mechanically broken-down material. Thus, the outcrops seem to be disintegrating in situ.

CHAPTER IV

PETROGRAPHY

A. INTRODUCTION

A wide variety of rock types and fabrics exist in the Hine's Pond area. They include the following groups to be discussed separately below:

1. High to low grade metabasites and metasomatites of the basal contact metamorphic aureole.

2. Strongly recrystallized gneissic amphibolites of the Hine's Pond Metagabbros.

3. Intensely deformed, recrystallized, and serpentinized ultramafic metamorphic tectonites*.

4. Moderately to intensely deformed and recrystallized gabbro to ultramafic rocks of the layered megalenses with some relict igneous texture.

5. Local, zones of anomalous high strain.

The petrography of these rocks is summarized in the form of tables that accompany the following discussion of textures and fabrics observed in thin section.

B. ROCKS OF THE BASAL CONTACT AUREOLE

Calcium-metasomatites of this zone are gneissic rocks with up to 100% veins of medium to coarse grained calc-silicate minerals including zoisite, clinozoisite, epidote, and prehnite. These have equigranular

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*Tectonites are any rocks whose fabric reflects the history of its deformation and clearly displays coordinated geometric features that indicate continuous solid flow during deformation (Turner and Weiss, 1963).

to bladed, acicular textures with sutured grain boundaries (Table I).

Gneissic Pyroxene Amphibolites are composed of coarse aggregates of intensely altered plagioclase, well recrystallized green hornblende and bright green diopsidic augite. These are cut by veins of variable number and width. Pyroxenes have blastoophitic textures. They enclose tiny plagioclase laths. Both pyroxenes and amphiboles in these rocks have strong dimensional preferred orientations.

Garnet amphibolites show conspicuous new layering defined by thin layers of opaques, green hornblende and poikiloblastic garnets. These cut an earlier layering defined by sodic-plagioclase and olive-brown hornblende-rich layers with ragged grain boundaries. The new layering seems to be localized in zones of high strain. Amphiboles of both layerings have strong dimensional and probably lattice preferred orientations.

Finer grained amphibolite grades into dark green phyllites. These are composed of fine grained aggregates of sodic-plagioclase, fine grained pale green hornblende and chlorite. Hornblendes in these rocks have straight grain boundaries.

All of the basal metamophic aureole rocks have weak microscopic compositional layering (S_1) and coplanar dimensional preferred orientation (S_d) of amphiboles. Plagioclase in all of these rocks is altered to fine-grained semi-opaque light brown to grey material. Calc-silicate metasomatic veins decrease rapidly with metamorphic grade.

These rocks reflect a complex history of deformation and recrystallization, including the development of secondary layerings. These may be widespread but unrecognized due to unclear earlier layering.

The older layering observed represents a higher grade metamorphic event in the history of the rocks. Preliminary petrofabric studies of these rocks indicate similar relations (Smyth and Williams, 1973).

TABLE I Petrography of Basal Metamorphic Aureole Rocks

Minerals / Rock Types	Amphiboles: Tremolite -Actinolite	Amphiboles: Green Hornblende	Amphiboles: Brown Hornblende	Clinopyroxene	Plagioclase	Calc-silicates	Others Present
Calcium-Metasomatite				trace	trace altered	90% Zoisite, Clinozoisite and Epidote Med-Crs-Grained	
Gneissic-Amphibolite	10% fine-grained	30% med-grained	trace		40% strongly altered	10-70% (veins)	prehnite
Clinopyroxene-Amphibolite	10% rim Cpx grains (needles)	30-40% med-grained	trace	5-20% Crs-Med-grained Diopsidic	40% altered	fine-grained veins	
Garnet-Amphibolite		5-10%	40% Med-Crs-grained	10% Med-grained	20% altered An_{20}	10-20%	10% pink garnet with opaque inclusions med-grained
Green Phyllite to Amphibolite	60% fine-grained				20% slightly altered An_{20}	10% Epidote+ Prehnite med-fine grained	minor quartz-carbonate laminae Chlorite to 20%

C. ULTRAMAFIC METAMORPHIC TECTONITES

These rocks are coarse grained aggregates of forsteritic olivine, enstatite and lesser clinopyroxene and chromite. They have been strongly deformed and show the effects of recovery and primary recrystallization. They are strongly serpentinized but due to the distinctive styles of serpentine psuedomorphs of olivine (mesh serpentine) and orthopyroxene (bastite) compositions can be estimated and fabrics can be observed. Clinopyroxene and chromite are not strongly altered (Table II)(Fig. 7).

Olivine grains are often coarse and poikiloblastic, enclosing euhedral chromites. Otherwise they are in the form of granuloblastic aggregates with strong dimensional preferred orientation. Large grains are strongly kinked and are preferentially recrystallized along kink-band boundaries and grain boundaries.

Orthopyroxenes may be greatly deformed. They are typically kinked and polygonized to give strong dimensional preferred orientation. Large xenomorphic grains enclose small grains of chromite. Orthopryoxene is not as strongly recrystallized as the olivines in the same rock.

Clinopyroxenes are rarely zoned and usually greatly deformed. They show preferential primary recrystallization in zones of high lattice strain and are coplanar with the olivine and orthopyroxene grain shape foliation. Large xenomorphic chromites have cuspate forms and rarely enclose tiny serpentine psuedomorphs. Small chromites seem to concentrate along zones of high strain.

D. MEGALENS ROCKS

Megalenses of layered gabbro and ultramafic rocks near Hine's Pond in the Lewis Hills include a wide variety of rock types. These are mainly olivine-rich gabbro, clinopyroxene-rich ultramafics and monomineralic rocks (Fig. 8). Most of these rocks are metamorphic tectonites reflecting

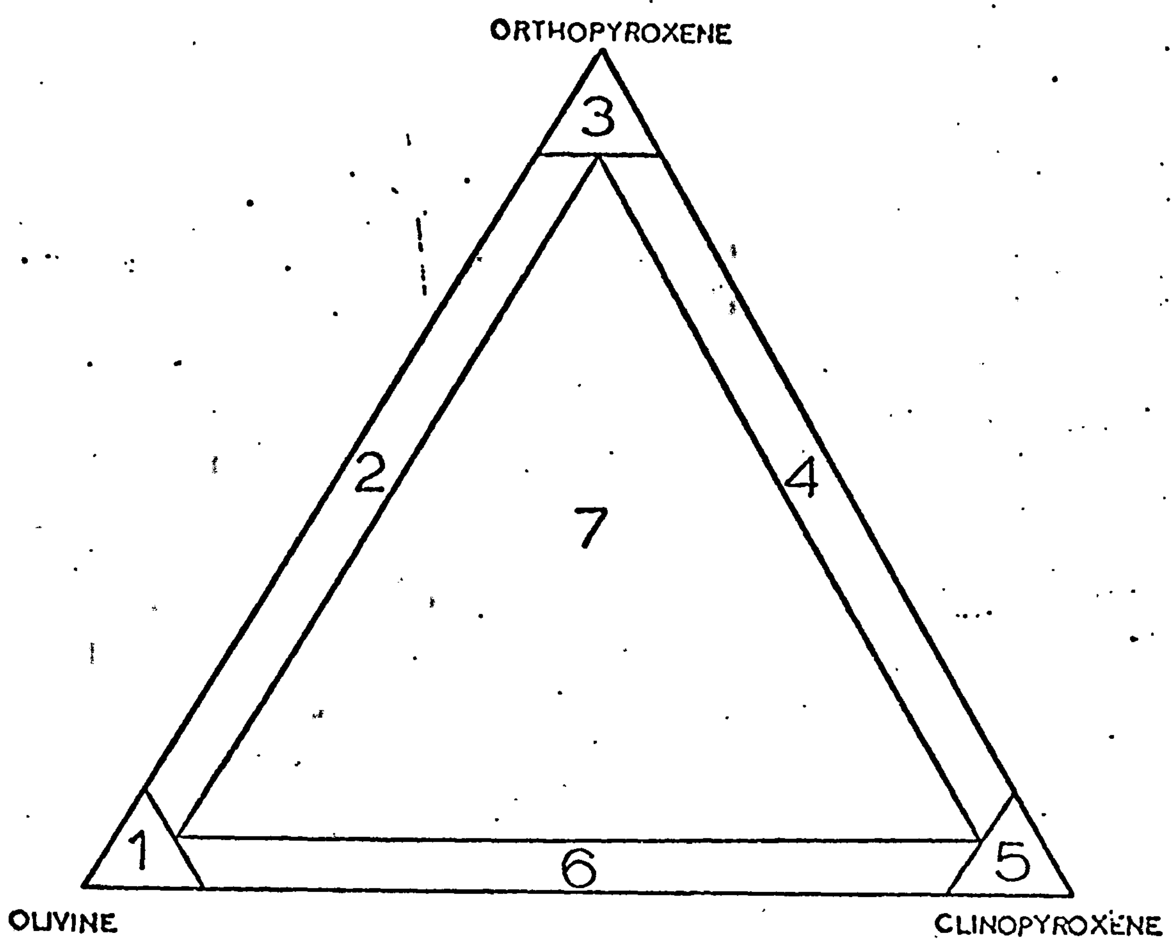

Fig. 7 Ultramafic Rocks of the Lewis Hills
(after Smith, 1958)

1. Dunite
2. Harzburgite
3. Othopyroxenite (Enstatolite or Hypersthenite)
4. Websterite
5. Clinopyroxenite
6. Wehrlite
7. Peridotite

TABLE II Petrography of Ultramafic Metamorphic Tectonites

Minerals	Olivine	Orthopyroxene	Clinopyroxene	Chromite	Serpentintes		Others Present
					Mesh	Bastite	
Rock Types							
Harzburgites	10-70% $Fo_{>88}$	15-60% Enstatite Crs-grained (altered)	5% Augite Crs-grained	10% fine-grains	up to 50%	up to 50%	
Orthopyroxenite	10% $Fo_{>88}$ Med-grain	90% Enstatite Crs-Med-grained	trace	5% fine-grains	up to 10%	up to 50%	some chlorite trace talc
Dunites	90% Med-Crs grained (relicts)	trace		trace (seams)	up to 90%	up to 5%	

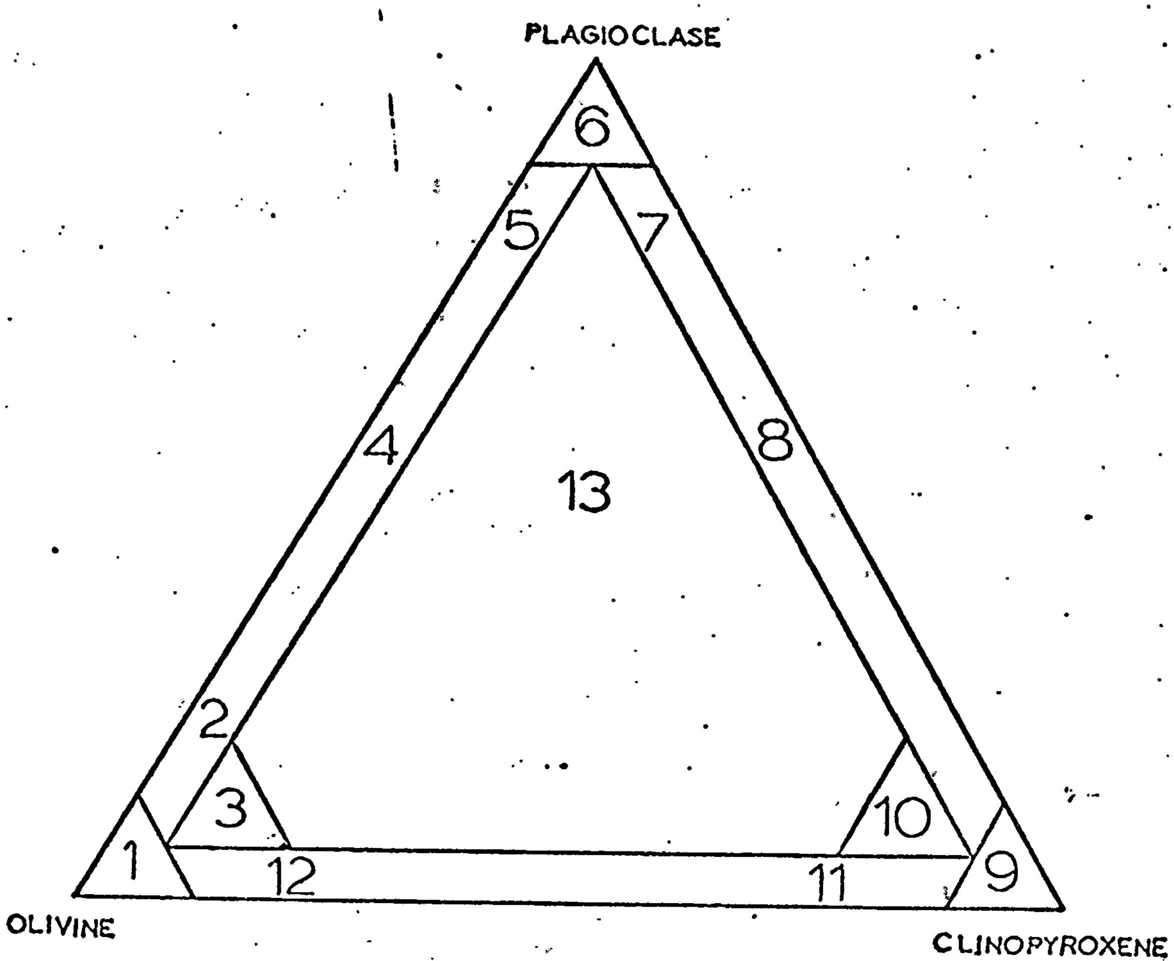

Fig. 8 Interbanded Rocks of the Lewis Hills
(after Smith, 1958)

1. Dunite
2. Feldspathic Dunite
3. Feldspathic Wehrlite
4. Troctolite
5. Anorthositic Troctolite
6. Anorthosite
7. Anorthositic Gabbro
8. Gabbro
9. Clinopyroxenite
10. Feldspathic Clinopyroxenite
11. Olivine Clinopyroxenite
12. Wehrlite
13. Olivine Gabbro

a complex history deformation recovery and recrystallization. Igneous textures are not widely preserved in the megalenses due to these processes.

Though silicates have apparently been widely recrystallized, chromitite is only slightly granulated. These rocks show cumulate textures in thin section (Fig.9). This includes size grade layering. Post-cumulus phases in these rocks are highly serpentinized. Other rocks in the megalenses are composed of nearly monomineralic aggregates whose shapes also suggest cumulate textures. This is best displayed in rocks with a single cumulus phase. Anorthositic troctotites have plagioclase psuedomorphs forming a framework for very irregular, cuspate aggregates of granoblastic olivine that might be recrystallized post-cumulus material. Coarse blastopoikilitic clinopyroxene that encloses rounded olivine and/or plagioclase are probably also igneous textures (Fig. 11).

Rocks of the megalenses typically have bimodal or multimodal grain size distributions. These reflect multiple generations of new grain growth or in some cases cataclasis along grain boundaries. Foliated aggregates of fine-grained granoblastic material is locally overgrown by coarser granoblastic material. If multiple episodes of deformation and recrystallization such as this have occurred throughout the megalenses it is possible that the earliest penetrative fabric seen there is a secondary one.

To further complicate the fabrics most of the rocks of the megalenses are strongly altered. Plagioclase is rarely seen due to its widespread replacement by brown to grey, fine grained, semi-opaque material. These form good psuedomorphs making the plagioclase shape and distribution possible to determine. Olivine and orthopyroxene are variably serpentinized and clinopyroxene is usually rimmed by uralite. Deep brown hornblende alters to chlorite and anhedral opaques (Table III).

TABLE III Petrography of Megalens Rocks

Minerals / Rock Types	Plagioclase	Clinopyroxene	Orthopyroxene	Olivine	Chromite	Brown Hornblende	Tremolite	Calc-Silicates	Serpentine
Wehrlite	trace	40-60% very coarse-grained	5-7% Crs-grained Enstatite	20-30% Crs Fo>88	up to 5% Fine	trace partial rims on Cpx	trace		35% mesh
(Anorthositic-) Troctolite	25-85% Crs-grained An 75	10% Med-grained Augite	5% Med-grained Enstatite	40% Med Fo<88	2% Fine	trace		70% alteration of plagioclase	5-10%
Olivine Gabbro	50-85% Crs-grained An_{65-80}	35-40% Med-crs-grained	5% Med-grained Hypersthene	15-20% Med Fo~88	trace	trace	trace	60%+	5% mesh
Gabbro	50% altered	35% Med-grained	5% Med-grained Enstatite	trace	2% Fine		2%		5% bastite
Hornblende-Gabbro	50-80% Med-grained An_{50-80} altered	10-25% Crs-grained Augite	5% Med-grained Hypersthene	5% Med Fo<88	3% Fine	20% thick rims on Cpx Kaersutite?	3%	70%+ alteration of Plagioclase, veins	trace
Hornblende-bearing Troctolite	10% fine-grained An_{50-60} altered	5-30% Med-grained Titan-Augite	trace	10-30% Crs Fo<88	3% Fine	10% Med-grained Kaersutite?	5%		5%
Feldspathic Wehrlite to Plagioclase-Lherzolite	5-15% Crs-med-grained An_{80} altered	20-35% Very crs-crs-grained	10-15% V. crs-grained Enstatite	30-40% Crs Fo>88 (fresh)	up to 5% Fine-med	trace	up to 10%	60%+	trace
High Strain Facies	trace altered	20-40% Fine-crs grained	trace	20% Med				10% of rock	15%

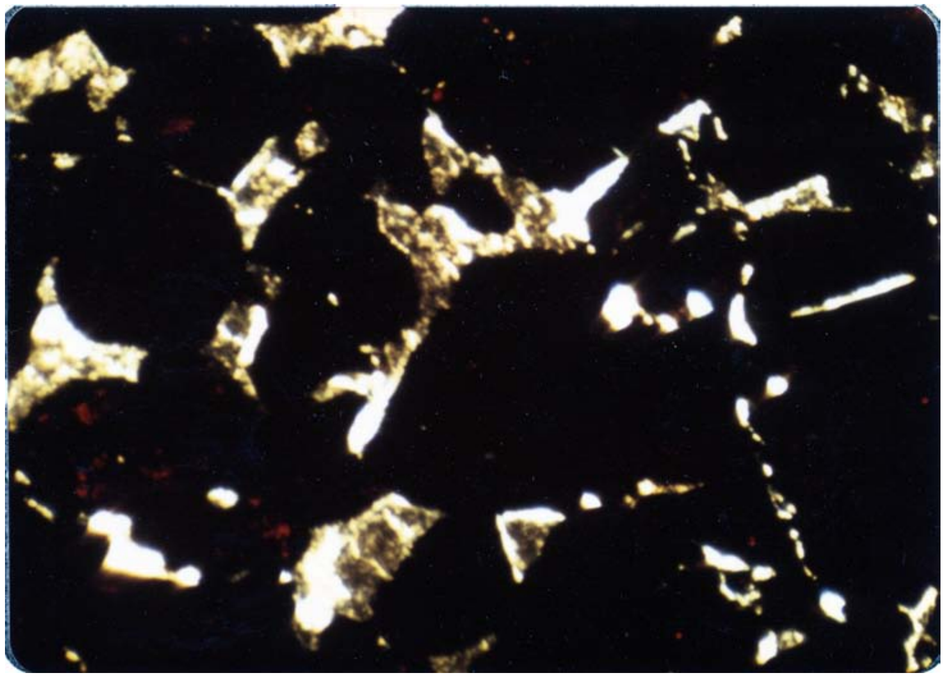

Figure 9: Chromitite cumulate with serpentinized post-cumulus phases (chromite has skeletal magnetite).
(All photomicrographs are 57x; long dimension of photo is 2.2 mm.)

Figure 10: Coarse clinopyroxenite with straight, serrated grain boundaries and slight undulose extinction.

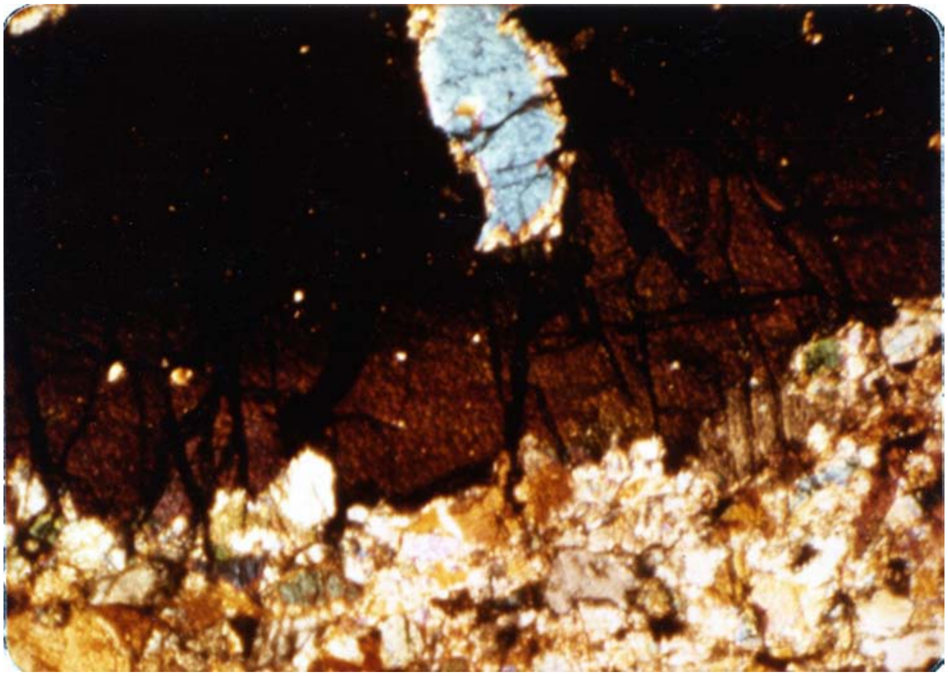

Figure 11: Large, kinked clinopyroxene with granoblastic grain boundary growth encloses olivine in olivine gabbro from a layered megalens.

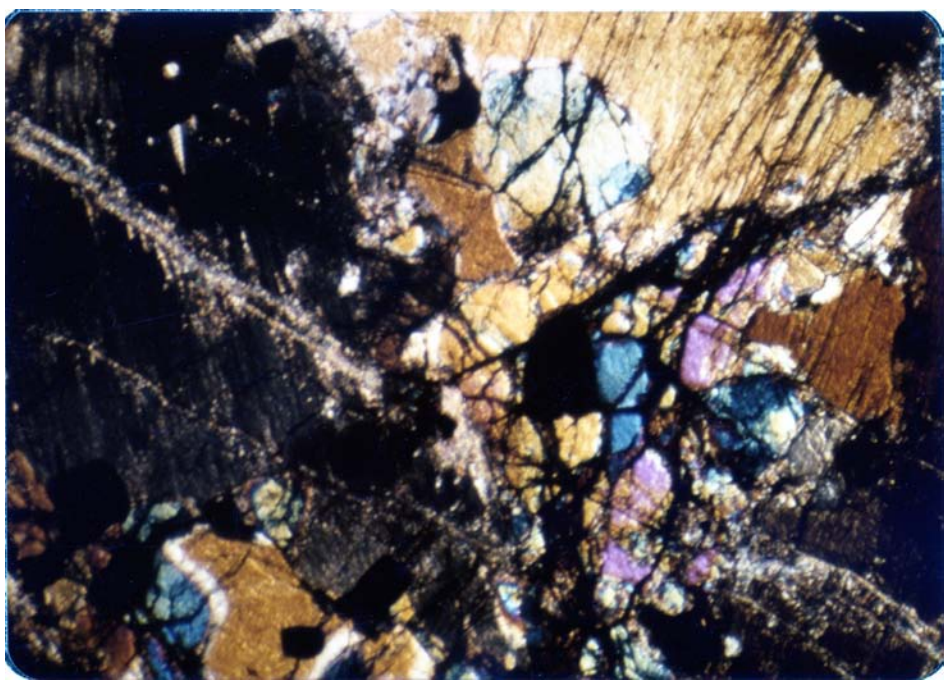

Figure 12: Large, poikilitic and interstitial brown hornblende encloses olivine and chromite. Large, kinked grain near extinction is augite. Note: serpentine vein cuts all grains.

Coarse olivine grains are not common. Where they are observed they are strongly kinked and can be seen to be changed progressively to granuloblastic aggregates which mimic the shape of the coarser olivine grain from which they were derived. These aggregates have strong dimensional preferred orientation.

