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A Study of Some Petrologic and Structural Aspects of the East Dover Ultramafic Bodies, South Central Vermont

Mark Allen Hoffman
University at Albany, State University of New York

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A Study of Some Petrologic and Structural Aspects
of the East Dover Ultramafic Bodies,
South Central Vermont

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree of Master of Science

Mark Allen Hoffman

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It is a pleasure to acknowledge the advice and criticism of the following people: George Putman, Winthrop Means, Steven Delong, Tsugio Shibata, William Gregg, and Bruce Nisbet. Volker Dietrich introducted me to the East Dover body and for that I am grateful.

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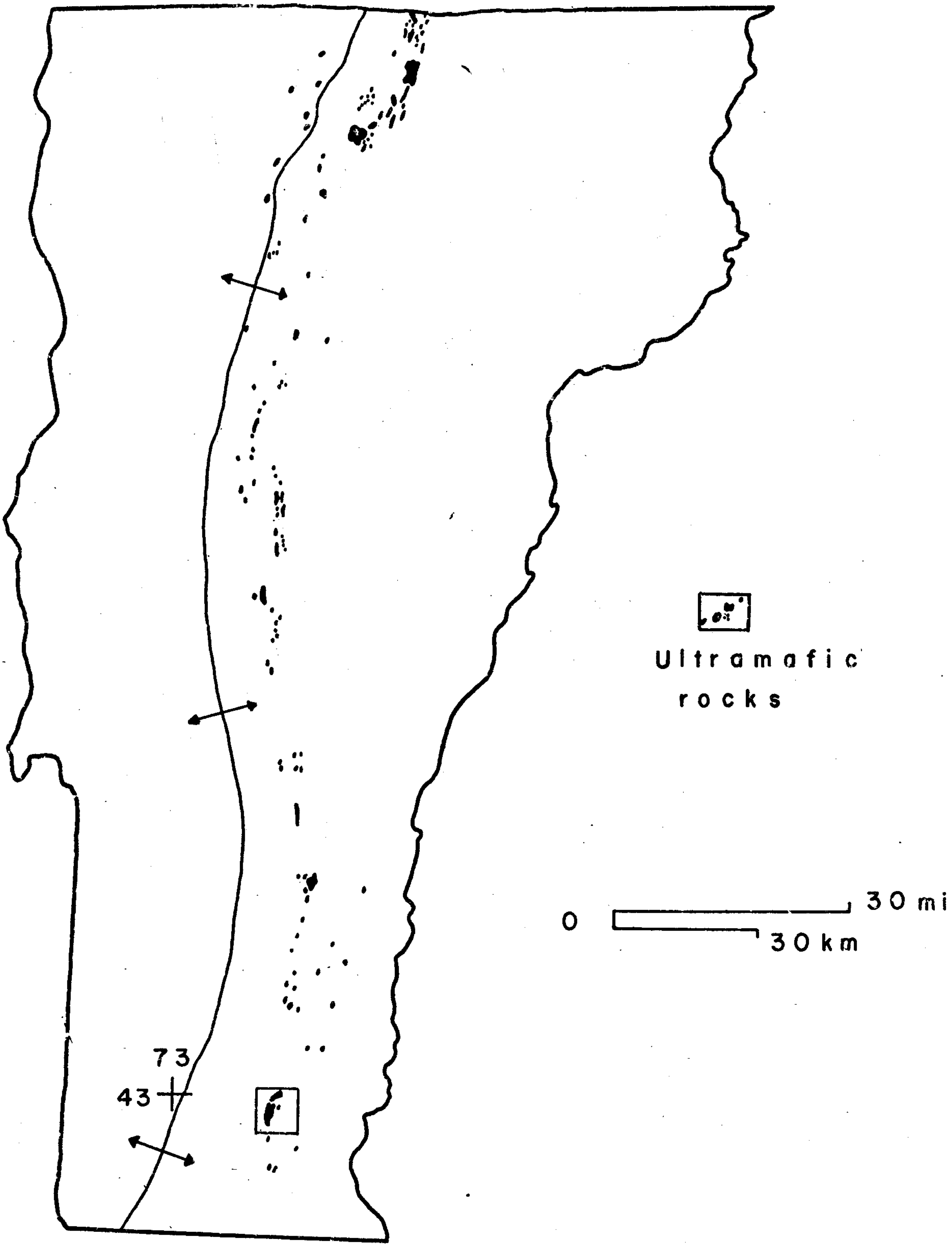
INTRODUCTION

Mineralogical, textural and chemical changes of ultramafic rocks in response to regional deformation and metamorphism are, at best, imperfectly known (Miyashiro, 1973, p. 30). In Vermont, which has an extremely prominent and well-exposed belt of ultramafics (fig. 1), investigation of these rocks has largely been directed toward such processes as serpentinization, steatitization, and the formation of metasomatic zones at the contacts with country rocks. With few exceptions, there is a lack of detailed descriptions of regional metamorphic textures, mineralogy, and structures developed in the Vermont ultramafic rocks.