Plagioclase domains' subfabric is rarely visible due to the alteration. Where seen it is granuloblastic. Coarse grains commonly show brittle fractures.

Clinopyroxenes have a wide range of sizes in single rocks due to multiple generations of new grain growth existing at the same time. Granoblastic aggregates replace coarse, kinked grains. Grain boundaries and kink-bands are the first regions to show signs of grain growth. Clinopyroxenes also show orthopyroxene exsolution lamellae parallel to (100), rare twins, and zoning.

Orthpyroxenes tend to show recovery but not recrystallization effects to the extent of other silicates. They commonly have (100) clinopyroxene exsolution lamellae.

These minerals make up the rocks of the megalenses by combination in different proportions (Fig. 8). The most common rock types are mentioned briefly below.

1. Wehrlites are the most common rocks of the megalenses. They have coarse strongly deformed pyroxenes and rather fresh olivine.

2. Troctolites and anorthositic rocks (leucogabbros) are strongly altered but psuedomorphs suggest cumulate textures. These form intrusive bodies within the megalenses. These may be cumulate layered sills or crystal mush intrusions.

3. Olivine gabbros are medium-grained and often anorthositic (Fig. 11). Locally red-brown hornblende (Kaersutite?)-bearing olivine gabbros form

dikes intruding ultramafic tectonites. They are strongly uralitized and have titanaugite and olivine subhedral phases enclosed by the interstitial amphibole (Fig.12). These usually have strong shape orientation fabrics.

4. Normal gabbros are rare. They form small dikes and sills and are relatively fresh. They have strong dimensional preferred orientation of inequant grains.

5. Hornblende gabbros (melagabbros) have little if any shape oriented fabric. They form bodies which intrude the layered ultramafic rocks. Hornblende is deep red-brown in these rocks also. It forms partial rims on clinopyroxenes. Some of these may have cumulate textures.

6. Coarse-grained feldspathic wehrlites to plagioclase lherzolites form small late, dikes and sills. These are typically strongly altered and recrystallized.

E. HIGH STRAIN FACIES

Locally megalens rocks are intensely deformed. Clinopyroxene and olivine augen and lensoid domains of variably recrystallized materials are surrounded by very fine grained (recrystallized or granulated?) material (Fig.13). Lensoid domains are of the following types: 1. coarse, bent, kinked large grains; 2. medium to fine grained material with granoblastic to mosaic texture; 3. greatly elongated, polygonized single pyroxene grains; and 4. fine grained (granulated or recrystallized?) material.

Material in these rocks tends to be alteration products of the normal mineralogy.

F. HINES POND METAGABBROS

These rocks are well recrystallized gneissic amphibolites with granoblastic textures. Aggregates of medium to coarse-grained altered

Figure 13: High strain facies feldspathic wehrlite. Large clinopyroxene augen in fine-grained granoblastic plagioclase + olivine + pyroxene aggregate. Augen are strongly kinked and have new grain growth along grain boundaries and kink-band boundaries.

TABLE IV Petrography of Hine's Pond Metagabbros

Minerals	Amphiboles				Clinopyroxene	Plagioclase	Calc-Silicates	Others
	Tremolite -Actinolite	Green Hornblende	Brown Hornblende	Orthorhombic				
Rock Types								
Gneissic-Amphibolites	10% rims Cpx	50-40% Med-grained		10% Cummingtonite	5% Med-grained	40-50% Med-grained An_{23} strongly altered	veins of fine-grained material	trace opaques
Hornblendites		95% Med-grained			trace	trace		trace opaques
Green Amphibolites	5%	65% blue-green fine-grained				20% strongly altered	10% fine-grained	very thin quartz-carbonate layers
Rodingite					30% Med-grained		50% very fine grained	trace opaques 10% hydrogarnet fine-grained

plagioclase, olive-green hornblende, clinopyroxenes, other amphiboles, and rarely olivine have strong dimensional preferred orientations. Diffuse layering complanar with these aggregates are defined by alternating plagioclase-rich and hornblendite layers (Table IV).

Clinopyroxenes in these rocks are medium-grained with rims of bladed tremolite. They are commonly blastopoikilitic, enclosing small, altered, subhedral plagioclase and/or opaque grains. Amphiboles have very strong dimensional and probable lattice preferred orientations. They have straight grain boundaries. Locally, calcium-metasomatic veins cut through and brecciate the amphibolite. Coarse hornblendite dikes also cut the layering.

High strain facies in the metagabbros include fine-grained dark green amphibolite with microscopic tightly folded quartz-carbonate laminations. At the contact with the ultramafic rocks gneissic rocks with olivine augen wrapped in medium-grained green amphibole blades. Rodingitized gabbros from here have elongate clinopyroxene, altered plagioclase, hydrogarnet and calc-silicate material with sutured grain boundaries.

CHAPTER V - STRUCTURAL GEOLOGY

A. INTRODUCTION

In the vicinity of Hines Pond, there are four main groups of rocks with distinct petrographic and structural characteristics. These will be discussed separately below. They include (Fig. 14): 1) a thick (3 to 4 km) sequence mainly of harzburgite, dunite and minor orthopyroxenite tectonites with a complex history of intense deformation; 2) a thick (4 km) section of massive dunite, which encloses 3) several large discontinuous megalenses, up to 3 kilometers x .5 kilometers in size, consisting both of strongly lineated, foliated, clinopyroxene-rich ultramafics and olivine-rich gabbros; and 4) a belt of strongly deformed, foliated greenschist to amphibolite grade metabasites and calcium metasomatites from 100 meters to 1.5 kilometers wide (Table V).

These groups have fairly restricted distributions and highly complex internal structures and relationships with one another. The first three units mentioned above form a grossly concordant layered sequence up to 10 kilometers thick. The metamorphic rocks are separated from them by high strain zones. All of the rock units have been deformed by open folding about steeply northwest plunging axes to produce the broad 'Z' pattern apparent in the generalized map of the area (see enclosed maps). They have also been cut by roughly east-west normal faults, with small displacements.

These units are separated from underlying clastic sediments by a subhorizontal overthrust fault and a volcaniclastic melange unit about 50 m thick. These sediments have no penetrative cleavage and are essentially unmetamorphosed (probably mostly zeolite facies). Therefore, the structural, igneous, and metamorphic events recorded in the Lewis Hills Ophiolite Com-

TABLE V Rock Type and Structural Units in the Hine's Pond Area

Unit	Dominant Rock Types	Penetrative Foliations	Lineations	Folds	Boudinage	High Strain Zones
Basal Metamorphic Aureole	Ca-Metasomatites, Cpx and/or Garnet Amphibolites, and Dark Green Phyllite	S_1^*, and Secondary S_1 (Garnet-rich) S_d^* (Hornblende+Plagioclase)	L_d^* (Cpx)	Tight, Isoclinal in S_1	Plagioclase-rich layers in green pyllites	Coplanar with Secondary S_1?
Hine's Pond Metagabbros	Gneissic (Cpx-bearing)Metagabbro	S_1 S_d (Hornblende+Cpx)	L_d (Hbl)	None Observed	(ductile) Hornblendite	
Ultramafic Metamorphic Tectonites	Harzburgite+ Dunite + Orthopyroxenite	S_1 S_d (pyroxene)	L_d (Opx)	Closed, Isoclinal, Similar	(ductile) Orthopyroxenite	Localized at Base
Massive Dunite	Serpentinized Dunite	None Apparent	None Apparent	None Apparent		Common(with deweylite)
Megalenses	Wehrlite, Feldspathic Wehrlite to Plagioclase Lherzolite Troctolite, Olivine Gabbro, Gabbro, Anorthosite, Dunite, Clinopyroxenite	S_1 (transposed?) S_d (Plagioclase+ Olivine?+ Cpx)	L_d (Cpx+ Plagioclase)	1. Tight to Isoclinal, Broken 2. Open to Closed in Cpx-ite 3. Open(large)	(ductile) Clinopyroxenite, Dunite Leucogabbro (brittle) Gabbro, Wehrlite	Rare in northern part of the area; increase in number toward High Strain Facies Area
Areas of High Strain Facies	Feldspathic Wehrlite Mylonite	S_s^* (S_1 locally preserved)	L_s (Cpx+ Olivine)	Drag Folds at High Strain Zones		Very Densely Distributed

* S_1=lithologic layering on any scale; S_d=planar preferred dimensional orientation of grains and aggregates; L_d= linear; S_s and L_s developed coplanar to narrow high strain zones; Cpx=Clinopyroxene; Opx=Orthopyroxene; Hbl=Hornblende.

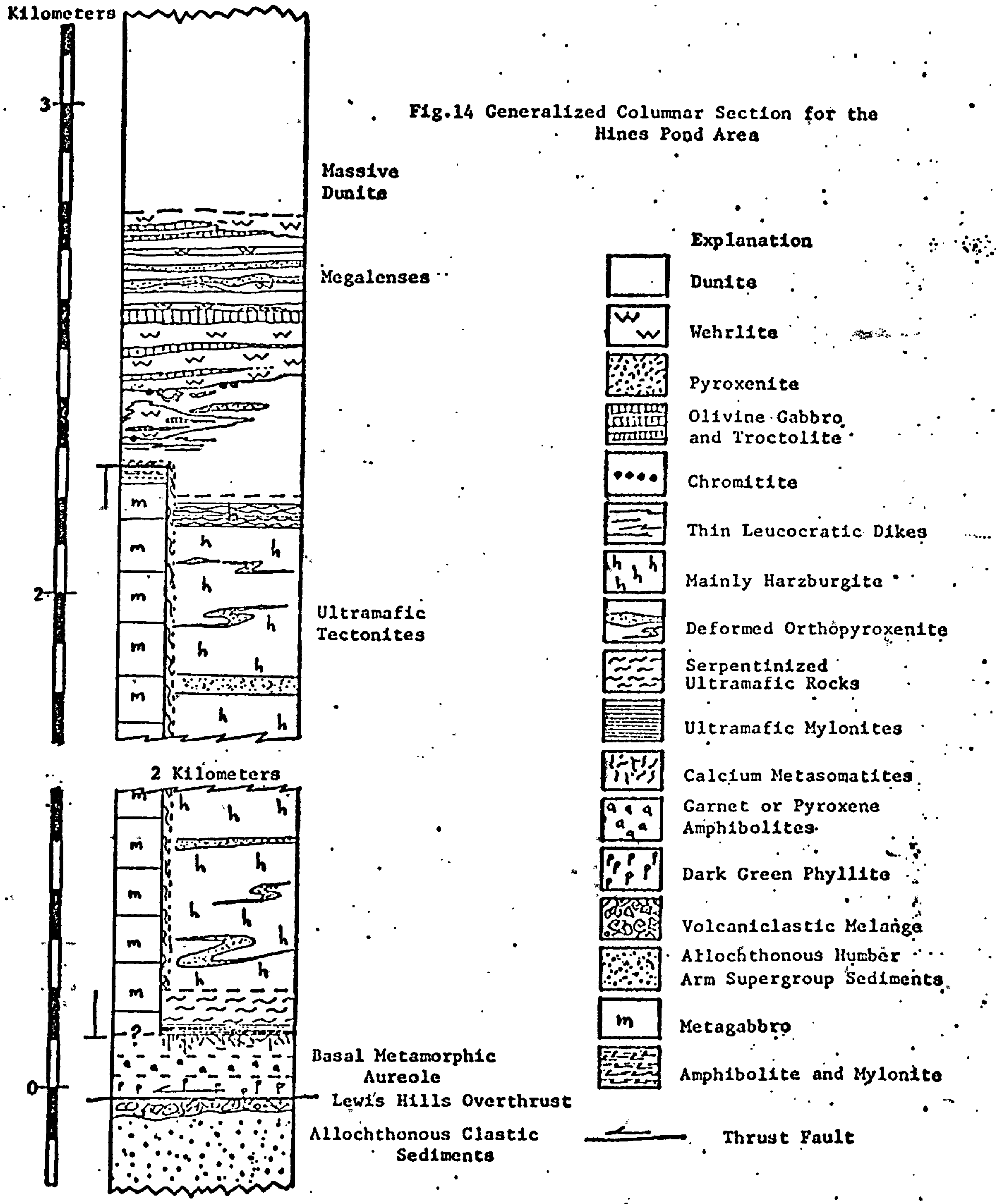

Fig.14 Generalized Columnar Section for the Hines Pond Area

TABLE VI Layering in Mafic Plutonic Rocks

	Layering and References	Composition	Scale of Layering	Layer Boundaries	Form of Layering	Grain Shape Orienation in Layers	Origin
Primary	*Cumulate Layering (e.g., Wager and Brown, 1967)	Variable, cyclic, cryptic, monomineralic possible	Single crystal to >100 meters	Often gradational	Generally planar with rhythmic and/or cyclic layers, Sedimentary structures	Coplanar shape/lattice oriented fabric	Deposition of cumulus crystals on the floor of a magma chamber or sill
Primary	*Sill Intrusion (Davies, 1971)	Sill: Fine-grained gabbro with opaques; Country Rocks: Coarse-grained gabbro to pegmatite	Sill: 1.5 meters; Country Rocks: 50cm	Sharp	Intrusive with fine-grained margins, slightly discordant to country rock cumulate layering	Shape orientation coplanar with sill walls (flow structure?)	Igneous intrusion coplanar with cumulate layering
Primary	*'Willow Lake-type' (Tauberneck and Poldervaart, 1970)	Plagioclase or hornblende or pyroxene-rich layers in norite to diorite (locally cumulate)	5cm to 30cm	Sharp	Regular, planar with xenoliths of surrounding rock types (norite to diorite)	Coplanar, perpendicular (harrisitic) to layers, also granular	Overcooling of magma in a chamber with intermittant convection currents
Primary	Syn-Plutonic Layering (e.g., Berger, 1971)	Coarse granodiorite and fine-grained trondjemite	few millimeters to 1 meter	Mainly sharp	Locally regular, planar but die out along strike within 3-4 meters	Shape orientation coplanar with layers	Syn-plutonic liquid segregation in a deforming crystal mush
Secondary	Metamorphic Differentiation	Variable (control by host rock)	up to 1 or 2 centimeters	Sharp	Regular planar	Shape and/or lattice orientations	Diffusion
Secondary	(Turner, 1939) (Vidale, 1974)	Granitic in quartzo-feldspathic rocks	up to a few centimeters wide and 3 meters long	Sharp	Irregular veins	None?	Diffusion into dilatant zones, with metasomatism?
Secondary	(Bowes and Parks, 1966)	Hornblende schists and Amphibolites	up to 30 meters	Sharp	Regular, planar to irregular with augen	Coplanar with layering	Metamorphic Segregation due to heterogeneous pressure
	Partial Melt Segregations (Boudier and Nicolas, 1972)	Plagioclase-rich lenses surrounded by 'depleted ultra-mafics' within lherzolite with an older layering	a few centimeters thick, discontinuous along strike	Diffuse	Lenticular, coplanar or en echelon with earlier layering, Lensoid, or in Sigmoidal forms	None?	Fractional fusion of lherzolite segregated in dilatant zones
Flattening and Rotation	Rotation of Dikes (Escher, et.al., 1975) and (Ramsay and Graham, 1970)	Dolerite in amphibolite to granulite gneiss	up to 10 meters thick	Sharp	Branching, slightly discordant to foliation of country rocks	None?	High shear strain such as to rotate dikes into approximate parallelism with country rock foliation
Flattening and Rotation	*Flattening-and-Elongation of Xenoliths (Davies, 1971) (Ramsay and Graham, 1970)	Fine-grained gabbro within layered gabbro	up to a few meters long and .5 meters thick	Sharp	Lensoid	None?	Flattening and elongation of xenoliths or small intrusive bodies

* described in layered rocks of ophiolite complexes

plex must have taken place prior to its transportation onto the sedimentary terrane and the subsequent transportation of both of these as a single mass.

In the following sections, structural relations within the Lewis Hills massif in the vicinity of Hines Pond are discussed from structurally lowest upward.

B. METAMORPHIC AUREOLE AND BASAL CONTACT

Immediately above the Lewis Hills Overthrust Fault there is a narrow (100 meter) zone of complexly deformed, high grade metabasites (Fig. 15). This zone is commonly found throughout the Bay of Islands and other ophiolite complexes (Dewey and Bird, 1971; Smyth and Williams, 1973). It is well exposed in stream sections along the escarpment between the ultramafic rocks and underlying sediments east of Hines Pond. At the foot of this escarpment they often form a 'low hog back.' This feature may be buried in ultramafic debris from the scarp above. The ultramafic rocks within 100 meters of this contact are completely serpentinized and have abundant but narrow (1 mm) asbestiform serpentine veins that cut all other structural elements. Leucocratic, aphanitic rodingite dikes locally cut the layering in the ultramafics, but are usually coplanar with it. These dikes are seen to be isoclinally folded in many float blocks. Near the contact the ultramafic rocks are strongly foliated mylonites* and also locally develop phacoidal shear polyhedra structures.

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*The term 'mylonite' in this thesis means "a foliated rock, commonly lineated and containing megacrysts, which occurs in narrow, planar zones of intense deformation. It is often finer grained than the surrounding rocks into which it grades" (Bell and Etheridge, 1973).

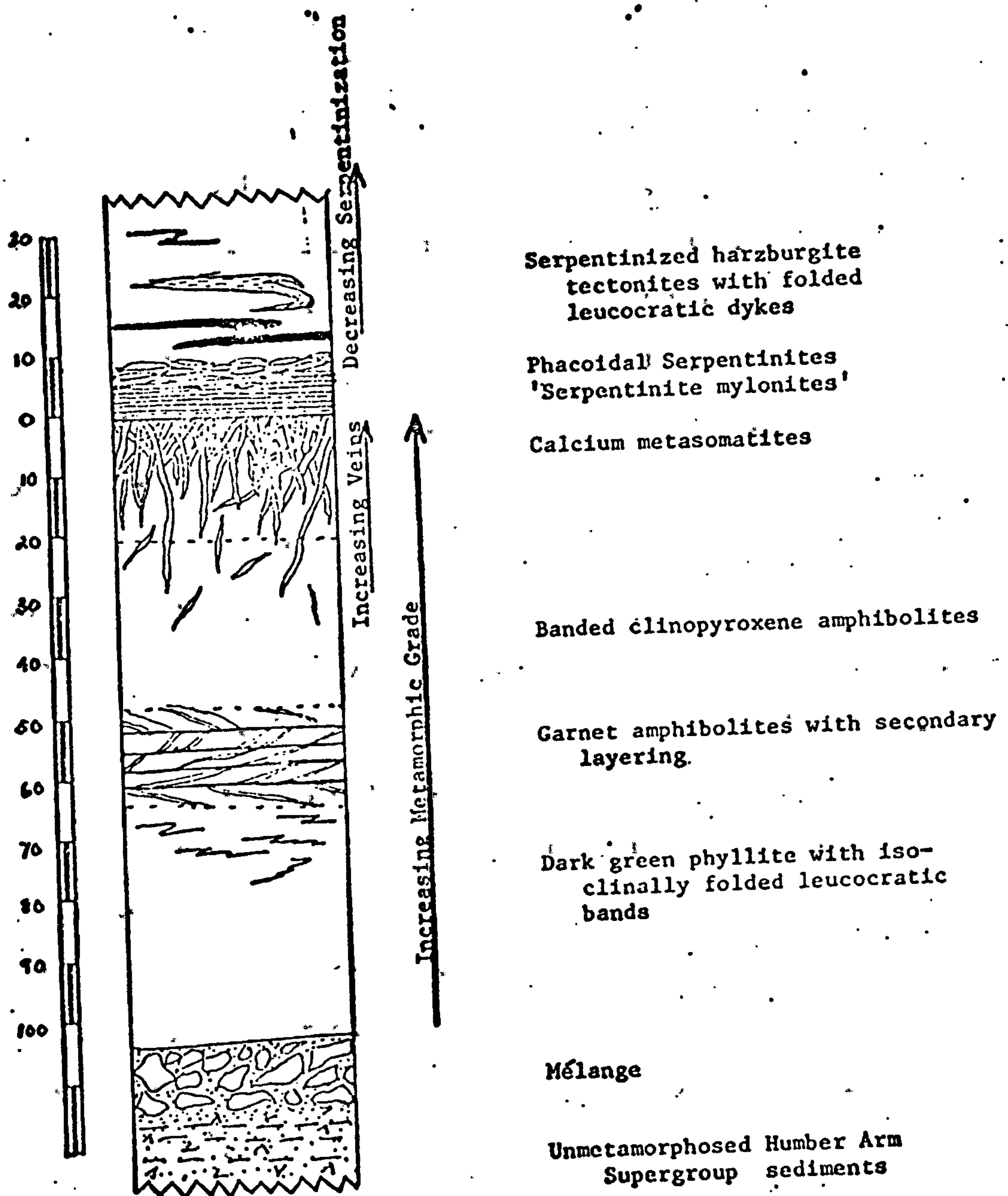


Fig. 15 Basal Metamorphic Aureole at Hines Pond

These ultramafics overlie a layer of very hard, resistant calcium-metasomatite which is about 5 meters wide south of Hines Pond. It can be seen to be made up of numerous veins from 2 to 1 cm wide. The rock weathers to a chalky white surface in outcrop and is gradational to underlying amphibolites.

These amphibolites are coarse, banded, green and white rocks with strong dimensional preferred orientation of grains. Elongate bright green clinopyroxenes define a lineation coplanar with the layering which is on the order of 1 cm thick. Hornblende-rich and plagioclase-rich layers define this layering. No folds were observed in this unit. Its total thickness is 50 meters.

Grain size decreases down section and the layering becomes more diffuse. The rocks here are dark green, medium-grained, garnetiferous amphibolites. Isoclinally folded diffuse banding is cut by an axial surface secondary layering rich in opaques and garnet. Strong planar dimensional orientation of grains in these rocks parallels this new layering. These rocks are only about 10 meters thick and grade rapidly downward into fine-grained dark green phyllites.

These phyllites are at least 50 meters thick and have sparse isoclinally folded plagioclase-rich stringers up to 2 mm thick. Folds have axial surfaces which are coplanar with the steeply north-west dipping cleavage. These are separated from underlying Humber Arm Supergroup clastic sediments by a volcaniclastic mélange unit at least 10 meters thick and the Lewis Hills Overthrust Fault. The mélange consists of angular blocks of red (pillow?) lavas in a black argillite matrix. The basal metamorphic aureole is considered to be part of the Bay of Islands Ophiolite Complex (Dewey and Bird, 1971; Williams and Smyth, 1973, Williams, 1973). These metabasites may have been derived from impure dolomitic limestones or mafic igneous rocks.

Gabbroic rocks occur higher in the ophiolite complex, completely enclosed in ultramafic rocks. Plutonic rocks originally in a similar situation could be deformed and metamorphosed along this basal contact during its formation. They may, therefore, at least partly contribute to the aureole lithologies.

These rocks might also be derived from rocks similar to those of the underlying allochthon. Obduction of the ophiolite complex over these sediments may have deformed and metamorphosed them. They could have then been welded to the ultramafics and transported into their final position along the Lewis Hills Overthrust where a melange developed.

All the late foliations and axial surfaces of folds observed in the basal aureole dip steeply to the northwest beneath the ultramafics of the ophiolite complex. Late foliations in these ultramafics are coplanar with those of the metamorphics where observed. Detailed structural analysis in this zone might prove helpful in working out the history of these rocks.

Thin high temperature metamorphic aureoles beneath allochthonous ophiolite complexes are common features (Dewey, 1975, Williams and Smyth, 1973; and Pike, 1973). These aureoles suggested an intrusive origin for mafic-ultramafic complexes to early workers. Increased understanding of the structure of the base of well-preserved ophiolite complexes has led to two hypotheses: 1) The basal aureole may represent part of a complexly deformed structurally lower allochthonous slice, such as the Little Port Slice (Dewey, 1975). 2) These rocks may represent a deformed contact metamorphic aureole welded onto the base of the ophiolite complex during obduction. The source of heat suggested for this has been retained heat in the ophiolite complex or strain heating during transportation (Williams and Smyth, 1973; Dewey, 1975).

C. ULTRAMAFIC TECTONITES

Above the basal metamorphic aureole and deformed, serpentinized ultramafics in the base of the complex is a thick section of ultramafic tectonites. The section, measured perpendicular to the steeply to moderately northwest dipping layering is about 3 kilometers. The rocks are harzburgites, dunites, and minor orthopyroxenites. Harzburgite and dunite form layers with gradational contacts from a few centimeters to a few tens of meters thick. The average thickness is about 0.5 meters. Orthopyroxenite forms layers up to 5 centimeters thick with sharp boundaries. This layering is isoclinally folded and shows widespread ductile boundinage.

In outcrop dunites weather to a smooth, dark yellowish orange surface with only a few euhedral black chromite crystals visible on the surface. Orthopyroxenites weather to a deep brown and have surfaces showing coarse enstatite crystal faces. Harzburgites have very rough surfaces with copper red to green weathering coarse enstatite grains and aggregates standing out in positive relief with respect to the matrix which is essentially dunite. These grains have a strong dimensional preferred orientation coplanar with the layering, except at fold hinges where it cuts the latter as an axial plane foliation. These grains are also elongated parallel to fold axes where mesoscopic folds have been observed.

Near the top of the section, dunite becomes the dominant rock type. The layering becomes more regular and thinner except for occasional lenses of dunite. Dunite in the banded areas pinches and swells.

D. MASSIVE DUNITE

The Lewis Hills contains huge areas of massive dunite. Northwest of Hines Pond an area of at least 20 square kilometers consisting of 98% dunite is present. Other large areas of dunite are separated by megalenses of highly deformed layered gabbros and clinopyroxene-rich ultramafic rocks.

In outcrop dunites weather to a smooth dark yellowish-orange color. Euhedral, black chromite grains up to 1 mm stand out in positive relief on this surface. No individual grains, penetrative lineations or foliations can be observed in these rocks in hand specimen. They are apparently so homogeneous that they are best termed 'massive.' Microscopically they are very strongly serpentinized and no olivine fabric can be determined.

The most common inhomogeneities in these rocks are chromite seams. These are considered to mark the median line of dunite dikes (Smith, 1958) but no dunite dikes were found in these rocks. These seams have apparently random distributions and orientations. They often cut one another without offset.

Pale green websterite to clinopyroxenite dikes cut the dunites and have branching forms. They are often isoclinally folded about axes coplanar with the layering in the megalenses with which they are always associated. These dikes occur in a zone about 60 meters wide just below, that is, east or south of the megalenses.

Serpentine veins apparently fill joint sets throughout the area. These often curve and have irregular shapes. They are dark green in outcrop and consist of asbestiform serpentine minerals that grow perpendicular to their walls.

Some serpentine veins are faults offsetting other veins. These have light blue-green porcellaneous surfaces with slickensides. The blue-green mineral is probably the serpentine deweylite.

The massive dunite is apparently disintegrating in place. Spheroidal, onionskin weathering and frost action along joints has left the area strewn with boulders to gravels of dunite and serpentinized dunite. Good outcrops within the massive dunites are mainly roches mountonnées.

The contact between the massive dunites and the underlying ultramafic tectonites is a gradational one. Dunite layers in the latter become thicker and more numerous upward until there is virtually nothing but dunite present.

Dunite completely encloses highly deformed layered megalenses of gabbros and clinopyroxene-rich ultramafic rocks. Contacts above and below these bodies are gradational and interlayered. Along the ends gabbro or wehrlite grades laterally through zones of interfingered and mottled dunite and feldspathic dunite or wehrlite.

In the areas between the megalenses and ultramafic tectonites a variety of rock types occur. They are associated with the megalenses and discussed in the next section.

E. LAYERED GABBRO-ULTRAMAFIC MEGALENSES

Within the massive dunites of the Lewis Hills are isolated megalenses of complexly interlayered, moderately to highly deformed clinopyroxene-rich ultramafic and gabbroic rocks (Fig.14). The regional foliation in these bodies describes a large, open 'Z' form (see enclosed maps). The structurally lowest parts of these bodies are conformable with the contact of the dunite and ultramafic tectonites north of Hines Pond.

These bodies are completely enclosed by massive, homogeneous dunite and the contacts between the two are gradational in all cases observed. Dunite grades through plagioclase or pyroxene-bearing rocks into plagioclase and/or clinopyroxene-rich rocks.

In the dunites below the megalenses intrusive features are common. In a zone 50 to 70 meters thick subparallel leucocratic sills cut any orthopyroxenite layers present at low angles. These increase in number and thickness toward the base of the megalenses. The first sills to appear are less than 1 cm thick and are spaced about one meter apart. They are aphanitic and weather light red to pink. Near the megalens these may become up to 3 to 4 cm thick and be typically spaced a few centimeters apart. These thicker sills have a few small greenish pyroxenes visible in hand specimen. These thin sills have irregular forms. They commonly branch and intersect at low angles. They are tightly folded in a few places, with axial-surfaces approximately coplanar to their plane of intrusion which is roughly concordant to the contacts between the major units.

Dunite is laminated with thin pyroxenite layers spaced at intervals of 1-3 centimeters from the base of the megalenses and appears to be rhythmically layered. Just below these rocks, irregular orthopyroxenite dikes occur. These are very coarse-grained and weather to copper red or pale green. Shiny pyroxene crystal faces are visible on the weathered surface. These cut diffuse chromite or pyroxene layers in the dunite and are sometimes isoclinally folded into parallelism with the base of the megalens. They commonly show ductile bondinage structures. They have dimensions usually less than 1x0.5 meters. North of Hines Pond, however, there is a huge (500 x 10 to 15 meters) concordant, lensoid body of this rock type. This may be a single mass or several smaller ones combined by tight folding. The coarse grain size in these rocks makes small folds nearly impossible to see. Interlayered thin (less than 1 cm) dunite suggests that folds are present.

The ends of the megalenses also have gradational contacts with the dunite. Wehrlites or troctolites grade laterally into pyroxene-bearing dunite or feldspathic dunite. These rocks commonly have a mottled appearance with irregular pyroxene or plagioclase-rich patches (1 to 4 cm across) surrounded by dunite. These rocks are interfingered with the troctolites and wehrlites near the megalenses and grade into massive dunite away from them.

The upper contacts are the sharpest. Here wehrlites grade rapidly into dunite within 50 to 100 meters. Wehrlite layers become progressively thinner and more widely-spaced away from the megalenses. Individual layers may become discontinuous and diffuse laterally.

The megalenses, studied in the vicinity of Hines Pond, have dimensions of up to 3 x 0.75 km and are usually less than half this size. They are apparently not extensive at depth as they are discontinuous along strike between high angle faults that are nearly perpendicular to their trend.

Each of the bodies studied is somewhat different from the others. Vertical and lateral variations together with variable distribution and proportions of rock types make them internally complex. Apparently, intense deformation is at least partly responsible for this complexity. The overall deformation of the area is recorded by the observed structures is as follows.

In all cases a lithologic layering (S_1) (Appendix) is present on a scale of a few centimeters to a few tens of meters. A strong dimensional preferred orientation of coarse grains and aggregates defines a coplanar lineation (L_d) and lesser foliation (S_d). These features are cut and rotated by ductile offsets forming high strain zones (S_s). A very strong clinopyroxene lineation (L_s) develops in highly-strained rocks which occur only locally.

Layering (S_1) is locally openly folded about shallow NE plunging axes. These develop no axial surface foliation, and no obvious penetrative deformation of the mass occurred. This was probably associated with the late, open 'Z' folding of the area.

The following sections describe the megalenses studied separately. The final section of this chapter discusses the history of these masses.

AREA I

About 200 meters west of the base of the massive dunite zone, north of Hines Pond, a complexly interlayered zone exists (Fig.16). Layered clinopyroxene-rich ultramafics and gabbros strike north northeast and are completely surrounded by dunite. Contacts above and below are gradational and interlayered. Laterally, there are interfingering relations and a gradation through a zone of dunite mottled with irregular patches of plagioclase and/or clinopyroxene-bearing material.

The 100 meters of dunite below the layered rocks has many subparallel aphanitic, leucocratic (probably rodingitized gabbro) sills within it. These increase upward toward the layered rocks and are sometimes isoclinally folded. Chromite concentrations up to a few millimeters thick occur throughout this zone in the ultramafic rock. They have the form of diffuse layers up to 10 cm thick or isolated, isoclinally folded, schlieren.

The lowest layered rocks are coarse-grained, dark green pyroxenites interlayered with lesser thin dunites. Pyroxene layers average about 4 cm while dunites are only a few millimeters thick. A few thin (5 mm) stringers of plagioclase-rich material are coplanar with these ultramafic layers. These rocks form a zone approximately 25 meters thick. Intertonguing relations suggest that the pyroxenite and dunite are isoclinally folded. Pyroxenite layers commonly show ductile bondinage. Some plagioclase-rich stringers show concentric folds.

Above this sequence, gabbros and troctolites up to 30 cm thick are interlayered with dunite. The gabbros have sharp boundaries and increase in width to the south. Gabbros are usually bounded above and below by thin (less than 5 cm) layers consisting of dunite and gabbro to anorthosite.

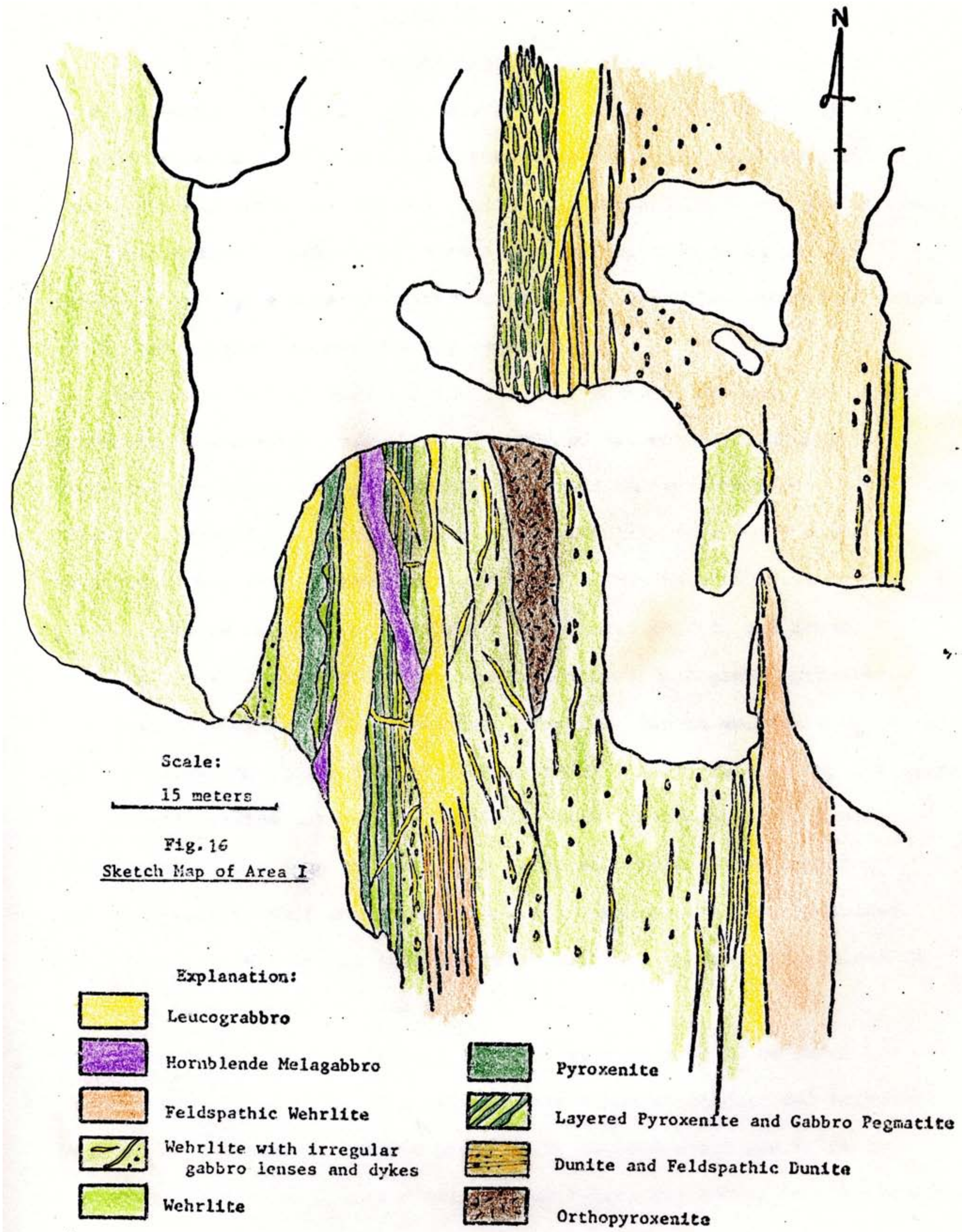


Fig. 16
Sketch Map of Area I

This zone is overlain by alternating wehrlite and gabbro layers. Wehrlite layers are up to 20 cm thick while the gabbros are less than 4 m thick. These gabbros also have interlayered zones above and below. They have a plagioclase-rich to plagioclase-poor layering on the scale of 1 cm or less, which usually contains alternating light and dark laminae. Both of these foliations are coplanar with the layering (S_1). Laterally, thicker gabbros may become very coarse and pinch-out or terminate abruptly in interfingered zones of thin (5-10 cm) gabbroic and plagioclase-bearing ultramafic layers. These are usually feldspathic wehrlites that have abundant coplanar, discontinuous, thin (2-6 cm) layers and lenses of leucogabbro. Plagioclase-bearing ultramafic rocks grade laterally into wehrlite and, eventually, dunite.

Above this zone masses of dunite with irregular pyroxenite dikes occur for a thickness of about 15 m. Some of these are isoclinally folded with axial surfaces concordant with the layering of the area (S_1). Rhythmically-layered (1 to 20 cm thick) dunite and clinopyroxenite forms the next 30 meters of section. These grade upward through 3 to 5 meters of wehrlite into dunite. Within the layered pyroxenites there is a layer of feldspathic wehrlite with an unusual texture. Thin gabbros (3 cm) within this layer are found as isolated tight fold closures or as lenses. Other thin (2-3 cm) gabbros are dikes cutting the layering (S_1) and usually the fabric (S_d) of the feldspathic wehrlite. These are truncated above and below by discontinuous layers of gabbro with coplanar S_1.

Lens-shaped patches of dunite 2 to 5 cm long occur in groups. This grades laterally into a similar rock with lenses (3 to 10 cm long) of foliated wehrlite, dunite, or pyroxenite separated by thin (dikes and sills?) of anorthosite.

Extreme lateral variations are found within this entire layered sequence

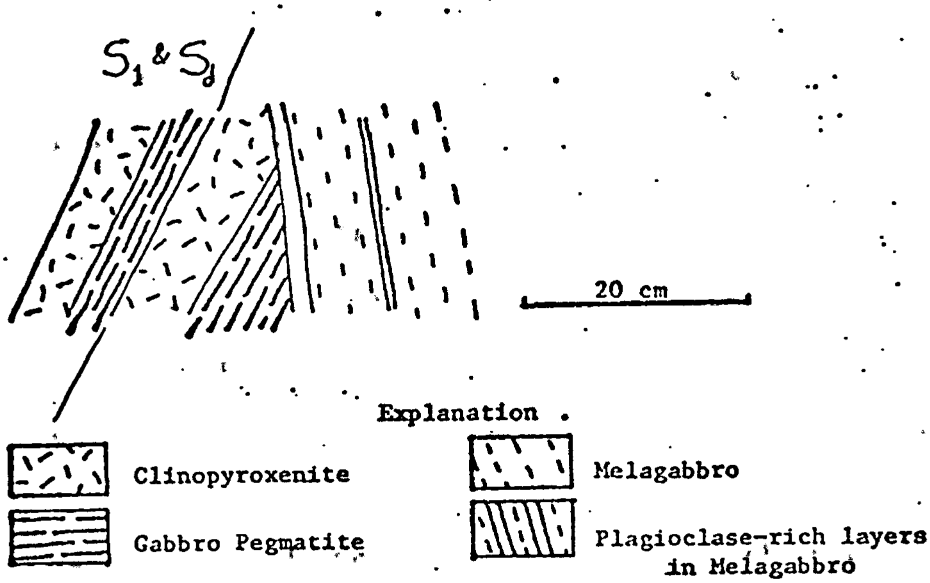


Fig.17 Contact between the layered sequence and a discordant melagabbro

so that no single vertical section gives a true representation of the distribution of rock types. A sketch map of the area (Fig.16) illustrates the complex relationships. S_1 and S_d are always coplanar in this area. They dip steeply westward, except in the case of the near vertical hornblende melagabbro dike which cuts the layered sequence (Fig.17). This strikes north-northwest and has a strong lamination and dimensional preferred orientation coplanar with the walls of the dike. This dike is cut obliquely by a later wehrlite dike (2 cm thick), which also has a weak foliation coplanar with its walls. A second slightly discordant body of orthopyroxenite-pegmatite cuts mottled wehrlite in the north end of the area. This body has no apparent tectonite fabric.

AREA II

This is about 50 x 200 meters in area (Fig.18). Ultramafic to gabbroic rocks here are nearly isolated by surrounding massive dunite. They are part of a larger mass to the west, which will be discussed in the next section.

In the southern part of this area, dunite has diffuse chromite layers up to 6 cm thick. Near the layered rocks a few meters to the north schlieren of chromitite are found up to 1 cm thick coplanar with the dunite-chromite layering.

The lowest layered rocks in the megalens are dunite and wehrlite up to 2 m thick. These are cut by irregular, branching, masses or veins of pegmatitic orthopyroxenite. These masses are up to 2 meters long and some are isoclinally folded with axial surfaces coplanar with the layering (S_1) but tectonite fabrics are not apparent in these rocks.

Above this area irregular patches of foliated (S_d) wehrlite to feldspathic wehrlite between a few centimeters and a few millimeters across are

Fig.18 Sketch Map of Area II

Explanation

Dunite	Wehrlite
Feldspathic Dunite	Orthopyroxenite
Feldspathic Wehrlite	Anorthositic Gabbro to Troctolite

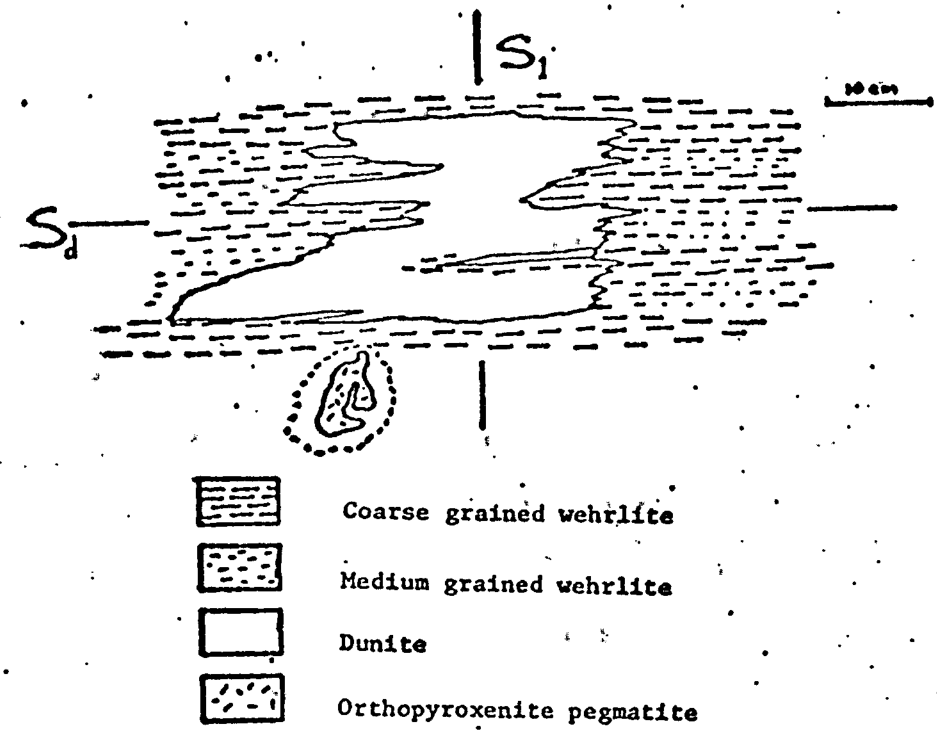


Fig. 19 Possible folded dunite mass in coarse wehrlite

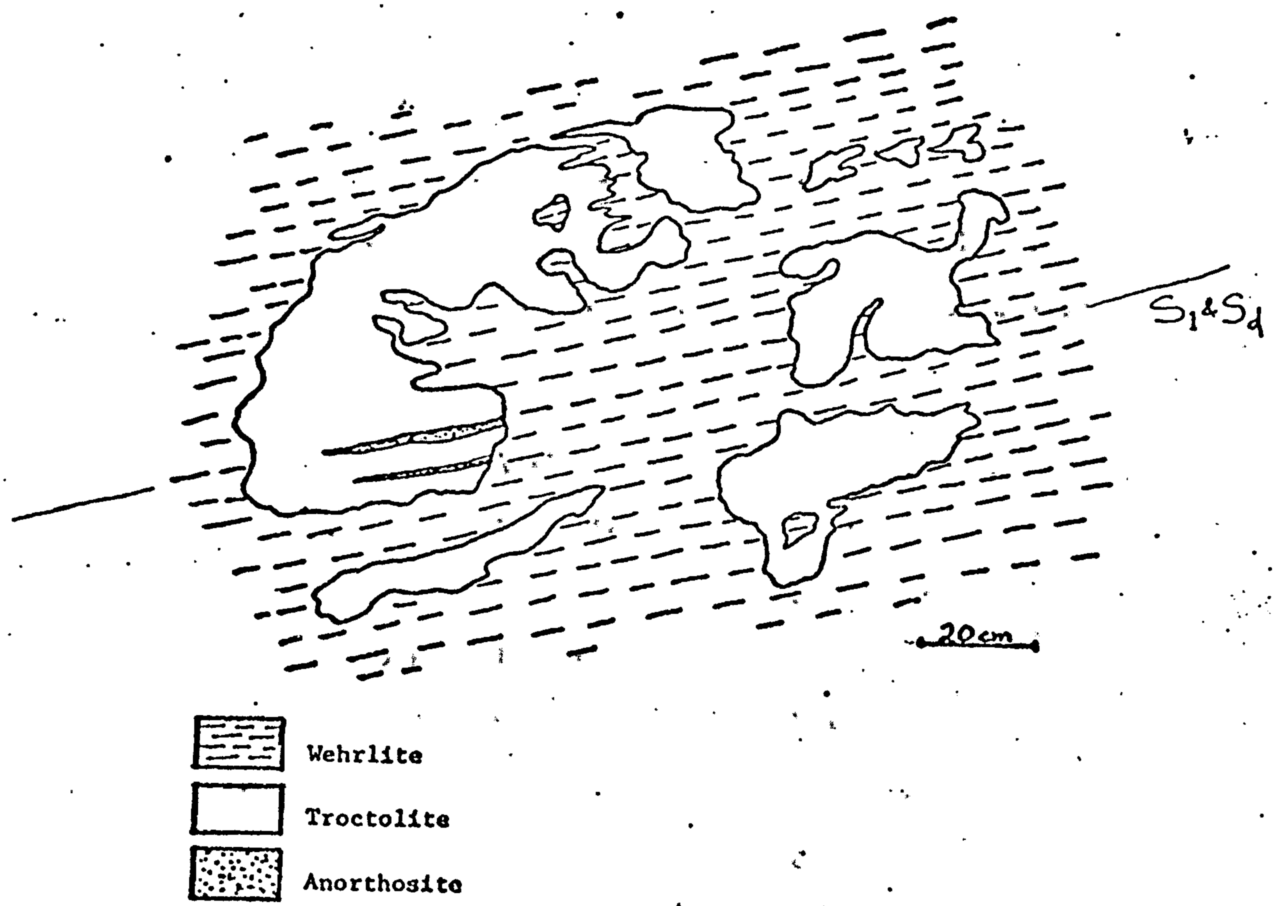


Fig. 20 Possible partial melt texture

enclosed by dunite. This produces a mottled-looking rock. The amount of dunite varies throughout this zone. Some dunites form conformable continuous layers; other are dikes that cut S_1 and each other. Since they show no apparent fabric their relation to S_d is unknown (Fig. 19).

A layer of coarse feldspathic wehrlite pinches out in this zone. Enclosed within this mass are some very irregular blebs of anorthositic troctolite from 1 to 30 cm across (Fig.20). These have thin (1 cm) internal layering concordant with that of the wehrlite (S_1) and its fabric (S_d). Haloes consisting of dunite to wehrlite surround these. The blebs enclose patches of wehrlite which are cut by S_d.

Higher in the section similar relations are found where thin (2 cm) anorthosite is interlayered with dunite (a few millimeters thick) in isoclinally folded masses or isolated, tight, fold closures. Axial surfaces parallel S_1 and, rarely, layers cut S_d.

The northern end of the mass is made up of a large irregular body consisting of coarse troctolite to olivine gabbro. There are plagioclase-rich tongues near the margins that are coplanar with S_1. The strong fabric (S_d) of these rocks is at high angles to the irregular contact between the troctolite and dunite.