It is the main purpose of this thesis to describe the mineralogical and textural changes that accompany regional metamorphism and deformation in the large ultramafic body at East Dover, Vermont. Serpentinization processes or the effects of hydrothermal alteration are not dealt with in detail, although some observations are made on these topics.

Two field seasons (1973-1974) were spent in an area approximately 6 x 3 km in and around East Dover, Vermont. When existing geologic maps of the area (Skehan, 1961; Vermont State Geologic map, 1961) were found to lack sufficient detail for these studies, field mapping was initiated to help correlate the petrology and structure of the body. Indeed, as mapping continued it became evident that complete analysis of the structural complexities of the body was far beyond the scope of this research. However, mapping of different rock types, measurement and description of the most prominent foliations, and a preliminary analysis of folding in the body were carried out to provide basic structural data.

Fig. 1: belt of ultramafic rocks in Vermont and position of the hinge line of the Green Mountain Anticlinorium. Area mapped for this thesis (fig. 2) is within small square.


73
43
Ultramafic rocks
0
30 mi
30 km

Structures in the country rocks at or near the contacts were studied to gain a better idea of the relationships of the ultramafic body to the country rocks. A preliminary comparison of structural elements in the ultramafic and country rocks was also attempted.

Only cursory petrographic examination of the country rocks was undertaken, mainly to determine the metamorphic grade and general rock types that surround the ultramafic body. The textures and mineralogy of the ultramafic rocks were studied in detail to provide information essential to interpreting the metamorphic and deformational history of the body. In this regard, previous petrographic work on these rocks was found to be inadequate and inaccurate.

REGIONAL GEOLOGIC SETTING

There are many fine reviews of the regional geology of this part of New England (Chidester, 1968; Rodgers, 1970; Cady, 1969). The following description is taken mainly from a synthesis of these works.

The most prominent structural feature of this area of Vermont is the Green Mountain Anticlinorium, whose hinge line strikes approximately north-northeast through the center of the state (fig. 1). Together with other smaller anticlinoria, the Green Mountains form part of a structural chain which can be traced from the northern Long Range of northwestern Newfoundland to the south end of the Blue Ridge in Georgia (Rodgers, 1970).

Precambrian rocks are exposed along the crest of this anticlinorium for about 160 km in central and southern Vermont. These Precambrian rocks show evidence of at least two deformational and metamorphic episodes, the younger of which is related to the formation of the anticlinorium. The Precambrian rocks are unconformably overlain by Paleozoic metasedimentary rocks (Rodgers, 1970).

Both to the west and east of the hinge of the anticlinorium the basal unit of the Paleozoic sequence consists of metamorphosed clastic, locally conglomeratic, strata. Above this basal unit the Paleozoic rocks west and east of the Green Mountains differ markedly, those to the west being the Cambrian and Ordovician carbonates of the Taconic region, while to the east the rocks are thought to comprise mainly a clastic-volcanic sequence. Just to the south of the Green Mountains these two rock sequences meet and interpretation of field relations has centered about the existence of a thrust fault or faults as being responsible for this juxtaposition (Rodgers, 1970; Skehan, 1961; Zen, 1967).

Ultramafic rocks in Vermont occur in a belt mainly to the east of the hinge of the Green Mountain Anticlinorium, although in northern Vermont some ultramafics are found slightly west of the hinge line (fig. 1). This belt of ultramafics has an average width of at least 16 km and is part of a zone of ultramafic rocks that extends for approximately 2900 km from Newfoundland to Alabama (Jahns, 1967). Along this belt, the country rocks containing the ultramafics are mostly phyllites and schists (locally gneissic), with minor amphibolites, quartzites and impure marbles. These may represent metamorphosed sediments and volcanic rocks of Cambrian and Ordovician age. The thickness of this sequence in southern Vermont, above the Precambrian and below the Silurian, is estimated to be less than 11 km (Chidester, 1968). Metamorphic grade in the country rocks along the belt ranges from greenschist to epidote amphibolite.