AREA III

Between Hines Pond and Petley's Pond to the north, there exists a huge outcrop area of layered gabbroic and ultramafic rocks. This area has dimensions of 3 x 0.5 km and is the largest of the megalenses studied.

The extreme northern end grades through mottled feldspathic dunite and wehrlite to massive, homogeneous dunite near Petley's Pond. To the south, the megalens is folded. The foliations (S_1 and S_d) dip steeply westward on the eastern side of the body and gradually flatten to moderate dips westward.

The mass is dissected by east-west to northwest trending normal faults with mainly south side down displacements. Displacements are small as they do not greatly offset the layered sequence. Some faults have had large enough displacements to cause the complete removal of the layered rocks. The southwestern end of the mass is truncated by a similar fault. Gabbroic rocks, with a similar trend, outcrop across an intervening valley with no apparent offset. These faults are much more widely spaced to the north but cause great confusion in tracing layering to the south, where they are more numerous.

There is a great variety of rock types within this mass most of which are included under the rock types: coarse grained wehrlite, feldspathic wehrlite, olivine gabbro, troctolite, anorthosite, dunite, and clinopyroxenite. The layered sequence is very complex. Rhythmic layering is present locally and has gradational contacts. Both compositional and size grading occur. No large scale repetitions or cyclic units within the layered sequence were found. Layers range from a few cm to several tens of meters thick. They grade laterally into rocks of different plagioclase or pyroxene contents. Individual layers are lensoid in shape so that S_d is observed to cut S_1 at very low angles at the ends of lenses. In most places, however, S_d and L_d are coplanar with S_1.

The mass can be divided into a few zones (Fig. 21) that run the length of the body. These are discussed separately below as they occur from east to west. These zones are thinner and better exposed to the north. Faulting, ductile offsets (shear belts?), and increased thickness and complexity of the sequence to the south obscure the overall pattern seen to the north. Thus, the section described below was compiled in the

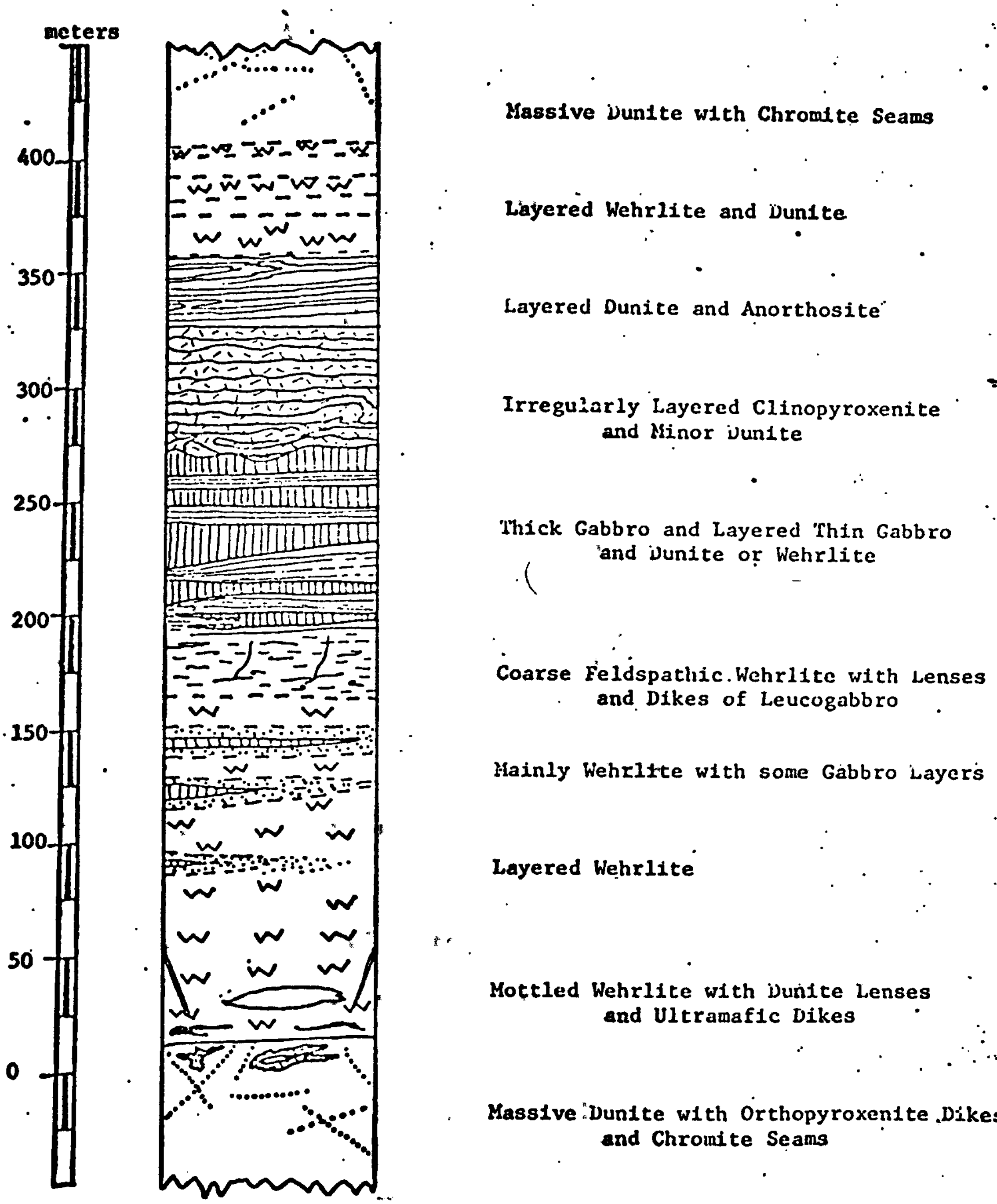


Fig.21 Generalized Columnar Section Through a Megalens North of Hine's Pond (Explanation is the same as in Fig.14)

northern part of the megalens.

The lowest zone in the sequence consists almost completely of olivine and clinopyroxene-rich rocks with very few plagioclase-bearing rocks. This zone is approximately 90 m thick. Very coarse wehrlites and dunite are the most common rocks. At the base of the megalens wehrlites overlie massive dunite with a sharp contact. They show vertical and lateral size and compostional grading of coarse clinopyroxenes and olivine. Lensoid bodies of dunite with sharp vertical and gradational lateral contacts occur up to 23 x 2 m in size. Wehrlite layers containing small (3-6 cm) irregular patches of dunite are also common.

At the base of this zone small (2 x 10 cm) schlieren of chromitite are found enclosed by dunite. The contact between chromitite and dunite is always sharp. The chromitites are usually isoclinally folded and occupy the cores of dunite lenses suggesting that these are fold hinges in which chromitite layers have been thickened. Plagioclase and pyroxene concentrations are also common in similar situations, but are not usually obviously folded (Figs.22&23). Folds are possibly not apparent because of the gradational contacts, coarse grain size, and lack of platy minerals in these rocks. Pyroxene and chromite tend to be concentrated along high strain zones within dunite.

Within this zone a few thin (5 mm to 10 cm) layers of leucogabbro are found. These are the cores of layers of feldspathic wehrlite that are about 30 to 40 cm thick. The gabbros have sharp contacts and usually have thin (5 mm to 2 cm) interlayered gabbro and dunite zones above and below a thicker central gabbro layer. The thin dunite layers pinch and swell in the interlayered zones, locally allowing thin gabbros to lie against one another.

In the northern part of the outcrop area individual gabbro layers

Figure 22: Closed isoclinal folds with highly attenuated limbs in dunite (buff), coarse wehrlite (grey), and chromitite (black). Note: chromitite segregations in hinge regions.

Figure 23: Closed isoclinal fold with attenuated limb in feldspathic dunite (buff), anorthosite (white), and coarse feldspathic wehrlite to plagioclase lherzolite (grey). Coarse grains and aggregates are strongly lineated.

more than 200 meters. Southward the gabbros and enclosing feldspathic wehrlites double in thickness. To the north these rocks grade into dunites.

Above these rocks lies a zone mainly of feldspathic wehrlites, feldspathic dunite and coarse-grained troctolites. These form apparently continuous or lensoid layers usually from 1 to 5 meters thick. To the south they grade into more plagioclase-rich rocks. Anorthositic troctolite and anorthositic olivine gabbro dikes from 1 to 8 cm thick cut the layering (S_1) and are not usually deformed by S_d. They have sharp boundaries and are usually zones of displacement. They commonly are coplanar with or (Fig. 31) intrude ductile "faults" (high strain zones) (S_s) where they occur. The dikes usually have a dimensional preferred orientation of inequant grains parallel to their walls. These dikes are nearly vertical and have nearly straight or slightly curving northwest to east-west trends.

Rarely dunite to wehrlite dikes occur (Fig.25). These are restricted to single layers and are penetratively deformed by S_d of the layered sequence.

All dikes seem to be rootless. They are usually truncated by S_1 often at both ends. Some dikes, however, cut the gross layered sequence (Fig.28). Some plagioclase-rich dikes originate where two lenses of the same plagioclase-rich material intersect (Fig.24). They are often truncated by discontinuous layers or lenses of gabbro coplanar with S_1 and S_s. These gabbro lenses sometimes can be seen to be isolated tight fold closures. Single coarse grains and aggregates in feldspathic wehrlite to wehrlite have shapes suggesting folded forms. Unquestionable tight folds are uncommon but may be seen occasionally in thin layers that have sharp contacts with surrounding rocks. Axial surfaces of these are coplanar with S_d. Fold axes are colinear with L_d in all cases observed (Figs. 26 & 27).

These gabbroic layers, lenses, and dikes having sharp boundaries are probably magmatic intrusive features. Dikes are sometimes cut by S_d. They

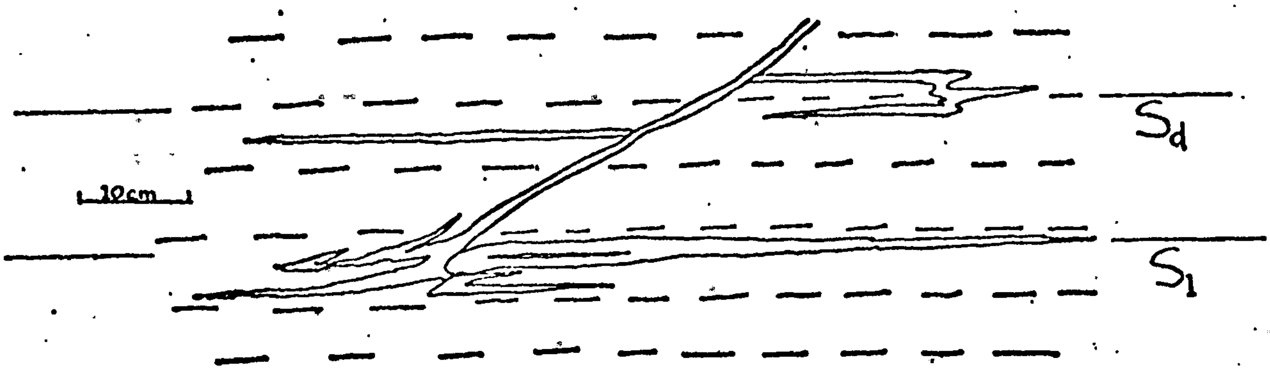


Fig.24 Leucogabbro dikes and sills in feldspathic wehrlite

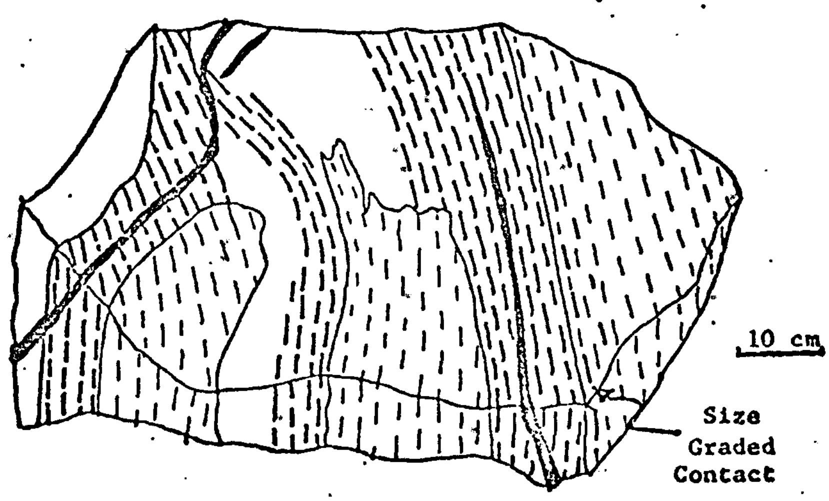


Fig.25 Relations in mottled wehrlites from Area 3

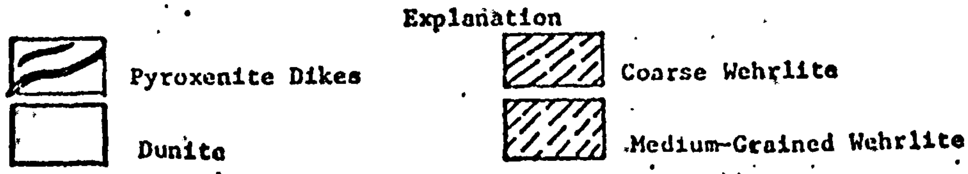


Figure 26: Tight isoclinal similar folds (S-shape) in layered dunite (buff) and chromitite (black) located at structural base of a megalens.

Figure 27: Tightly folded, thin layered anorthositic troctolite (white) and dunite (buff). Note: strong lineation of coarse grains and aggregates of plagioclase is colinear with fold axis.

cut S_1 and some are not folded or rotated into parallelism with S_1 and S_d. These record the complex deformation of the area to be discussed in the final section of this chapter.

The next zone to the west is dominated by leucogabbros. These are usually relatively thick (2 to 5 meters) layers slightly discordant to the layered ultramafic rocks that surround them. They have sharp contacts and are probably sills intruding the layered ultramafics. Anorthositic troctolites and olivine gabbros have diffuse internal layering and good dimensional preferred orientation of at least mafic grains coplanar with their walls. Some of these rocks seem to lack this (S_d) fabric.

These have the same lateral relations as the gabbros lower in the sequence. They are always separated from layered ultramafic rocks by dunite, clinopyroxene-bearing dunite with thin, layered anorthosite to gabbro within at least 1 meter of either contact. Masses of coarse pyroxenite sometimes overlie gabbros near the top of this zone.

Some ultramafic rocks of this zone have very unusual textures. They are essentially dunites or wehrlites with abundant clots of clinopyroxene and plagioclase-rich material 2 to 3 cm across (Fig.29). These are elongate parallel to L_d and are apparently distributed randomly throughout the rock.

The next zone consists of irregularly interlayered coarse clinopyroxenite and lesser dunite. This sequence is of variable thickness, but ranges up to about 40 meters thick. Individual layers of pyroxenite are from 1 to 20 cm thick. Dunite layers are usually somewhat thinner. Pyroxenites pinch and swell and, near the base of the zone, are open to close concentrically folded about rather variably oriented axial planes striking generally northwest. Irregular masses of pyroxenite at the base of this zone discordantly overlie the thick gabbros of the zone below. Within a dunite layer in this zone an open concentrically folded band of single, coarse

Figure 28: Layered dunite (buff) and coarse feldspathic wehrlite (grey) with discontinuous layers and lenses of anorthositic troctolite (white) cut by anorthositic troctolite dike along a sharp offset.

Figure 29: Strongly lineated, folded blebs of plagioclase and clinopyroxene-rich material show size grading in dunite to more homogeneous feldspathic wehrlite.

(1-2 cm) clinopyroxene crystals was found.

The rocks of this zone are apparently relatively undeformed. They have no apparent tectonite fabric and are more irregularly layered than rocks of the zones below. They may have been remobilized and slightly deformed during the intrusion of the gabbro sills below.

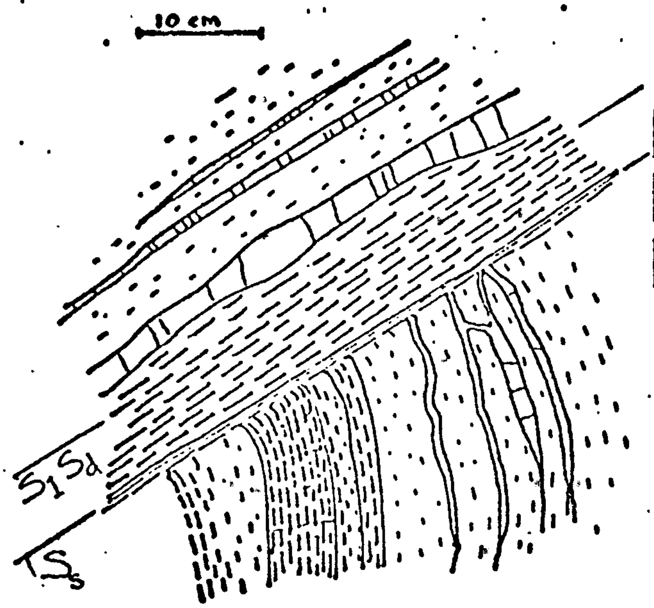
The last zone to the west consists mainly of regularly-layered dunite, anorthosite, and minor feldspathic dunite. Layering is about 5 to 20 cm thick. Sharp contacts between dunite and anorthosite make mesoscopic folds easier to see where they are present. Tight to isoclinal folds here have axial-surfaces coplanar with S_1 and S_d. Axes are colinear with L_d. Anorthosite layers are reoriented and attenuated along ductile offset zones at moderate angles to S_1. Surrounding ultramafics respond in a more brittle manner. Gabbro may be removed from these zones completely leaving ultramafics from either side of the gabbro in contact across a high strain zone (Fig.30).

These rocks grade rapidly upward into interlayered wehrlite and dunite. Wehrlite layers or lenses become diffuse and thinner to the west and disappear within 50 to 100 meters of the last plagioclase-bearing rocks.

In this zone irregular, possibly folded, forms of dunite in wehrlite are occasionally found suggesting strong deformation and the possible development of secondary ultramafic layerings rich in clinopyroxene (Fig.19).

Much of the structural history of this area can be determined from a single outcrop sketch (Fig. 31). The following sequence of events could lead to the formation of this outcrop area:

1. Formation of lithologic layering (S_1)
2. Intrusion of ultramafic dike with coplanar displacement
3. Development of preferred diminsional orientation of grains and aggregates (?) (S_d)



Explanation:

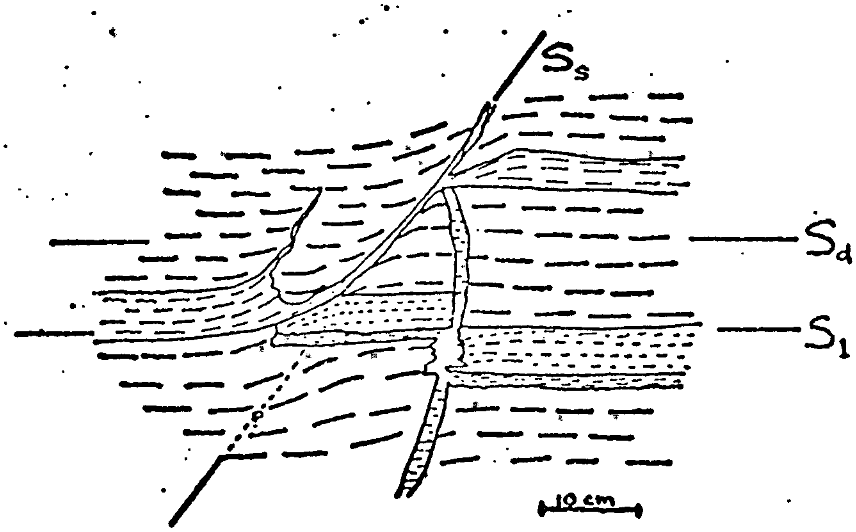
Pyroxenite

Medium Grained Wehrlite

Coarse Grained Wehrlite

(Note size grading in layering)

Fig. 30 S_1 deformed by S_s



Coarse Grained Feldspathic Wehrlite

Plagioclase-bearing Wehrlite

Wehrlite Dyke

Olivine Gabbro

Leucogabbro

Fig. 31 Ductile "fault" with leucogabbro dike (S_s)

4. Intrusion of a gabbro sill with a fabric developed coplanar with its walls. (This might also be a dike originally oriented at high angles to S_1 that has been rotated by strong deformation.)
5. Development of a ductile "fault" along which gabbro behaved in a much more ductile manner than the ultramafic rocks above and below it.
6. Intrusion of a dike of the same composition as the gabbro sill along the high strain zone. This has a fabric coplanar with its walls. (S_s).

AREA IV

In this area, complex intrusive relations, localized deformations and faulting complicate the outcrop distribution of layered ultramafics and intrusive hornblende gabbros. Dunites surround the area except for a zone of layered ultramafic rocks which extends from the northeast corner of the area eastward, toward the southwest corner of Area III (Figs. 32&37).

Southeast of the area, light green websterite and pink orthopyroxenite pegmatite masses are isoclinally folded with shallowly northwest-dipping axial planes. They are also affected by ductile bondinage. They increase in number toward the base of the layered rocks.

The lowest layered rocks include laminated dunite (3 to 6 cm thick) and minor pyroxenite (a few millimeters to 1 cm thick) with the pyroxenite (affected by ductile bondinage) and irregular, lensoid segregations of chromitite up to 5 cm thick.

These are conformably overlain by a 10 meter thick layer of hornblende melagabbro. This has sharp contacts and strong internal foliations coplanar with its walls. These foliations are defined by plagioclase-rich and hornblende + pyroxene-rich layers from 1 to 10 cm thick. These layers have

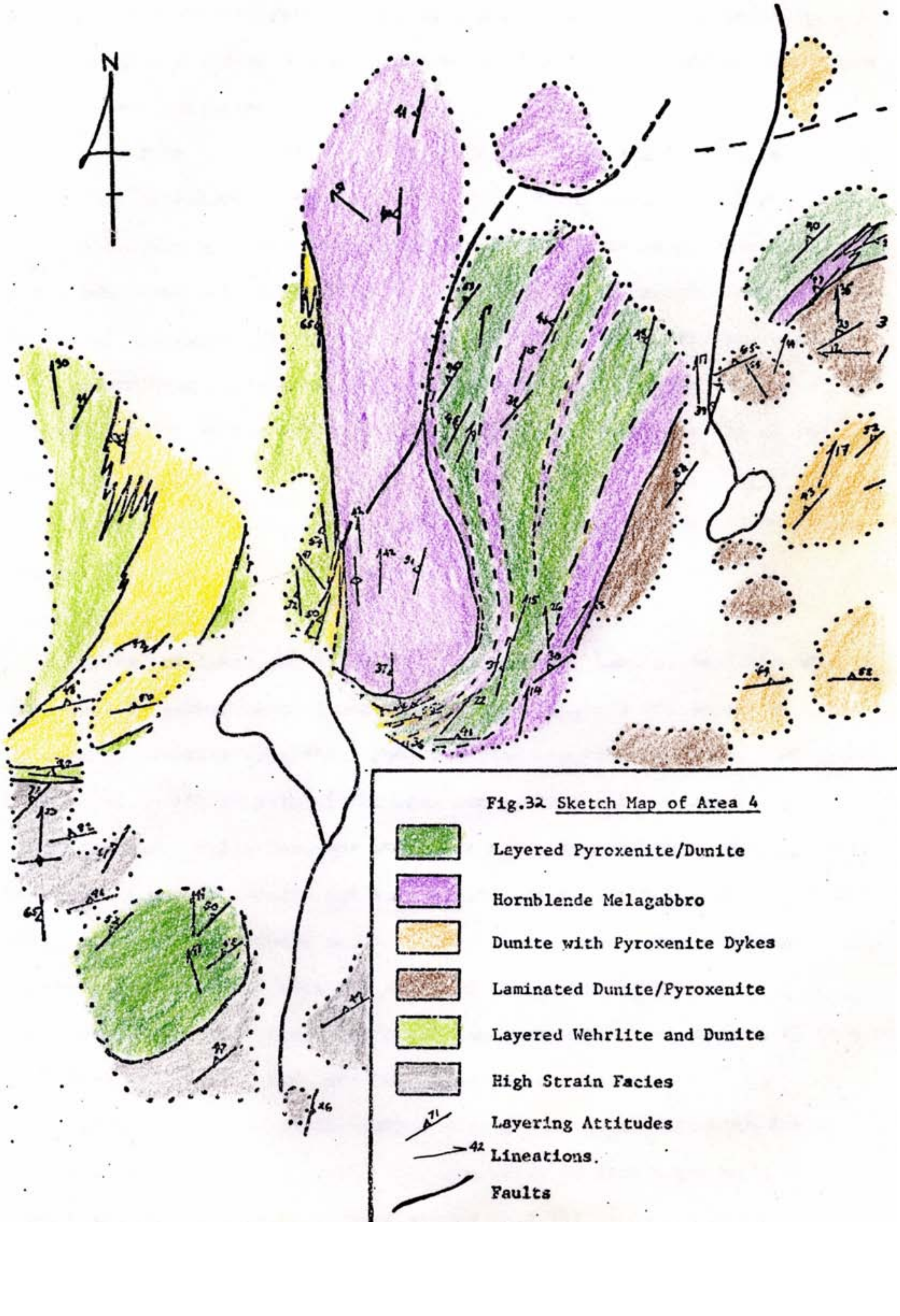


Fig.32 Sketch Map of Area 4

laminations of approximately the same compositions as the thicker layering. There is also a strong dimensional preferred orientation of inequant grains. All of these foliations are coplanar.

Above this lies a 30 to 40 meter thick zone of fairly uniformly layered clinopyroxenite and dunite. Dunite layers usually vary from a few millimeters to a few centimeters thick. Pyroxenites average about 3 cm thick and stand out in positive relief. Very coarse anorthositic gabbros are found intermittently through this zone. They are no thicker than 0.5 m.

Pyroxenites in this zone pinch and swell gently. They also have sigmoidal forms within wehrlite layers which occur near the top of the sequence.

The next zone above the pyroxenite-rich zone is at least 100 meters thick. This includes layered wehrlite and dunite. The former show strong tectonite fabrics.

Layers of laminated feldspathic pyroxenite, hornblende gabbro and anorthositic gabbro up to 3 meters thick are slightly discordant to the layered ultramafics (Fig.32). They are probably rotated dikes. Laterally, especially on the NW side of the area the gabbros and ultramafics are interfingered. Foliations are strongest near the margins of these gabbros and thin (1 cm) pyroxenite and anorthosite layers are isoclinally folded along the margins of these masses. These folds have axial-surfaces approximately coplanar with the walls of the gabbro layer.

Lenses of clinopyroxene-rich material are surrounded by thin (1 to 4 cm) layers of anorthosite that are low angle dikes (Fig.33).

Xenoliths of anorthosite with a strong and folded tectonite fabric are enveloped by gabbro. Folds here are variable from tight to more open forms which resemble slump features (Fig.34).

Ductile "faults" with displacements of a few meters indicate that

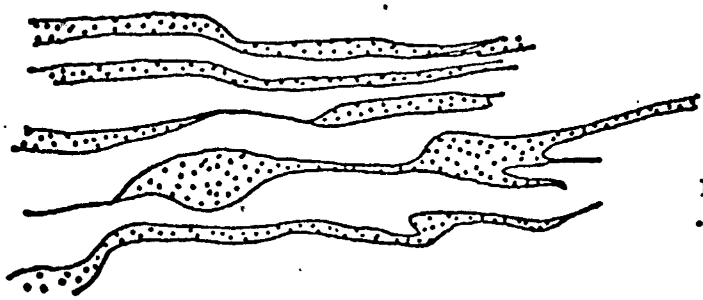


Fig.33 Irregular melagabbro dikes in anorthosite

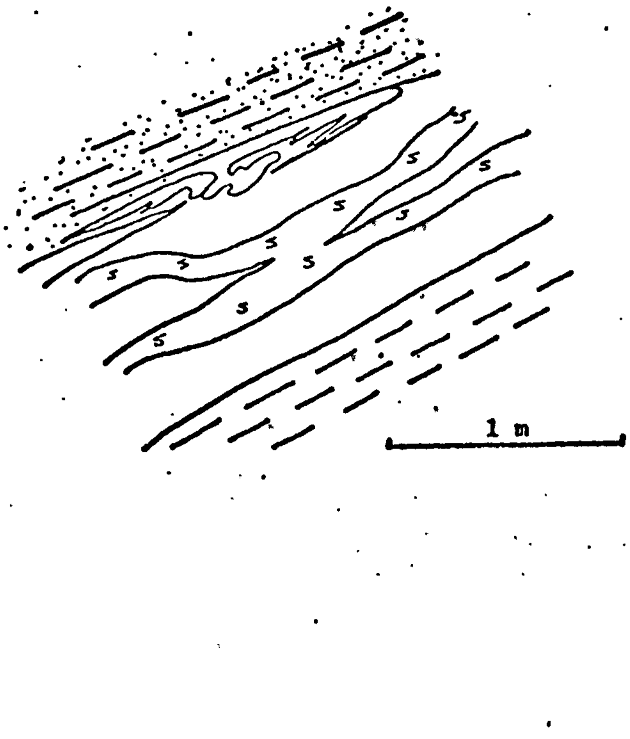


Fig.34 Deformation zone between leucogabbro layers

gabbros responded in a more ductile manner than ultramafic rocks. Gabbros are greatly attenuated and develop a fabric coplanar with the high strain zones (S_s). Later brittle boudinage has affected the gabbros and ultramafics both. This may be due to high strain rates during the time of the ductile deformation.

On the southeast side of the area a southeast dipping normal fault has exposed a highly strained facies of the layered dunite and wehrlite. These are discussed in a later section.

AREA V

Southeast of Hines Pond, a small (200 x 30 meters) mass of interlayered rocks outcrop. They have layered ultramafics and intrusive gabbros much like those of Area IV. These rocks are only 200 meters from the top of the basal contact metamorphic aureole. They are surrounded mainly by harzburgite tectonites rather than massive dunite like the other megalenses. Masses of metagabbro (up to 30 meters long) occur nearby and have sharp, vertical faulted contacts with the ultramafics. Dunites containing pyroxene-rich laminations occur just below, within and above the megalens.

The lowest rocks of the layered sequence are interlayered, isoclinally folded dunite and chromitites up to 5 cm thick. This zone is about 3 meters thick. Axial surfaces dip northwest and are conformable with the layered sequence above. Chromitites die out rapidly upward.

The next 18 meters of the section are thin layered dunite and pyroxenite with thin (1 to 3 cm) sills of pink, aphanitic material (rodingitized gabbro?) increasing in thickness and number upward through the section. These end abruptly beneath a layer of gabbro about 5 meters thick.

This gabbro is strongly laminated coplanar with its walls with alternating light and dark layers. Large (up to 1.5 cm long) hornblende augen also have dimensional preferred orientation coplanar with these foliations.

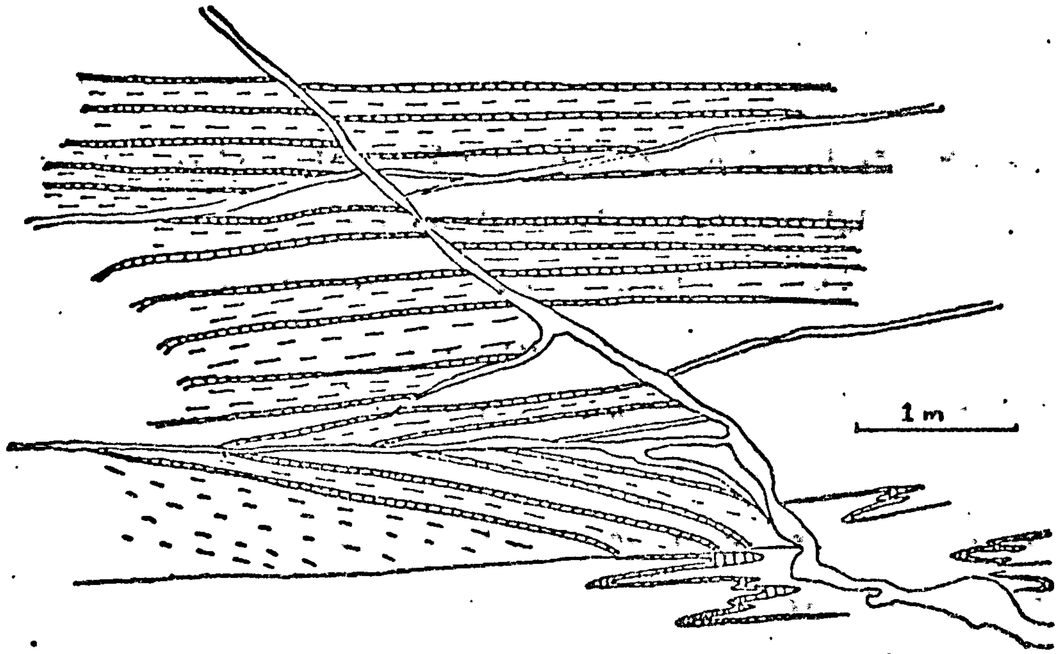
Above the gabbro lies a lensoid mass of dunite with pyroxene-rich laminations which is about 4 meters thick. The lamination is truncated by the layered wehrlite/gabbro units above and below. It cuts through the lens in a sigmoidal form. The contacts above and below this mass may be faults (or high strain zones?). Laminations are parallel to these contacts near the margins of the body.

Above this mass there is a layered sequence of wehrlite, feldspathic wehrlite and gabbro about 20 meters thick. Gabbros here have sharp contacts against ultramafic rocks and are up to 2.5 meters thick. They are offset by ductile "faults," of variable displacement and width. The greatest displacement observed is about 2 meters. Laterally, gabbros pinch and swell slightly. They terminate with interfingering relations in deformed harzburgites that have isoclinally folded leucocratic sills. At the ends of gabbro lenses, gabbros are pegmatitic. Within the wehrlites in the middle of this zone, folds resembling slump structures occur. Individual layers are folded about different axial surfaces that have no coplanar foliation. The forms of the folds vary from similar to concentric. Gabbro layers above and below are coplanar with each other and show no folding. These may be sills, whose intrusion is perhaps connected with this local deformation.

AREA VI

South of Hines Pond small layers up to 3 meters thick of gabbroic rocks exist. These have the form of low angle dikes cutting an earlier harzburgite, dunite and minor orthopyroxenite layering (Fig.35).

1 cm and thinner leucocratic, aphanitic (rodingitised gabbro?) dikes appear in the ultramafics just south of Hines Pond. They increase in width,



Explanation

Orthopyroxenite Layers

Harzburgite

Dunite

Leucocratic Dikes

Fig.35 Relations in Area 6

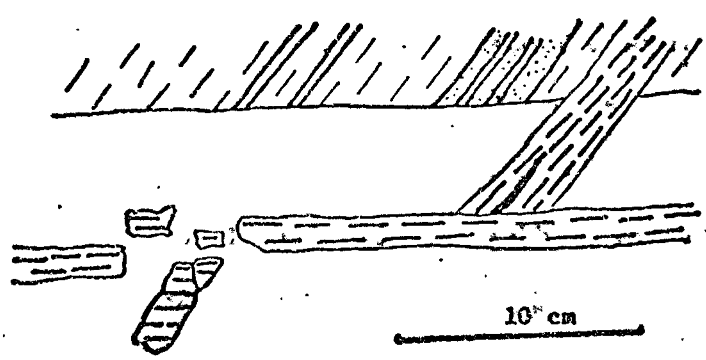


Fig.36 Wehrlite and Gabbro dike relations in a discordant area

Explanation

Chromitite

Leucogabbro Bands

Gabbro to Leucogabbro

Wehrlite

Feldspathic Wehrlite

Dunite

grain size and density to the middle of the area where only a few 2-3 meter dykes are present. These are kaersutite-bearing olivine gabbro. They have a strong dimensional preferred orientation of inequant grains. This foliations is coplanar with the walls of the dikes. Dikes decrease in density, width and grain size to the south away from the thickest gabbros.

The gabbro is usually slightly discordant to the earlier deformed layering in the ultramafics. Orthopyroxenite layers have sharp boundaries and show isoclinal folded layering (S_1). An axial-surface dimensional preferred orientation of inequant grains (S_d) is seen in harzburgites having coarse enstatites. This foliation (S_d) cuts the early ultramafic layering (S_1) at fold hinges.

The dikes are usually coplanar with S_d and the axial-surfaces of folds in S_1. These surfaces dip steeply to the northwest. Fold axes plunge moderately to the west. Some dikes and apophyses are isoclinally folded with their fabric coplanar to axial surfaces. A few dikes cut across the earlier subparallel dikes. These have fabrics coplanar with their walls. All foliations are cut by very thin (less than 1 mm), near vertical serpentine veins.

A few masses of strongly deformed metagabbros are found in this area. They have discordant contacts adjoining which high strain zones are developed in strongly serpentinized, olive-grey weathering ultramafic rocks. These may be klippen on, or windows in the ultramafics.

AREA VII

Northwest of Hines Pond, megalenses of layered rocks lie near the contact between the Hines Pond Metagabbros and ultramafic rocks. This contact is a high strain zone; rocks within 50 to 100 meters of this zone are, in addition, more deformed than similar rocks elsewhere in the area. Layered gabbroic and clinopyroxene-rich ultramafic rocks which have been described above have a well developed new layering (S_s) cutting them.

Small ductile offsets in areas I to V develop S_s locally. In the southern part of area III and other areas between area III and Hines Pond high strain facies are found. Here S_s is the dominant foliation. It is cut only by late steep serpentine veins.

S_1 and S_d are reoriented within 1 cm or less from places where S_s cuts them. Ductile "faults" cut through one another very complexly. The high strain zones are narrow, but displacements across them may be large. Most offsets observed were on the order of a few centimeters.

The lineation in the less-deformed rocks of the megalenses (L_d) is obliterated and a new lineation appears. The new lineation (L_s) is defined by very elongate clinopyroxenes in the form of rods. These have aspect ratios of approximately 5 to 1 or greater. They are porphyroclasts in a much finer grained matrix. They are sometimes seen to be sliced and the fragments displaced up to a 2 cm.

In outcrop these rocks are pink with a very rough surface of resistant coarse pyroxenes. They have a phacoidal texture formed by lenses of less deformed material separated by narrow, intersecting very high strain zones containing mylonites. The phacoids are usually about 5 to 7 cm across.

Dunite in these areas shows no effects of this intense deformation on its smooth outcrop surface.

AREAS WITH HIGHLY STRAINED FACIES

Areas which display evidence of intense deformation post-dating that recognized in the previously described areas are located near the Hines Pond Metagabbros. The contact between the metagabbros and adjacent ultramafics is a high strain zone. Strong deformation affects the metagabbros within a few tens of meters of the contact. Megalenses within 300 meters of the present outcrop position of this contact are affected. Ultramafic rocks in this zone are strongly serpentinized. (Fig. 37).

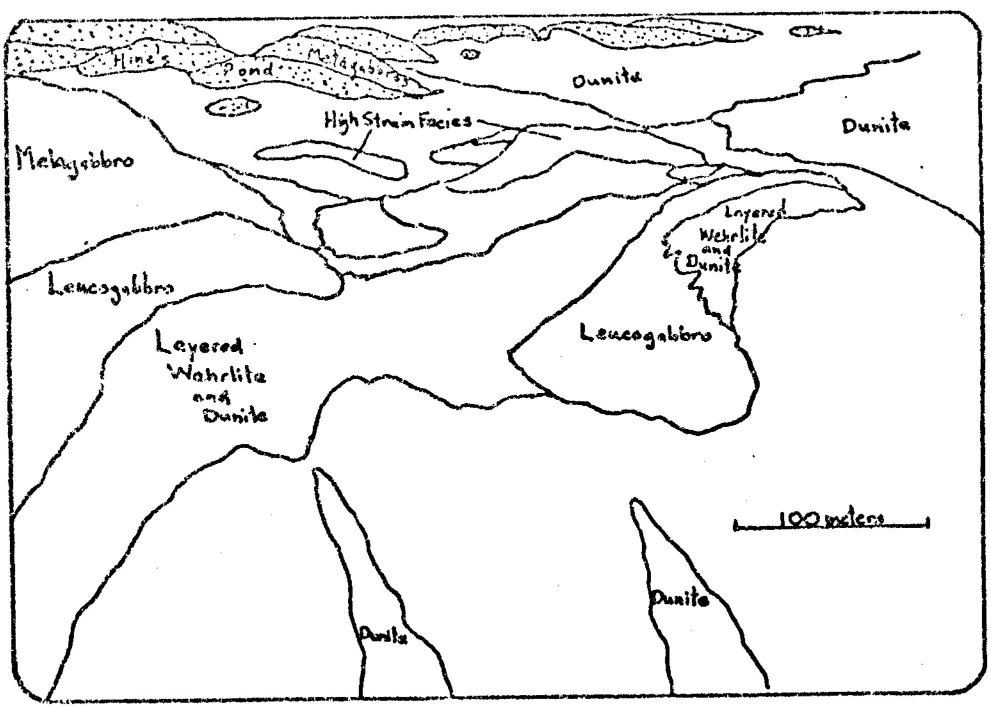
The layering in the megalenses (S_1) can be seen to be progressively destroyed by multiple crosscutting high strain zones (S_s). Gabbro and clinopyroxene-rich ultramafic layers respond in a more ductile manner than adjacent dunite layers. Strong fabrics develop in these high strain zones. Fine grained material wraps around large strongly lineated (L_s) augen of pyroxene.

The rocks have phacoidal structures with less deformed lensoid bodies of material surrounded by narrow high strain zones. Coarse pyroxenes and a few greatly deformed plagioclase grains are the only recognizable minerals. Individual coarse grains can be seen to the bent into S_s at high strain zones. Some pyroxenes can be seen to the sliced and displaced at least 1 cm. Wehrlite dikes cut one another and the early layering (S_1) and gabbro layers (Fig.36). Sometimes these have median chromitite concentrations up to one centimeter thick. Some dikes show the effects of brittle deformation.

F. HINES POND METAGABBROS

The Hines Pond Metagabbros are here so named for their widespread occurrance in the vicinity of Hines Pond. They form a topographically high area of the Lewis Hills but are not clearly related to the rocks of the ophiolite complex. It is proposed here that they form a separate thrust sheet overlying the ultramafic tectonites and dunites of the Lewis Hills. The alternative, that they represent the core of a recumbent antiform exposing part of the basal contact metamorphic aureole, is rejected

Figure 37: Helicopter view to the southeast from above the megalens at Area 4. Steeply dipping contact between dunite and the Hines Pond Metagabbros outcrops along the prominent ridge in the background. High strain facies outcrop between the megalens and the contact.



because they do not resemble the rocks of the aureole. The layering in this 1 km thick mass of rocks is due to alternating plagioclase-rich and hornblende-rich layers from 1 cm to 1 meter thick. Hornblende-rich layers are often irregular and commonly boudinaged in a ductile manner. Overall, the layering is rather discontinuous and lenticular. Gradational contacts between light and dark layers makes this difficult to see. There is also a strong dimensional preferred orientation of grains which define a foliation and lineation coplanar with the layering. No folds were observed within this rock mass except at the margins. Here narrow (1 cm) high strain zones fold the foliation. In these narrow zones, layers and single grains are highly attenuated and, locally, finely laminated, fine-grained mylonites form.

The layering is cut by coarse-grained, dark green hornblendite dikes and sills up to 20 centimeters wide (Fig 38). These usually seem to be boudinaged in a ductile manner. They apparently have a weak tectonite fabric. There are also a few thin (3-8 cm) leucocratic cross-cutting veins of recrystallized calc-silicate material, probably Ca-metasomatised gabbro to anorthosite. These enclose angular xenoliths of fine grained hornblende-rich country rock up to 5 centimeters across.

The boundaries of this mass of metagabbro are faults marked by discordant contacts and high strain zones which seem to be best developed in the adjacent rocks of the ophiolite complex proper. At the western edge of the metagabbros the contact is vertical to steeply east dipping against serpentinized dunites. The contact here is a high strain zone with ultramafics in sharp contact with a thin layer (1 meter or less) of rodingite. Laminated black and white mylonite grades into dark green, fine-grained amphibolites with isoclinally folded layering and incipient development of a secondary layering. This secondary layering is an axial

Figure 38: Coarse mafic (hornblendite) dike cuts banding in Hines Pond Metagabbros.

surface feature and is coplanar with a crude cleavage in the rock. These grade through approximately 2 meters into normal metagabbro.

Near this contact lensoid tectonic inclusions of harzburgite are enclosed by metagabbro. These have highly deformed pyroxenes in them and are strongly serpentinized. These range in size from about 10 cm to 1 meter across.

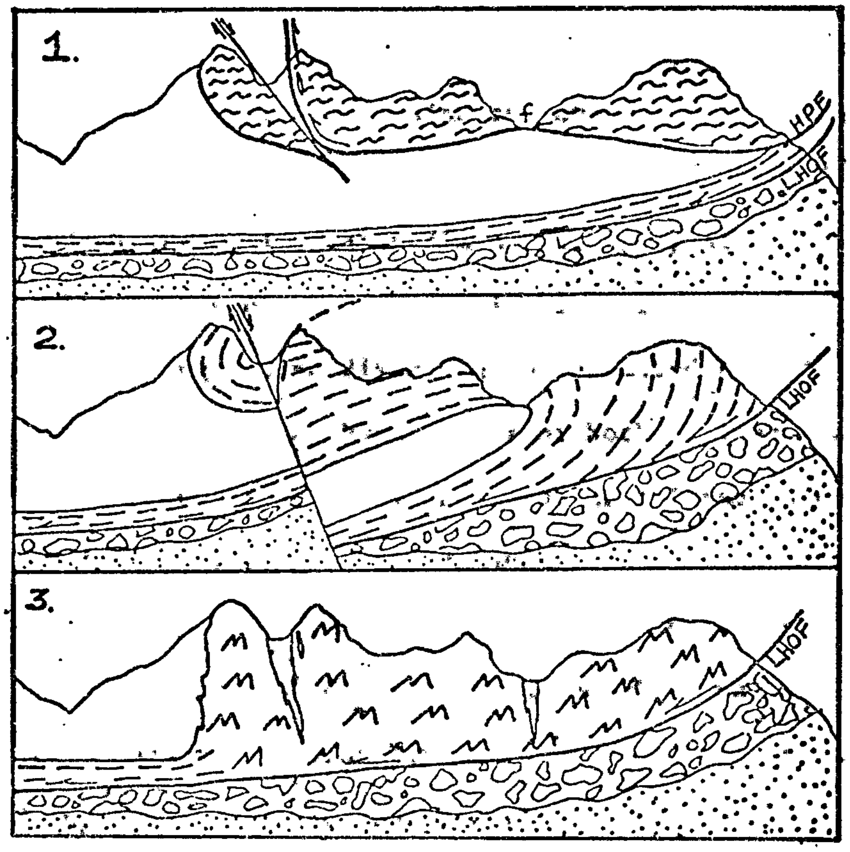
Contacts elsewhere are narrower zones. Ultramafics near these contacts with the metagabbro are highly serpentinized and weather olive-grey instead of dark yellowish orange as elsewhere. Where pyroxenes are present they may be greatly elongated on surfaces coplanar with the contact. These pitch at low angles in this plane. Foliations in the ultramafic rocks are always coplanar with this contact. Metagabbros locally have their foliations truncated by this contact. They have narrow high strain zones oriented at high to moderate angles to the contact (Fig. 37).

The contact itself is vertical along the western and northern margins of the metagabbro. The western margin is fairly straight but the northern one is irregular on all scales. At one locality, near its northwest corner, the metagabbro overlies dunite across a subhorizontal fault. Klippen (10 meters across) lie just west of here. Also, south of Hine's Pond the foliation in the most southerly outcrop of ultramafic rocks dips moderately south and they seem to underlie the metagabbros found in the ridge to the south.

Within the metagabbros several small masses of ultramafic rocks are exposed. These range in size from 1 to 100 meters across. They all lie in topographically low areas beneath high, resistant ridges of metagabbro. Contacts between the two are nowhere exposed. The ultramafic rocks in these areas are always very highly serpentinized. They are layered harzburgites and dunite with variable amounts of thin (up to 4 cm) red weathering, aphanitic (rodingitized gabbroic) dikes. Extension of mapped contacts beneath the metagabbros shows that these masses are probably parts of the layered sequence seen through fensters in the metagabbros. These may also be tectonic inclusions like the smaller inclusions near the contact mentioned above. Normal faults or frontal schuppen may also be responsible for their exposure. The metagabbros, along with the megalenses within the massive dunite, have been openly folded about a steeply northwest dipping axis. The metagabbros must, therefore, have been structurally attached to the ophiolite complex prior to its last phase of deformation.

The metagabbros seem to be a separate nappe (Fig.39) overlying part of the ophiolite complex rather than part of the basal contact exposed by folding (Fig.39,2). This is supported by metagabbro overlying ultramafics in a few localities, ultramafics overlying metagabbro only at apparently overturned contacts, localized high strain and metasomatic zones at contacts, apparent klippen of metagabbros and fensters exposing ultramafics, and absence of mesoscopic isoclinal folds with subhorizontal axial surfaces and north south axes. Another possibility is that these metagabbros are metamorphosed equivalents of the mafic-ultramafic megalenses (Fig.39, 3). Ultramafic material within the metagabbros could be xenoliths or lenses as are commonly observed in the megalenses described above.

This hypothesis is rejected for several reasons: 1) The contact between the ultramafics and metagabbros, is a high strain zone. Gabbros and ultramafics of the megalenses do not have this type of contact. 2) The ultramafic rock types within the metagabbros are not found within the megalenses. 3) Ultramafic rocks in the metagabbros are not lensoid



Ultramafic Rocks of the Lewis Hills Ophiolite Complex
Thrust Sheet
Metamorphosed megalens
Basal Metamorphic Aureole
} Hine's Pond Metagabbros
Volcaniclastic Mélange
Allochthonous Humber Arm Supergroup Sediments
Thrust Fault
Fenster

Fig.39 Structural Interpretations of the Hine's Pond Metagabbros or layered. 4) Metagabbros do not grade into less deformed megalens rocks in any area studied.

G. GABBRO-ULTRAMAFIC LAYERING AND FABRICS IN OPHIOLITE COMPLEXES

The origin of the layering and tectonite fabrics in the rocks of the megalenses near Hine's Pond is a complex problem. Dimensional preferred orientation of coarse grains and aggregates of plagioclase and/or clinopyroxenes is coplanar with the foliation defined by large and small scale layering in nearly all areas. Only at fold hinges and where high strain zones cut this foliation is this fabric oblique to compositional layering. Some dikes are not affected by this foliation. The grains and aggregates may have either or both a planar and linear preferred orientation. This fabric need not have formed synchronously with the lithologic layering nor by related processes. Petrography and elementary petrofabric observations indicate that these rocks have been weakly to very strongly deformed in a ductile manner. Deformation and recovery processes have probably, in most or all cases, largely obliterated any earlier fabric that the rocks may have had. This greatly hinders the investigation of the origin of the layering. All described forms of layering in mafic plutonic rocks, especially those of ophiolite complexes, are considered in following pages.(Table VI).

One type of layering to be considered is cumulate layering. These layers are formed by the settling of crystals in a magma chamber or sill. These accumulate on the floor of the chamber and have compositional and/or size variations of cumulus phases from layer to layer.

In outcrop, cumulate layering is commonly a regular rhythmic layering often in cyclic units in which size and composition grading are common. Experimental work by Bowen (1915) suggests that grains that settle for

TABLE VI Layering in Mafic Plutonic Rocks

	Layering and References	Composition	Scale of Layering	Layer Boundaries	Form of Layering	Grain Shape Orienation in Layers	Origin
Primary	*Cumulate Layering (e.g., Wager and Brown, 1967)	Variable, cyclic, cryptic, monomineralic possible	Single crystal to >100 meters	Often gradational	Generally planar with rhythmic and/or cyclic layers, Sedimentary structures	Coplanar shape/lattice oriented fabric	Deposition of cumulus crystals on the floor of a magma chamber or sill
Primary	*Sill Intrusion (Davies, 1971)	Sill: Fine-grained gabbro with opaques; Country Rocks: Coarse-grained gabbro to pegmatite	Sill: 1.5 meters; Country Rocks: 50cm	Sharp	Intrusive with fine-grained margins, slightly discordant to country rock cumulate layering	Shape orientation coplanar with sill walls (flow structure?)	Igneous intrusion coplanar with cumulate layering
Primary	'Willow Lake-type' (Tauberneck and Poldervaart, 1970)	Plagioclase or hornblende or pyroxene-rich layers in norite to diorite (locally cumulate)	5cm to 30cm	Sharp	Regular, planar with xenoliths of surrounding rock types (norite to diorite)	Coplanar, perpendicular (harrisitic) to layers, also granular	Overcooling of magma in a chamber with intermittant convection currents
Primary	Syn-Plutonic Layering (e.g., Berger, 1971)	Coarse granodiorite and fine-grained trondjemite	few millimeters to 1 meter	Mainly sharp	Locally regular, planar but die out along strike within 3-4 meters	Shape orientation coplanar with layers	Syn-plutonic liquid segregation in a deforming crystal mush
Secondary	Metamorphic Differentiation (Turner, 1939)	Variable (control by host rock)	up to 1 or 2 centimeters	Sharp	Regular planar	Shape and/or lattice orientations	Diffusion
Secondary	(Vidale, 1974)	Granitic in quartzo-feldspathic rocks	up to a few centimeters wide and 3 meters long	Sharp	Irregular veins	None?	Diffusion into dilatant zones, with metasomatism?
Secondary	(Bowes and Parks, 1966)	Hornblende schists and Amphibolites	up to 30 meters	Sharp	Reguler, planar to irregular with augen	Coplanar with layering	Metamorphic Segregation due to heterogeneous pressure
	Partial Melt Segregations (Boudier and Nicolas, 1972)	Plagioclase-rich lenses surrounded by 'depleted ultramafics' within lherzolite with an older layering	a few centimeters thick, discontinuous along strike	Diffuse	Lenticular, coplanar or en echelon with earlier layering, Lensoid, or in Sigmoidal forms	None?	Fractional fusion of lherzolite segregated in dilatant zones
Flattening and Rotation	Rotation of Dikes (Escher, et.al., 1975) and (Ramsay and Graham, 1970)	Dolerite in amphibolite to granulite gneiss	up to 10 meters thick	Sharp	Branching, slightly discordant to foliation of country rocks	None?	High shear strain such as to rotate dikes into approximate parallelism with country rock foliation
Flattening and Rotation	*Flattening and Elongation of Xenoliths (Davies, 1971) (Ramsay and Graham, 1970)	Fine-grained gabbro within layered gabbro	up to a few meters long and .5 meters thick	Sharp	Lensoid	None?	Flattening and elongation of xenoliths or small intrusive bodies

* described in layered rocks of ophiolite complexes

longer periods of time grow larger. For two crystals deposited on the floor of a magma chamber, the one that nucleated further from their point of deposition should be the larger of the two. This may not be applicable to large magma chambers where many variables might influence crystal nucleation and sedimentation.

Sedimentary structures produced by currents in the magma chamber have been described in cumulates. These include cross bedding, shallow scour and fill structures, irregular slump structures and current lineation of elongate grains (Jackson et al., 1975). Preferred dimensional orientation of tabular grains lying on the floor of a chamber result in igneous lamination and planar fabrics. These types of features are good evidence for cumulate layering.

In thin sections from layered cumulate mafic igneous rocks, those with sedimentary structures show cumulate textures. These consist of settled cumulus phases and interstitial post-cumulus phases*. The former may be overgrown euhedral grains showing zoned, euhedral grain upon grain sedimentary textures. Post-cumulus phases are commonly very large irregular oikocrysts. Textures alone may not be proof of cumulate layering. They are often complicated by lack of zoning in crystals, massive overgrowth or resorbtion of cumulus phases, alteration causing minor shape changes in grains (e.g., uralitization of clinopyroxene) and veins, and lack of preferred orientation due to rapid accumulation or slumping. Cumulates with more than two cumulus phases are often very difficult to identify (Davies, 1971).

Petrofabric studies of cumulates show dimensional preferred orientation

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*The terminology of Jackson (1961) is followed here, as it is clear and free of jargon.

textures (e.g., Jackson, 1975). Shapes of grains reflect internal symmetry of cumulus phases so dimensional preferred orientation results in an overall lattice preferred orientation (Brothers, 1964). Cumulate layered bodies are also sometimes characterized by progressive large-scale phase compositional changes that have been called cryptic layering (Wager and Deer, 1939).

Cumulates have been extensively studied in stratiform mafic intrusions such as the Skaergaard (Wager and Deer, 1939), Bushveld (e.g., Cameron, 1963), Stillwater (Hess, 1960; Jackson, 1961) or Muskox (e.g., Smith and Kapp, 1963) Complexes and smaller bodies such as the Palisades Sill (Walker, 1970). Undeformed cumulates are also reported from the transition zone into the lower gabbro zone of many ophiolite complexes (Thayer, 1969; Davies, 1971; Juteau, 1970; Moores and Vine, 1971; Bezzi and Piccardo, 1970, 1971; Parrot, 1969, 1975; Greenbaum, 1972; Alemann and Peters, 1972; Gass and Smewling, 1973; England and Davies, 1973; Patterson et al., 1974; Brown and Bradshaw, 1974). Smith (1958) and Cooper (1936) both report probable cumulate textures and structures from the Bay of Islands Ophiolite Complex. Primary layering of the 'Willow Lake-type' (Tauberneck and Poldervaart, 1960; Loomis, 1963) develops around xenoliths in orbicular structures and near the wall of bodies of norite and quartz diorite which elsewhere may also display cumulate layering. Plagioclase-rich layers from a few millimeters to a few centimeters thick alternate with 1 meter thick layers of finely layered and/or homogeneous rock. Individual layers are relatively continuous and have sharp contacts due to their contrasting mineralogy. Dimensional preferred orientation fabrics observed in these are coplanar with layering (Leveson, 1963) or perpendicular to the layering (harrisitic). Granular textures are also observed. The mechanism proposed for the formation of this layering is overcooling of magma with diffusion between the magma and interstitial liquid of a crystal mush (Taubeneck and Poldervaart, 1960) possibly with intermittent pressure variations (Loomis, 1963).

This type of layering has not been reported from ophiolite complexes. Orbicular structures, however, are observed in some Alpine Ultramafic bodies. 'Willow Lake-type' layering may have formed and since been altered by deformation and/or recrystallization.

Another type of layering that should be considered is that described for synplutonic deformation of magmatic bodies. 'Regular banding' (a few millimeters to 1 meter thick) is formed in the Main Donegal Granite by localized feldspathization of trondhjemitic material (Berger, 1971). Planar and linear fabrics coplanar with the layering have developed penetratively through these rocks. Deformation of a mafic crystal mush might lead to similar layering and fabrics.

Another type of layering would result from multiple, coplanar intrusion of sills. This could produce layering on a large or small scale. These could have cumulate textures resulting in layered cumulates and noncumulates.

Magmatic layers should have sharp boundaries with their county rocks and would probably be discordant, at least locally, to any earlier layering. Branching, crosscutting and pinching-out might occur.

Textures in these sills might be cumulates or flow fabrics dimensionally oriented parallel to their walls. These might form during the intrusion of a crystal mush.

A few small gabbro sills generally coplanar with earlier layering are reported to intrude cumulate gabbros in the ophiolite complex of Papua (Davies, 1971).

Dikes could be rotated by strong deformation into near parallelism with earlier layerings that they originally cut at high angles. These might look much like the sills mentioned above but the rocks would be much more deformed. Tectonite fabrics forming in these rocks, in response to the deformation, would not necessarily be coplanar with either the dikes or the earlier layering.

New layering commonly develops in deformed rocks of a wide variety of compositions and metamorphic grades. These usually form as axial surface foliations of older folded foliations (Nisbet and Gregg, in prep.). In high grade rocks these layers usually have more diffuse boundaries than those formed at lower grades. Tectonite fabrics are widely developed, with planar more common than linear fabrics.

At high metamorphic grades one process which might form new layering is metamorphic differentiation controlled by diffusion (Turner, 1939). This would probably form discontinuous layering with diffuse boundaries. Diffusion probably is not active over not more than about 1 cm. Layering formed by this process would be thinner than this, and probably only a few millimeters in most cases. Domains that have been enriched in some component relative to the parent rock would be surrounded by a domain relatively depleted in that component. Veins forming in dilatant zones in high grade felsic rocks show this relationship (Vidale, 1974). Metasomatic transport also seems to be important in these structures, though no fabric indicating flow parallel to the vein walls has been found.

Rocks deforming at high temperatures are likely to begin partial melting. This might take place homogeneously throughout a rock body or be localized along high strain zones.

At estimated oceanic upper mantle confining pressures (2 to 3 kb) and relatively high strain rates (10^{-3} sec^{-1}), strain heating of a few hundred degrees is probable (Goetze, 1975). Molten material might form along high strain zones due to this elevated temperature.

Partial melting of ultramafic material to produce plagioclase-rich melts has been suggested by a few workers (Menzies, 1973; Boudier, 1972; Boudier and Nicolas, 1972; Dickey, 1970). This material is segregated in joints, sigmoidal tension gashes, or lenticular layers surrounded by ultramafic material. Electron probe analytical work shows enrichment and depletion of different oxides in the partial melt lenses and in the surrounding ultramafic material relative to the proposed parent rock (Menzies, 1973).

Along with those of the primitive material from which they were derived, chemical analyses of these enriched and depleted materials plot as the earliest part of a fractionation curve (Menzies, 1973; Boudier and Nicolas, 1972).

Deformation synchronous with partial melting could help concentrate this liquid into lenses or dikes forming in dilatant zones. Lenses in the Lanzo Massif have been observed coplanar or in en echelon orientations with respect to the dominant tectonite fabric of the surrounding rocks, which may cut through the lenses (Boudier and Nicolas, 1972). Textures suggestive of partial melts have been briefly described (Menzies, 1973). These include subhedral plagioclase and clinopyroxene surrounded by a framework of anhedral, residual, olivine, and orthopyroxene. Depleted ultramafic rocks have interlocking anhedra of residual phases. These textures could be destroyed by subsequent deformation and recrystallization.

Any layering in a body might be isoclinally folded and transposed. The original layering in this case would be complexly folded back over itself. With continued strain fold limbs would become bondinaged and highly attenuated leaving hook-shaped, isolated, tight fold hinges. These could be further deformed to make their identification as closures very difficult. This could result in discontinuous layering defined by lenses and schlieren. Thus, in highly deformed rocks, regions with abundant folds may be regions of lower deformation than adjacent regions where folds are not recognized. The thickness of these bodies and the sharpness of their contacts with surrounding material probably depends in part on the original form of the layering.

Transposed layering is not a new layering, but rather a mechanically rearranged earlier layering. Transposition renders the original sequence of layers undeterminable in the affected region. Gross original relationships may be preserved through a transposed body but details, in most cases, would not be possible to work out (Nisbet and Gregg, in prep.).

In transposed layering some fold closures should survive indicating the intense deformation of the rocks. In layered rocks of ophiolite complexes folds are very uncommon and are often attributed to slump structures. Folds may be difficult to recognize due to the coarse grained, gradational nature of the layers. Such strong deformation would produce strong tectonite fabrics. Planar axial surface fabrics in transposed rocks would be coplanar with the long axes of the remaining lensoid bodies of the original layering.

The fabric of any layering might be destroyed by subsequent deformation. Strong dimensional and/or lattice preferred orientations may develop, obscuring the original fabric. Gabbro and ultramafic tectonites are found in some ophiolite complexes some of which may be deformed cumulates (Moores and Vine, 1970; Davies, 1971). Fabrics of these are similar to those reported from Alpine Ultramafic bodies (e.g., Nicolas et al., 1971) and those produced experimentally under simulated upper mantle conditions (Nicolas et al., 1973; Carter and Avé Lallemant, 1970). Two mechanisms have been described.

One process is synkinematic recrystallization (Carter and AveLallemant, 1970). Recrystallization is controlled by host grain lattice orientations and the local stress field. The latter ultimately allows grain growth which consumes the host grains and any unfavorably oriented new grains. The earliest grain growth is localized along grain boundaries and regions of high strain in the crystal lattice (deformation bands, high angle grain boundaries, etc.).

A second method of developing strong fabrics is deformation and subsequent recrystallization (Nicolas et al., 1971). Plastic deformation with intergranular and intragranular gliding is evident from the fabrics observed. These have deformation bands forming perpendicularly to slip planes. Coarse grains are sliced into narrow slivers along these planes and separated by narrow domains of fine grained material. Subsequent recrystallization is controlled by the deformation structures.

Complex combinations of layering and fabrics of primary and later metamorphic, igneous, or mechanical origin may not allow the complete history of a body of rock to be determined. In the coarse-grained, gradational layered rocks of the Hine's Pond area a single penetrative deformation could have completely obscured the original nature of the rocks. Layering and fabrics may have been destroyed and/or overprinted by new ones. The extent to which a mass of rocks has been deformed depends upon the recognition of primary structures, fabrics, etc.

The megalenses of the Hine's Pond area have a complex (overlapping?) history of igneous, deformation, and recrystallization activity. The following section is an attempt to put together outcrop and microscopic observations to propose a working hypothesis for the history of the Hine's Pond megalenses.

H. HISTORY OF DEFORMATION AND IGNEOUS ACTIVITY

Fractional fusion seems to be the most likely possible process by which the gabbroic and basaltic components of the Bay of Islands ophiolite Complex could be generated from supposed mantle material (Kay, Hubbard, and Gast, 1971; Irvine, 1972). This would leave a residue of depleted ultramafic material such as the harzburgite-dunite tectonites that make up the base of the complex. The megalenses of the Lewis Hills are likely to be masses of partial melt material surrounded by depleted ultramafic material.

The study of outcrop relationships, polished slabs and thin sections allows more than a single hypothesis for the history of deformation of these megalenses. The known types of layering in plutonic rocks described above are used in these hypotheses (see Fig.40).

The earliest foliation in the megalens rocks is a lithologic layering. Layers are from a few millimeters to several tens of meters thick. They have gradational contacts with both size and compositional grading. Contacts between olivine-rich rocks are especially diffuse. Chromitite, anorthosite and clinopyroxenite layers have very sharp contacts with olivine-rich ultramafic rocks. Of these monomineralic rocks only clinopyroxenites are abundant. Locally, apparent density grading (rhythmic layering) exists but no well defined repeated sequences of layers (cyclic layering) was observed. This layering seems to be cumulate, and therefore probably formed by the accumulation of cumulus crystals on the floor of a magma chamber. None of the other types of layering discussed above satisfy the observations. Cumulate textures were only observed in thin sections of chromitite. All other phases have been so completely recrystallized or altered so that cumulate textures are not recognized and have probably been obliterated. This reflects the relative resistance of chromite to recrystallization compared to the silicates present.

No unquestionable mesoscopic sedimentary structures were observed.

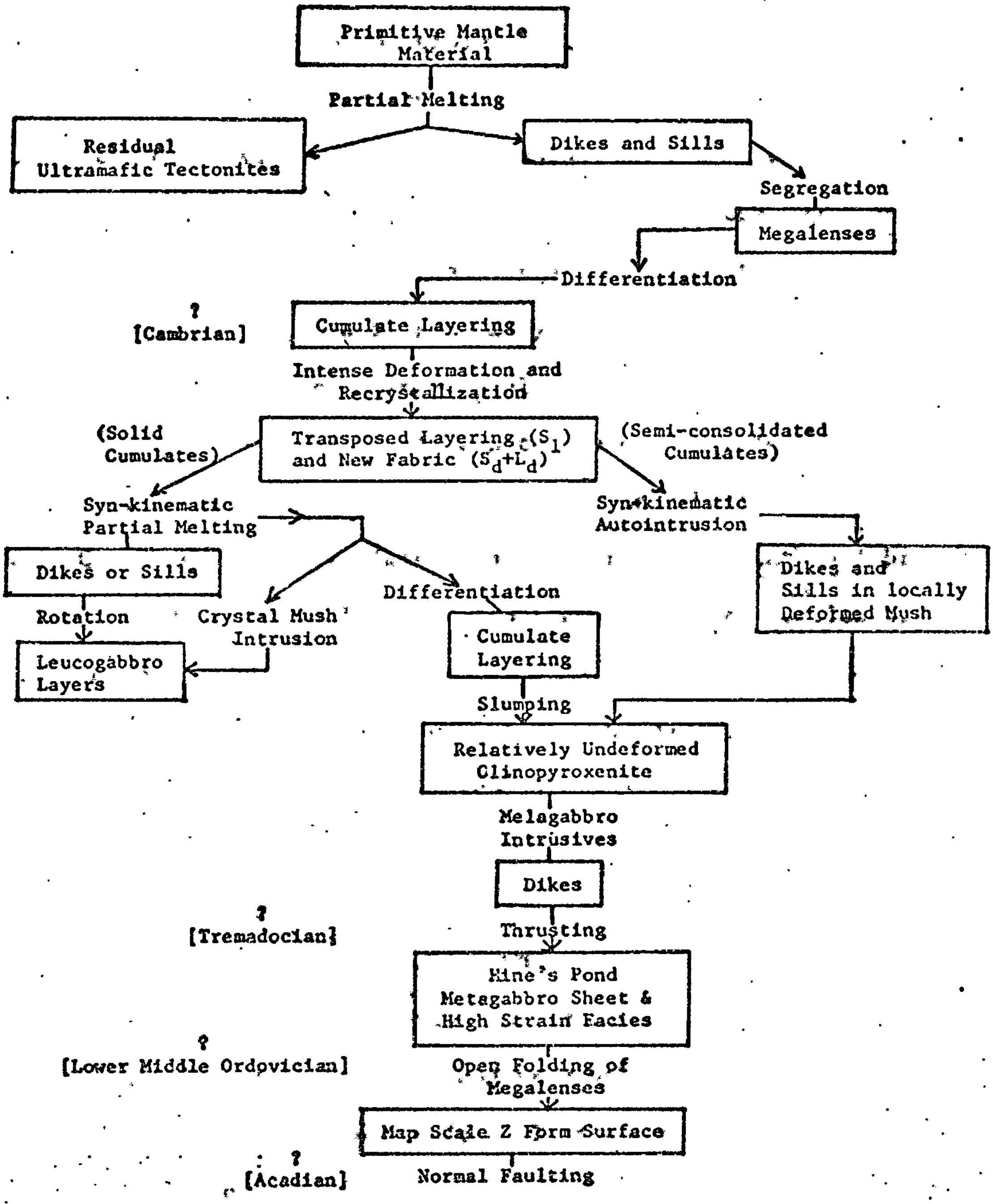


Fig. 40 Generalized History of Deformation and Igneous Activity within the Hine's Pond Megalenses

No consistant facing direction was obtained from observations of common graded beds. There may be one possible way to determine facing in this sequence. Any anorthosites are found only at the tops of these sequences. Considering the density, and order, of crystallization expected for these rocks it seems logical from these data to suppose that the megalenses near Hines Pond are right-side-up and face westward. The rest of the Bay of Islands Complex to the north also generally faces westward and is openly folded. Within the megalenses, in general, the following sequence of rock types are found from bottom to top: dunite, chromite, feldspathic wehrlite, olivine gabbro and troctolite, clinopyroxenite, anorthosite, wehrlite (Fig.14). Cumulates may have dimensional preferred orientation fabrics (e.g., Brothers, 1964) and at least the Vourinos Ophiolite Complex has some lineated, but apparently tectonically undeformed cumulates, supposedly formed under the influence of currents within the magma chamber (Jackson et al., 1975). Any such fabrics, at least within the silicates of the Lewis Hills megalenses, have not been recognized, and are thought to have been destroyed.

The cumulate layering is difficult to see in the megalenses. Layers now have the form of lenses and discontinuous layers. The cumulate layering has probably been isoclinally folded and transposed so that the original layered sequence cannot be determined, at least on a mesoscopic scale. Though the layering in the megalenses is apparently transposed internally, the large scale layering of the Lewis Hills need not have been. The discontinuous outcrop pattern of gabbroic rocks with strong tectonite fabrics, however, suggests that it is perhaps likely to have been. No megascopic folded forms have yet been found.

Evidence for the intense internal deformation of the megalenses is as follows. In layers with sharp boundaries, such as anorthosite or chromitite, the layering is often isoclinally folded. Isolated intrafolial fold closures and lenses are common in these lithologies. Single crystals and aggregates in coarse grained wehrlites and feldspathic wehrlites often appear to be folded. Polished slabs of these lithologies did not confirm the presence of folded forms. Boundaries of aggregates in these rocks are more sharply defined on weathered surfaces. Hook-shaped concentrations of clinopyroxene, chromitite, and plagioclase in the noses of lensoid ultramafic layers suggest that these diffuse lenses are also fold hinges. Folds in the ultramafics are difficult to recognize for the following reasons: 1) very coarse grain size; 2) high relief on weathered surfaces; 3) gradational contacts between rock types; and 4) absence of platy minerals. Strong axial surface foliation defined by dimensional preferred orientation of coarse grains and aggregates or secondary layering might also obscure fold hinges (Fig.19).

Mesoscopic folds in these rocks have axial surfaces coplanar with the strong dimensional preferred orientation of coarse grains and aggregates which define a foliation (S_d) and strong lineation (L_d). This strong fabric is penetrative in the megalenses except within later gabbro sills, clinopyroxenites, and localized high strain zones. The S_d foliation cuts through the noses of lenses in the ultramafic rocks. It has probably developed either by syntectonic recrystallization (Carter and Avé Lallemant 1970) or by plastic deformation followed by recrystallization (Nicolas et al., 1973). There is abundant thin section evidence for the development of this fabric.

Sills of leucogabbro (up to 4 meters thick) whose position is controlled by the eariler foliations (S_1 and S_d), are slightly discordant to the olivine-rich ultramafics. Clinopyroxenites discordantly overlie them. These sills pinch-out laterally into less plagioclase-rich rocks or layered plagioclase-rich and plagioclase-poor rocks. The sill rocks are strongly altered but strong tectonite fabrics are not always developed in them. These rocks are layered on a scale of 0.5 to 2 cm. Plagioclase is greatly altered but the overall shapes of recrystallized mafic domains suggest cumulate textures. These might be crystal mush intrusions or cumulate sills.

During the deformation mentioned above and to some extent during the intrusion of the leucogabbro sills, plagioclase-rich material was segregated into localized zones. This material is concentrated in lenses, discontinuous layers to 5 cm thick and dikes to 4 cm wide. These are localized along high strain zones and dilatant zones and may represent nearly in situ partial melt material. The following observations support this hypothesis. The plagioclase-rich lenses are surrounded by plagioclase and clinopyroxene-poor material, usually dunite (Fig.23). They are apparently magmatic since they have the same composition and are sometimes continuous with dikes which cut S_d, S_1, and other layers of the same composition. These layers and lenses often truncate dikes indicating that they mark planes of tectonic dislocation. Some dikes seem to form at the intersections of layers and lenses which are often in the form of isolated fold closures. These may be dikes or masses of any form that have been rotated and flattened into approximate parallelism with earlier foliations. Very irregular masses of anorthositic-troctolite form in some places. These may have a small scale layering within them (Fig.20).

Dikes often form at moderate to high angles to the lithologic layering. They are often coplanar with or occupy ductile "faults" with offsets of up to at least 1 meter (Fig.31). These dikes generally have dimensional preferred orientation of grains coplanar with their walls. They have not been seen to be affected by S_d.

Dunite layers containing irregular clots, up to 3 cm across, of coarse clinopyroxene and plagioclase are found in several localities (Fig. 27). They are usually near the leucogabbro sills. The clots may represent secondary or relict primary partial melt segregations within depleted dunite.

The large leucogabbro sills themselves may be partial melt segregations. With few exceptions, they are bounded above and below by 1 to 2 meter thick zones of interlayered (3 to 6 cm) anorhtositic gabbro and dunite. There is usually a dunite layer adjacent to the gabbro. In the rocks outside this zone plagioclase becomes more homogeneously distributed and the rock has no small scale layering. These grade from wehrlites with discontinuous schlieren and stringers of plagioclase-rich material to homogeneous feldspathic wehrlite. There is an apparent increase in modal plagioclase from the interlayered zone outward for as much as 5 meters. Thick leucogabbro sills sometimes grade laterally into feldspathic ultramafics and eventually dunite. They also may be interfingered with feldspathic ultramafics with abundant magmatic lenses and discontinuous layers. All the leucogabbro sills in the area thicken to the south and west.

Where the lenses pinch-out they are often pegmatitic. Processes here seem to have produced rocks enriched in plagioclase and clinopyroxene and others depleted in those components. These may reflect on a smaller scale the processes that formed the megalenses of the Lewis Hills entirely enclosed by dunite.

The partial melting processes may have formed the large leucogabbro sills along major dislocation zones. These could have been added to by the dikes that cut the layered sequence (S_1).

The deformation and heat that generated the magmatic material may have remobilized the overlying clinopyroxene-rich ultramafics. These are mainly irregularly layered and bondinaged clinopyroxenites (1 to 2 cm), separated by thin (.5 to 5 cm) dunite layers. These are deformed by tight concentric to similar folds with boudinaged limbs. These rocks show no strong fabric unlike the rest of the rocks in the megalenses. In thin section these apparently are the least deformed rocks in the area. Deformation in them dies out away from the leucogabbro sills and these sills are locally crosscut on a small scale by these clinopyroxenites. These rocks are difficult to explain.

The part of the magma generated from the volume now represented by the residual dunite-harzburgite tectonites or that form a secondary episode of partial melting may have had secondary episodes of fractionation, crystal accumulation and minor deformation. This would also account for the apparently underformed nature of the clinopyroxenites. Layered dunite (2 to 5 cm) and anorthosite (3 to 4 cm) above the clinopyroxenites, in at least one megalens, is tightly folded. It seems unlikely that the pyroxenites could have selectively escaped this deformation.

Another possible way to allow for relatively undeformed clinopyroxenites would be by deformation of the megalens prior to complete solidification of the magma. The lower parts of the sequence would be relatively solid and could deform as described above and possibly generate local partial melts. Near the floor of the chamber, material might have been a crystal mush, which could now be represented by the pyroxenites. Crystals and interstitial magma of overall gabbro composition could have been intruded into the semi-consolidated mass during deformation. This intrusion might have been localized along the solid-crystal mush interface and have caused massive slumping in the mush. This would perhaps account for the irregular layering and variable folding in these rocks.

Melagabbro dikes cut all of the foliation of the layered sequence. They have strong fabrics and a 0.5 to 2 cm layering developed coplanar with their walls. They are in turn cut by wehrlite dikes with grain shape foliations coplanar with their own walls. Locally the metagabbros enclose xenoliths of monomineralic rocks such as anorthosite and clinopyroxenite. These may have intruded unconsolidated cumulates as they form migmatitic rocks (Fig.33) and possible slump folding is seen near the walls against the pyroxenite county rocks (Fig.34).

Elsewhere, similar rocks intrude generally along axial surfaces of isoclinal folds that are often broken near their hinges and displaced along their axial surfaces. These cut no older gabbro layering. They may, therefore, be older or younger than the other metagabbros. A small megalens occurs along strike 200 meters east of such rocks south of Hine's Pond. The relationship between the dikes and the megalens is unknown.

Fabrics and layering in the megalenses have strong, local high strains superimposed upon them. These are reflected in the strong ($L_s + S_s$) fabric and the obliteration of previous structures. They are localized near the contact with the Hine's Pond Metagabbros, and are probably a result of their tectonic emplacement as a higher thrust sheet. The metagabbros are locally deformed along this contact. They have a pre-existing layering, and strong dimensional preferred orientation of hornblende and plagioclase. It is not possible to correlate structures predating the high strain zones in the metagabbros with those of the megalenses.

Both the metagabbros and the gabbros of the megalenses of the Hine's Pond area are folded about steep northwest plunging axes. This may have accompanied obduction of the ophiolite. This marked the formation of new garnetiferous layering in the rocks of the basal aureole which was followed by calcium-metasomatism and serpentinization at and near the base of the ophiolite complex.

The open folding might alternatively have taken place during the Acadian Orogenic event. East-west normal faulting is probably Acadian in age.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND SPECULATIONS

The study of many layered mafic-ultramafic bodies in orogenic belts has revealed a recurring assemblage of rock types with consistent large-scale igneous relations and internal proportions. These assemblages are known as ophiolite complexes and from base to top generally consist of ultramafic metamorphic tectonites, interlayered ultramafic and gabbro (transition zone), cumulate and massive gabbro, altered to low grade metamorphosed mafic dikes forming a sheeted complex, altered mafic pillow lavas and a cap of volcaniclastic sediments or marine lutites with radiolarian chert. Minor intrusive bodies of tonalite; trondjemite and hornblende gabbro are common in the higher levels of the plutonic part of the complexes.

Complete and dismembered ophiolite complexes occur in various parts of orogenic belts. The form and detailed tectonic setting of ophiolites is quite variable (Dewey and Bird, 1971; Miyashiro, 1975).

Dismembered and/or metamorphosed ophiolite complexes are probably common but potentially very difficult to impossible to prove as such. The Vermont serpentine belt is probably a good example of such a situation.

Other occurrances of ophiolite complexes include mélange units containing blocks of all the characteristic members of the ophiolite assemblage. These melanges are considered to have formed in the inner wall of deep sea trenches which have been subsequently uplifted as parts of orogenic belts.

Complete ophiolite complexes are mostly found in the form of giant high level nappes in orogenic belts. The best examples of these are the Semail Nappe of the Northern Oman Mountains (Reinhardt, 1969; Alleman and Peters, 1972), the Papaun Ultramafic Belt (Davies, 1971) and the

Bay of Islands Complex.

The best hypothesis for the origin of ophiolite complexes is that they are slices of oceanic crust and upper mantle which were formed at some type of accreting plate margin and subsequently tectonically emplaced into various parts of orogenic belts. Many tectonic models can be devised for the obduction of ophiolite nappes over continental margins (e.g., Dewey, 1975).

Much recent work has focused on the correlation of ophiolite complexes with oceanic crust and upper mantle. The following, taken together strongly suggest a positive correlation:

1. Similar gross physical characteristics of intact ophiolite complexes with geophysical models of the oceanic crust and upper mantle for various ocean basins (LePichon, 1969; Dewey and Bird, 1971).

2. Lithologic similarities between rocks of ophiolite complexes and dredged or drilled rocks of the ocean floor and its tectonic escarpments (e.g., Dewey and Bird, 1971; Moores and Vine, 1971; Gass, 1967).

3. Similarities in physical properties (e.g., velocity of compressional wave transmission and magnetic properties) of ocean floor and comparable ophiolite complex rocks (Petersen, Fox, and Schrieber, 1974).

4. Chemical similarities between some rocks of ophiolite complexes and abyssal tholeiites and associated metamorphic rocks (Aumento et al., 1971).

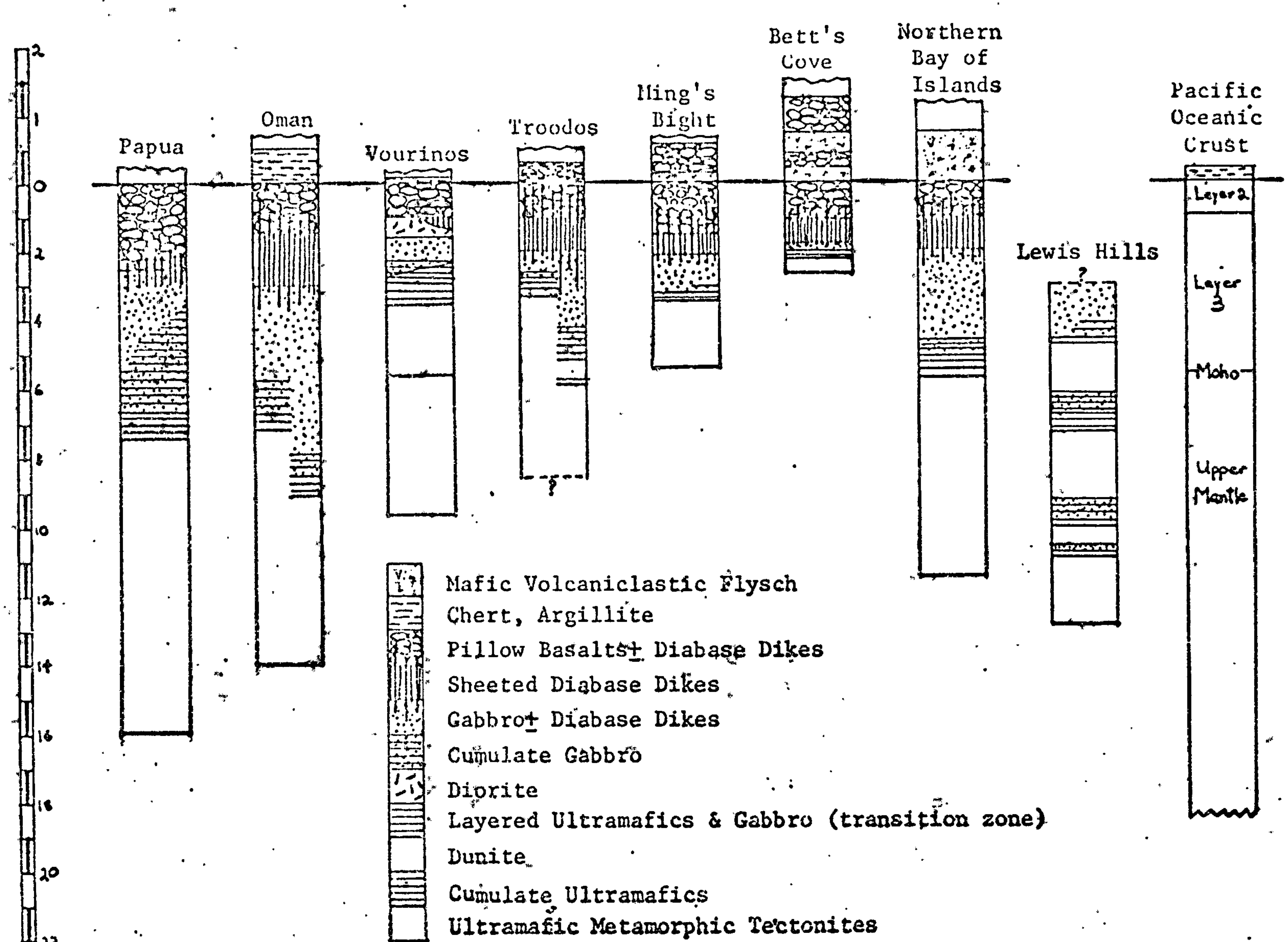
5. Presence of high pressure and temperature mineral assemblages indicative of mantle conditions in ophiolite complex ultramafic metamorphic tectonites (Church 1972; Irvine, 1972).

6. Common fabrics and sub-fabrics like those produced experimentally under supposed upper mantle conditions in ultramafic metamorphic tectonites of ophiolite complexes (Nicolas, 1969; Nicolas et al., 1972, 1973; AvéLallemant and Carter, 1970).

7. Similar metamorphic assemblages in ophiolite complexes and dredged rocks, and vertical metamorphic relations in these complexes similar to those predicted to exist in the oceanic crust based on depth and geothermal gradient considerations (Dewey and Bird, 1971; Williams and Malpas, 1972).

8. Dismembered ophiolite complex is found on Macquarie Island

Fig. 41 GENERALIZED COLUMNAR SECTIONS OF VARIOUS OPHIOLITE COMPLEXES



after compilation by Kidd, 1971

and is considered to be exposed ocean floor (Varne and Rubenach, 1972).

9. Sheeted diabase dikes in ophiolite complexes demand 100% lateral extension of the crust, up to greater than 100 km, probably possible only at accreting plate margins (Gass, 1967; Moores and Vine, 1971).

10. Restored compressionally telescoped continental margins in orogenic belts indicate that ophiolite nappes were derived from deep oceanic regions (Stevens, 1970; Glennie et al., 1972; Dewey, 1975).

11. Sediments characteristic of abyssal depths in ocean basins (radiolarian chert, manganfierous lutites, etc.) or marginal basins (volcaniclastic flysch) interbedded with and overlying pillow lavas of ophiolite complexes (e.g., Reinhardt, 1969; Williams, 1973).

Despite this evidence some authors have challanged this hypothesis on the basis of chemical analysis of basalts from ophiolite complexes (Ewart and Bryant, 1974; Miyashiro, 1973; Miyashiro, 1975). Ambiguities in the chemistry of these altered mafic rocks probably reflect our rather meager knowledge of processes beneath spreading centers and the inherent biases of deep sea dredging. Detailed structural work has not been done within many ophiolite complexes, so presently unknown structural complications may also cause ambiguities. Chemical analysis without adequate structural control of sampling could cause great confusion.

These problems underline the need for deep drilling in the ocean basins and detailed mapping within ophiolite complexes. Chemical analysis and radiometric age determination done in conjunction with detailed mapping could resolve many currently important problems concerning ophiolite complexes.

Although the Bay of Islands Ophiolite Complex is thought of as one of the world's best exposed, complete exposures, the Lewis Hills area is quite anomalous. Generalized columnar sections of some of the world's best known ophiolite complexes and the Lewis Hills illustrates this (Fig. 41).

The Lewis Hills has the thick ultramafic tectonite basal member characteristic of well developed ophiolite complexes. It also has, along its basal contact, a thin contact metamorphic aureole. which is commonly found beneath the ultramafics elsewhere in the Bay of Islands Complex.

By the similarity of its lower units to those of the northern two massifs of the Bay of Islands Complex and the spatial distribution of the massifs, the Lewis Hills is certainly part of the ophiolite complex. It is different from all other complexes reported and may provide some on-land evidence, otherwise unobtainable at the surface, of processes beneath spreading ridges of main ocean basins or in marginal basins.

This study has defined significant differences between the Lewis Hills and the complete ophiolite complex to the north. The Lewis Hills is distinguished by the following unique features:

1. It lacks the thick (4 km) sequence of massive gabbro and structurally higher units (2 km) characterisitc of the ophiolite suite.

2. There is a very thick (6 km) section of rocks characteristic of the transition zone of other ophiolite complexes, where this zone is not normally over 0.5 km thick.

3. Well developed foliations and strong lineations indicate unusually intense and widespread high temperature deformation. They form a complex and apparently rather irregular sequence recording a complex history of regional and local deformation as well as igneous and metamorphic activity.

4. Very large volumes of massive, homogeneous dunite are present that enclose megalenses of layered olivine-rich gabbroic and clinopyroxene-rich ultramafic rocks.

5. Large masses of high grade metamorphic rocks are found apparently overlying ultramafic rocks of the ophiolite complex proper with an apparent

thrust fault contact and locally developed high strain facies.

Beyond these large scale relationships this detailed study of the internal structure of the layered gabbro-ultramafic megalenses permits the following generalizations:

1. The megalenses consist in large part of a highly deformed cumulate (?) layered sequence in which it is no longer possible to determine the original layered sequence except on the grossest scale. Less deformed cumulates are reported from a few ophiolite complexes (Moores and Vine, 1971; Davies, 1971; Brown and Bradshaw, 1974).

2. Penetrative foliations and lineations defined by strong dimensional preferred orientation of coarse grains and aggregates have developed generally coplanar with the lithologic layering. These have probably developed by either syntectonic recrystallization or deformation with subsequence recovery and primary recrystallization.

3. Igneous activity synchronous with the high-temperature deformation is recorded by leucogabbro intrusives controlled preexisting within the megalenses. No dikes enter or leave their boundaries. Thus, the megalenses seem to closed systems. Dikes of the same composition both cut the layering and are either affected by the fabric in the surrounding rocks or more commonly have fabrics coplanar with their walls.

4. Ductile deformation along high strain zones (shear belts?) is common, and these are used synkinematically to intrude magma and/or crystal mush between the layers. Gabbro responds much more plastically than the surrounding ultramafic rocks. They may have been unconsolidated at the time of deformation.

5. Irregularly layered clinopyroxenites are apparently unrecrystallized and may represent late magmatic, remobilized or annealed material.

6. The whole area has been openly folded about steeply northwest plunging axes without the development of a penetrative foliation.

7. The area has been dissected by west to northwest trending normal faults with small displacements.

All the deformation, and igneous and metamorphic activity, except the normal faulting, (1 through 6 above) probably took place before or during the obduction of the ophiolite complex while the complex was at high temperatures. Ductile deformation, widespread recrystallization of olivine, plagioclase, and pyroxene, and lack of chilled margins suggest this.

Considering all the data from the Hine's Pond area several hypotheses can be made concerning the history of the Lewis Hills Ophiolite Complex, as an oceanic crust/upper mantle fragment. The following suggestions assume that no penetrative deformation, except possibly in the metamorphic aureole and adjoining basal ultramafic rocks, occurred during the transportation of the ophiolite complex as a part of the allochthonous sedimentary and metamorphic terrane upon which it now lies.

One possibility is that this ophiolite complex represents a deeper, presently unknown crustal or upper mantle level than is exposed in ophiolite complexes elsewhere. Since none of the upper members of the ophiolite suite are presently known in the Lewis Hills there can be no certainty as to the depth below the seafloor at which the rocks now exposed in the Hine's Pond area were formed.

Most models for processes beneath spreading ridges call for partial melting of primitive upper mantle material rising through adiabatic conditions. Flexural rigidity calculations show that no large magma chamber can exist below spreading centers (Dewey, Fox, & Kidd in prep.). It is more likely that many small repeated magma injections coalese to form oceanic layer 3.

Megalenses of plagioclase and clinopyroxene-rich material in the Lewis Hills may represent fractionated, deformed, partial melt blobs frozen within depleted upper mantle material below or near the M seismic discontinuity. This discontinuity probably represents the level at which ultramafic material becomes dominant beneath lower velocity mafic material. This is defined by seismic refraction, which is based on the assumptions of laterally continuous, homogeneous layers of rocks which increase in density with depth. Such megalenses could therefore exist in the upper oceanic mantle and not be detected by seismic refraction.

Their lower velocity of transmission of compressional waves would be averaged with the ultramafic rocks that surround them. This could lower the velocity of a mainly ultramafic layer. Furthermore, if these megalenses are sufficiently common and have strong dimensional preferred orientations in the upper mantle, they may at least partly account for seismic anisotropy observed there (e.g., Raitt et al., 1969).

Another possibility is that during the initial stages of obduction oceanic crust has been deformed and metamorphosed. Transition zone-type lithologies lie over ultramafic tectonites of the Lewis Hills. These ultramafics are typical of other ophiolite complexes and are considered to be upper mantle rocks (Moores and Vine, 1970; Moores, 1970; Dewey and Bird, 1971). The Lewis Hills may represent deformed crustal rocks in which the typically higher levels of which have been altered or removed during obduction. The abundant amphibolites and metagabbros may represent metamorphosed basalts, dolerites, and gabbro of the oceanic crust.

Rocks similar to those of the Hine's Pond Metagabbros have been dredged from transform fault zones of the ocean basins. It is not known to what extent if at all these are present in oceanic crust away from these tectonically active areas. At transform fault zones, oceanic crust of two diverging lithosphere plates slide past one another between midoceanic ridge offsets. Cataclastic, granulated, and mylonitic rocks are dredged from here reflecting brittle deformation. At deeper crustal levels plastic deformation probably takes place. The results of such processes here are unknown at present.

The history of a mass of oceanic crust produced at a spreading ridge at a transform fault zone involves complex deformation and igneous activity (Fig. 42). From the time it is produced at the ridge crest until it reaches a point opposite the offset portion of the ridge crest the rocks should be

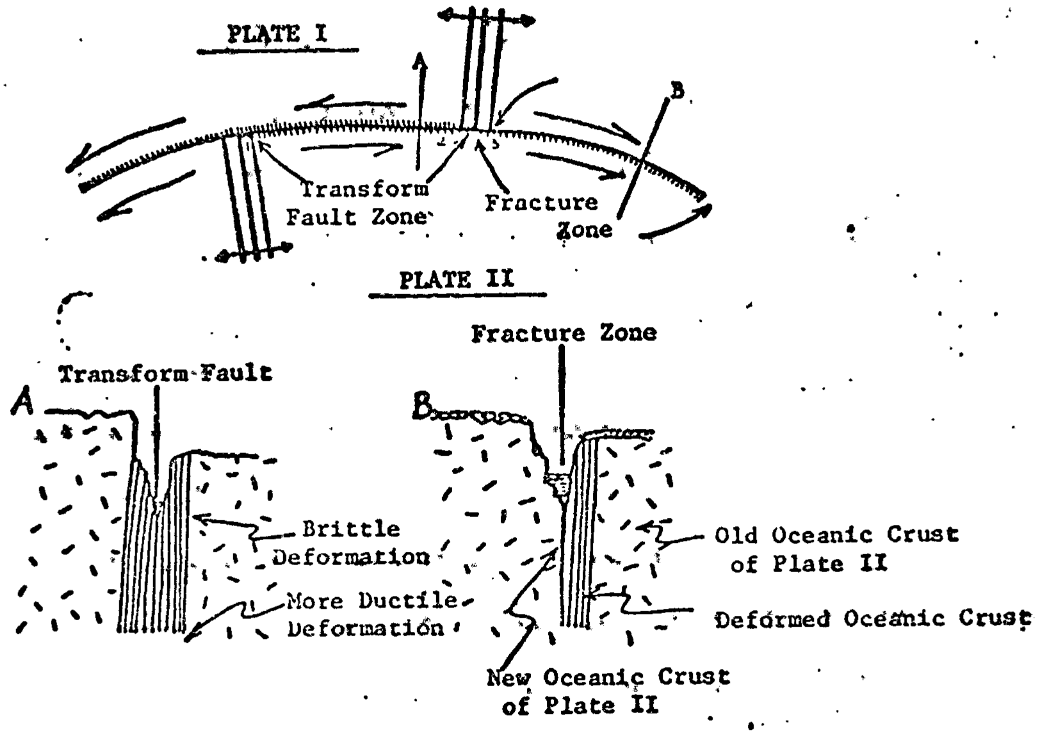


Fig. 42 Transform Faults and Fracture Zones: 1. Oceanic crust is formed at the mid-oceanic ridge crest on to Plate II. 2. The edge of Plate II is deformed from 1 to 2 in the transform fault zone. 3. Opposite the offset portion of the ridge crest (3) new oceanic crust forms an igneous contact against older deformed oceanic crust of the same plate.

deformed by brittle failure at high crustal levels and flow at deep levels. Deep levels of the new ocean floor will begin being deformed soon after its formation. Higher levels would enter the zone of deformation as the crest cooled, subsided and moved laterally relative to the adjacent plate. Deformation in this region would cease opposite the axis of the offset ridge crest. Here the transform becomes a fracture zone. The trace of the fracture zone is an igneous contact where new ocean floor is formed against older rocks of the same plate that have a transform fault zone deformation history.

At Hine's Pond metagabbros have a sharp contact against highly deformed ultramafic rocks. This might represent plastically deformed deep crustal rocks in contact with younger metagabbros of the transform fault zone. Deformed lenses of ultramafic rocks in metagabbro near this contact might be xenoliths of deformed older rocks.

Another possibility is that, during the very earliest stages of obduction, unconsolidated ultramafic and mafic material under a spreading center became tectonically mixed. This would require decoupling of the oceanic crust at a ridge crest where the crust was young, hot, and probably in part molten, perhaps in the form of a crystal mush. Conceivably, ultramafic and mafic components could be mixed in any proportion.

The significance of the Hine's Pond metagabbros may be great. If they are interpreted as a thrust sheet overlying the peridotites they need not be part of the ophiolite complex. The relationship between the ophiolite complex and the Little Port Slice is uncertain. Dikes similar to those of the ophiolite complex cut deformed gabbros of the Little Port Complex suggesting that it is an older crustal remnant caught near a spreading center (Williams, 1973). The Hine's Pond metagabbros may be part of the Little Port Complex. A zircon radiometric date of 508 ± 5 m.y. has recently been obtained brom a quartz diorite body in the Little Port Complex near Trout River (Mattinson, 1975).

If the stacking scheme followed in the lower allochthon of the Bay of Islands area may be extended into the highest slices, then this slice may be thought of as having been derived from beyond the Bay of Islands Slice. This might be part of an island arc formed on the opposite side of the Bay of Islands basin from the Cambro-Ordovician continental shelf-slope-rise of the Western Platform.

However, the metagabbros might be interpreted as rocks lying structurally below the ophiolite complex but exposed by folding of the basal contact near Hine's Pond. These underlying rocks might be part of the Little Port Complex (508 ± 5 m.y.). For reasons given elsewhere they are unlikely to be part of contact metamorphic aureole. The basal aureole has been dated as 460 ± 5 m.y. by $^{40}Ar/^{39}Ar$ release spectra work on amphiboles (Dallmeyer, 1975). They might also be deformed gabbroic rocks of the megalenses near the basal contact of the ophiolite, or masses of deformed oceanic metagabbros from a higher crustal level apparently absent in the Lewis Hills.

No matter what the history of the Hine's Pond area has been, it is clear that the Lewis Hills Ophiolite Complex represents a previously undescribed, apparently unique variation of an ophiolite complex.

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Appendix I Contoured Stereographic Projections of Foliations and Lineations in the Hine's Pond Area

All the following stereograms are equal area plots on a lower hemisphere projection. The number of data points contoured in each figure is listed with each diagram. Contours are 30% to 3% per 1% area with a contour interval of 3%. The figures represent the distribution of foliations, lineations and fold axes in various sub-areas of the Hine's Pond area in the Lewis Hills. They are as follows:

a. all foliations in Area I (layering and grain shape orientation are coplanar except where cut by dikes)

b. all foliations in Area II

c. all foliations in Area III, southern section

d. all foliations in Area III, northern section

e. lineation L_d in Area III, southern section

f. lineation L_d in Area III, northern section

g. lineation L_d in Area IV

h. all foliations in Area IV

i. all foliations in Area VI (mafic rocks)

j. all foliations in Area VI (ultramafics)

k. lineation L_d in Area VI

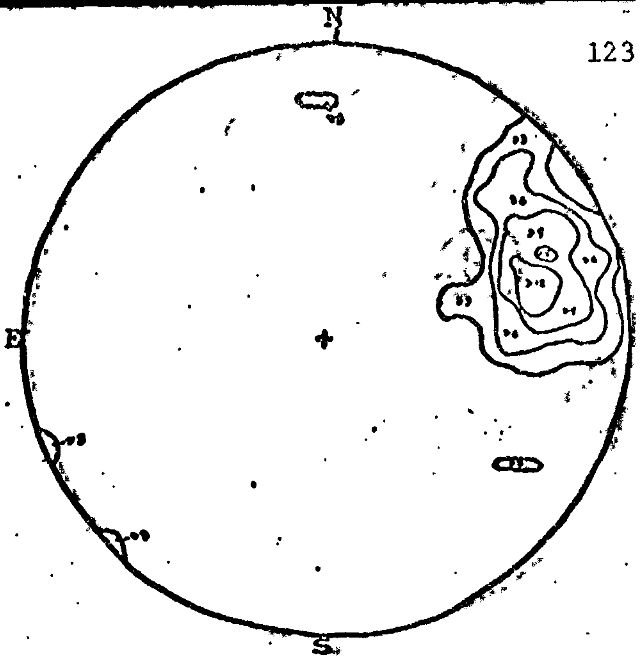
l. all foliations in Area V

m. linations in Areas I-VI

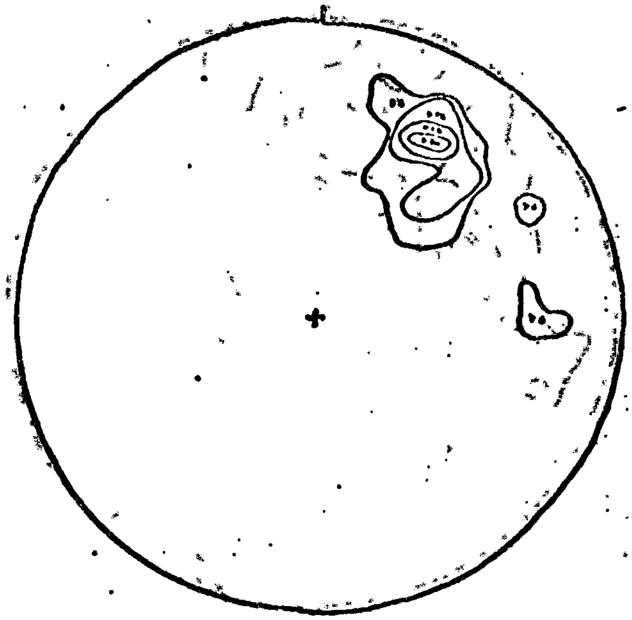
n. fold axes from Areas I-VI

o. lineations L_d in the Hine's Pond Metagabbros

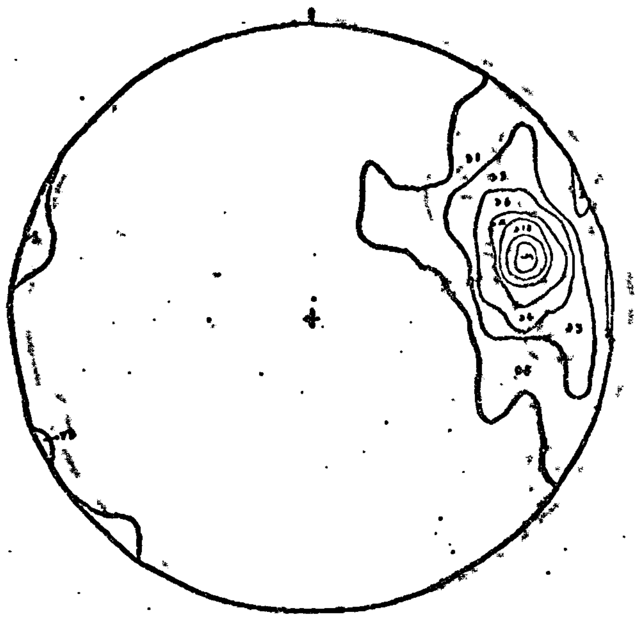
p. foliations in the Hine's Pond Metagabbros (S_d & S_1 coplanar)



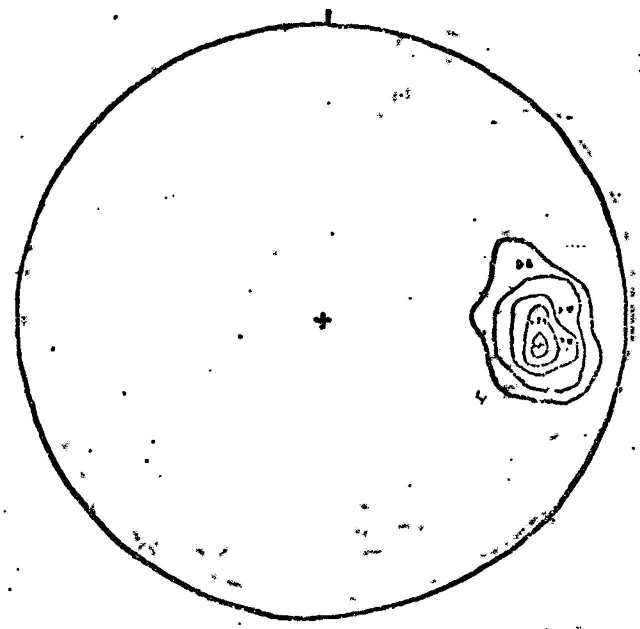
a. 100 points



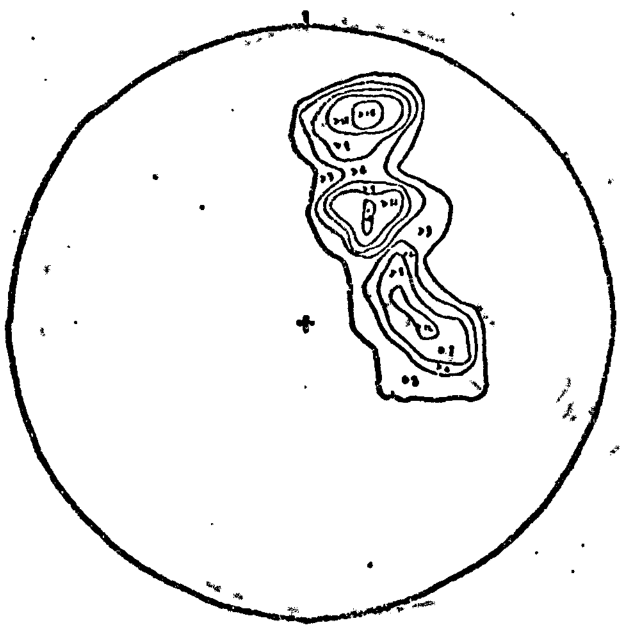
b. 25 points



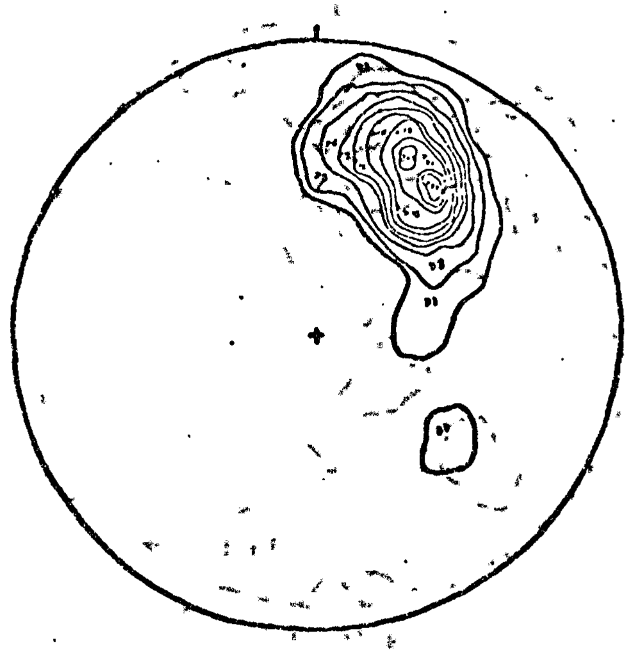
c. 173 points



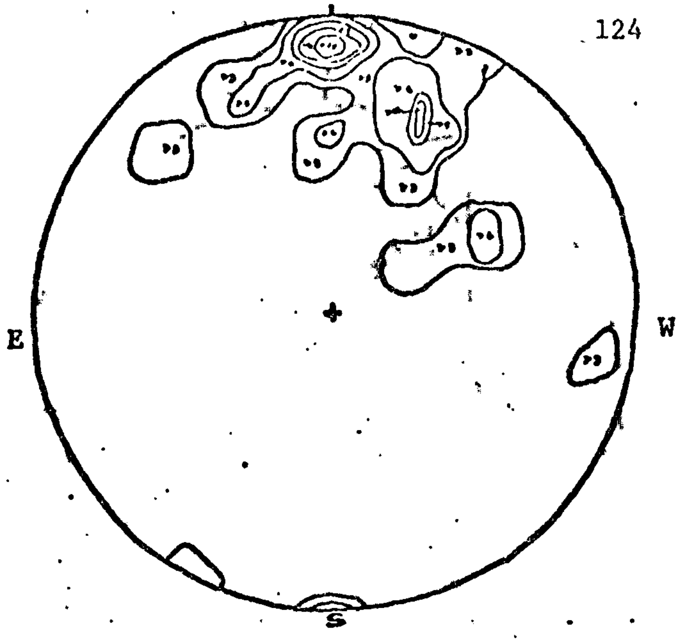
d. 94 points



e. 40 points

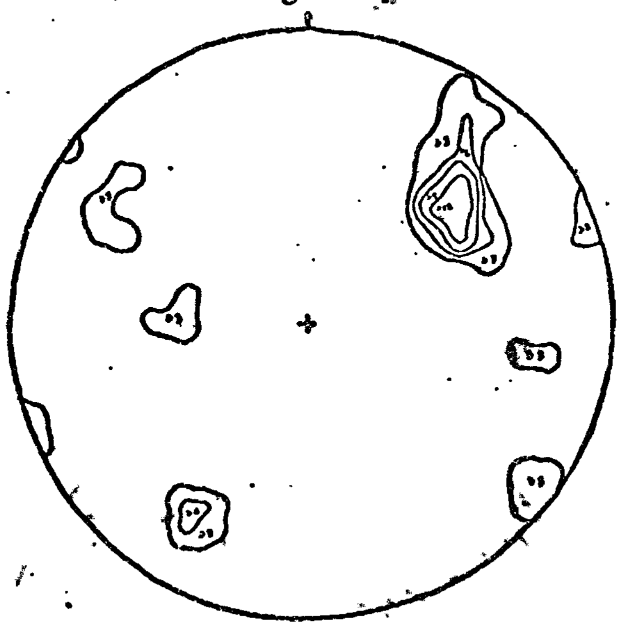


f. [illegible]

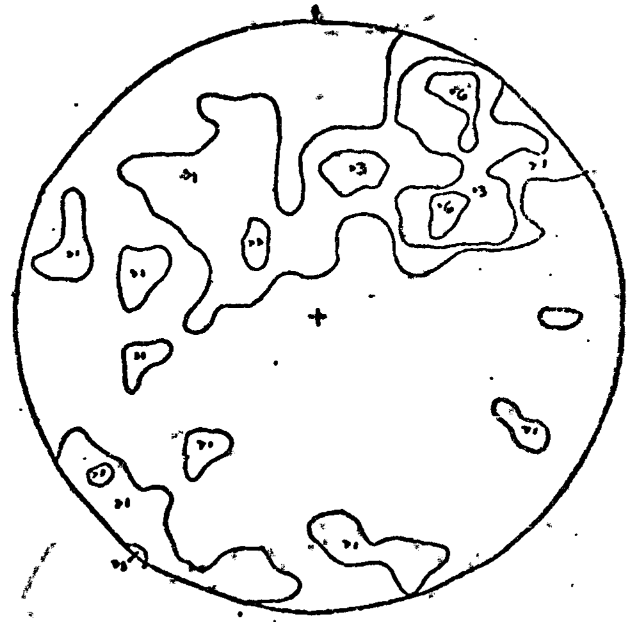


g. 25 points

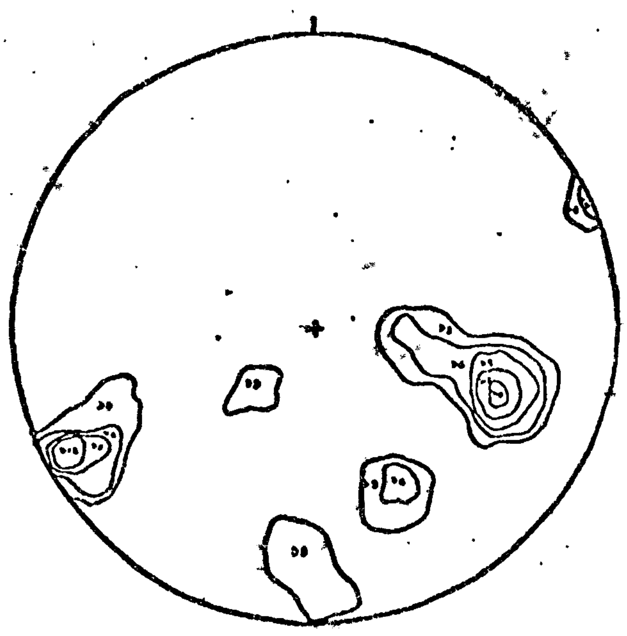
h. 93 points



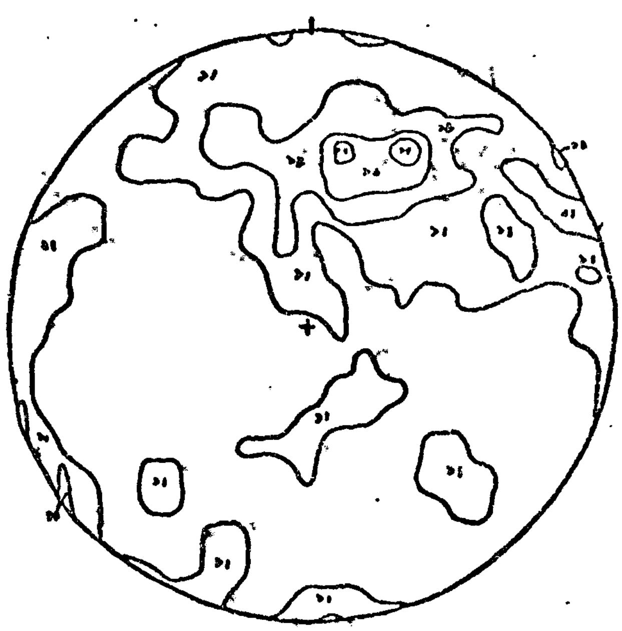
i. 50 points



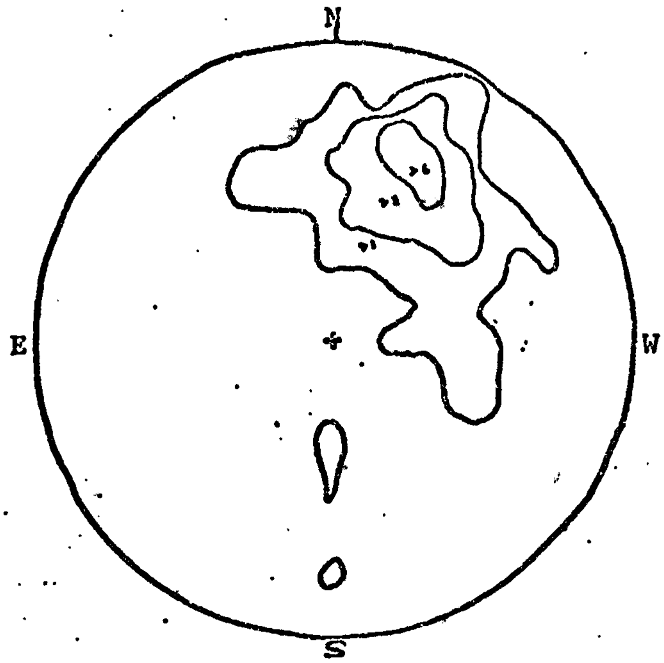
j. 150 points



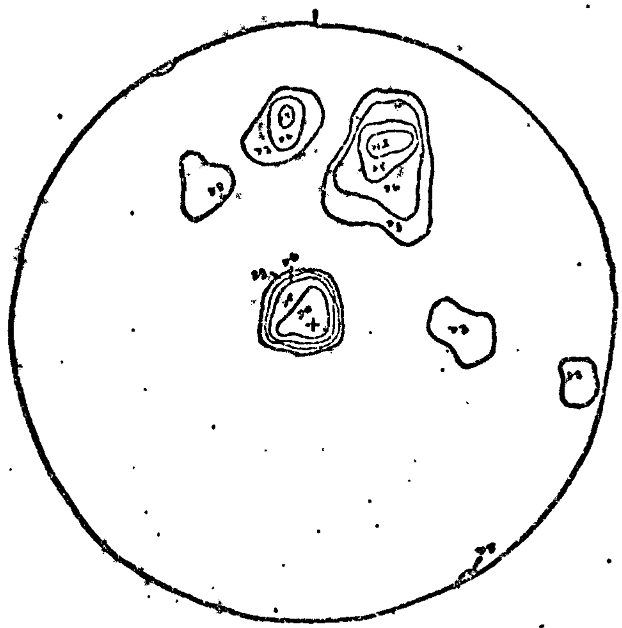
k. 36 points



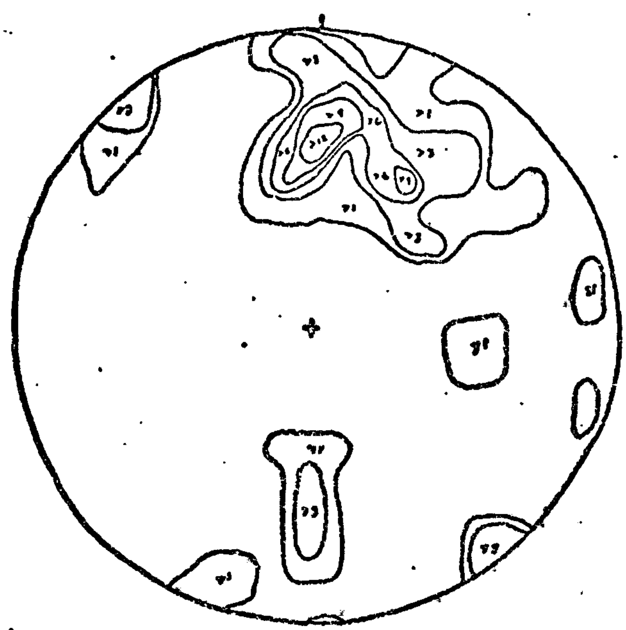
l. 91 points



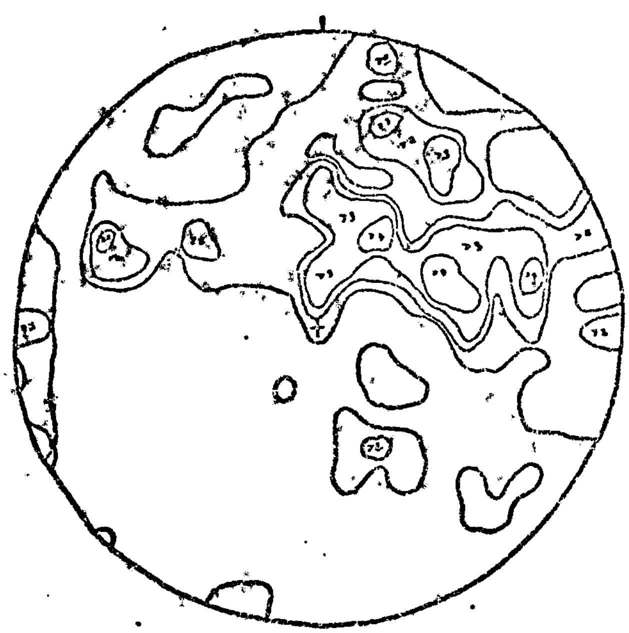
m. 280 points



n. 40 points



o. 42 points



p. 160 points