Two generations of folds, corresponding to two deformational-metamorphic events, can be readily recognized in the country rocks surrounding the ultramafic bodies (a possible third generation will be commented upon later). The younger generation is related in distribution, pattern, style, and age to the Green Mountain Anticlinorium (Chidester, 1968). These two generations of folding are thought to represent Taconic (Ordovician) and Acadian (Devonian) orogenic-metamorphic events (Lanphere and Albee, 1974).

Some controversy exists as to the age of emplacement of the Vermont ultramafic rocks. They are entirely contained in rocks older than the Silurian but some authors (especially Jahns, 1967) contend that they show only evidence of the Acadian deformation.

GEOLOGIC SETTING: THE EAST DOVER AREA

The East Dover ultramafic body is located in south-central Vermont, just northeast of the town of Willmington, and is easily accessible by road from the east and west. As mapped here, the largest continuous unit of the ultramafic body is about 4 km long by 1.2 km wide (fig. 2). The body is in the northeastern corner of the Wilmington quadrangle, approximately bisected by the NNE-trending town line separating Dover from South Newfane.

The topography on the ultramafic rocks is dominated by many small hills, one river, and two major streams (fig. 2), with elevations ranging from about 240 m to over 545 m above sea level. Ultramafic rocks are well exposed along the main road and the river and streams. Topographic highs within the body also provide good exposures. The total area of outcrop within the ultramafic body is estimated to be at least 15-20 percent.

The East Dover ultramafic body is entirely surrounded by rocks of the Moretown Formation, which consists of a Middle Ordovician (?) sequence of metapelitic and metavolcanic rocks in the upper greenschist (garnet grade) to epidote-amphibolite facies.

A SHORT HISTORY OF THE STUDY OF VERMONT ULTRAMAFIC ROCKS

Early Investigations

In reviewing the early literature dealing with Vermont ultramafic rocks (Hess, 1933, 1935; Phillips and Hess, 1936; Bain, 1936) it is evident that early workers were mainly interested in the serpentinization and steatitization processes. This is readily understandable, due to the economic importance of serpentine and talc. Though many of the early investigators' ideas on the movement of solutions and the scale of metasomatism during these processes have been greatly modified or discarded, the observational data in their papers are especially instructive and deserve attention.

Hess (1933), building on a foundation laid by Benson (1918), separated serpentinization and steatitization into two genetically different processes; i.e. steatitization was considered a hydrothermal alteration while serpentinization was considered a metamorphic process. According to Hess, solutions causing steatitization were derived from acid plutonic rocks "below" (stratigraphically ?) ultramafic "intrusions," while solutions causing serpentinization were already contained in the ultramafic rocks when they were emplaced (this was termed "autometamorphism") Some of Hess' (1933) observations which are pertinent here include:

1. petrographic data indicated to Hess that serpentinization always preceded steatitization;
2. he noted that the distribution of serpentinization in the Vermont ultramafic bodies is usually haphazard and unrelated to the margins of the body, although some exceptions (such as uniform or zonal distribution) were noted;

3. his sketches (Hess, 1933, figs. 3 and 5) depict Vermont ultramafic bodies as concordant, lenticular, podlike and dismembered units.

Bain (1934) considered serpentinization and steatitization both to result from hydrothermal processes, the solutions being derived from outside the ultramafic rocks. He then concisely described (1936) the various ideas then extant concerning serpentinization and steatitization, and attempted to reconcile the various hypotheses with his observations in Vermont (see next section).

This early literature is filled with debates (Hess, 1935) about, and attempts to unify, different theories of serpentinization and steatitization (Bain, 1936).

In 1936, Phillips and Hess presented the most detailed study up to that time of the metasomatic reactions at the contacts of ultramafic and country rocks. They were able to divide the metasomatic zones into what they termed high and low temperature types, on the basis of the mineralogy developed in these zones (chlorite versus biotite and the absence or presence of actinolite defining low and high temperature types respectively). The geographic area delineated by the higher temperature types of Phillips and Hess (1936, fig. 4) is centered around the Chester Dome area and extends for approximately 24 km both north and south of Chester, Vermont. Phillips and Hess (1936) also noted the absence of high temperature contact-metamorphic effects at the contacts of ultramafic with country rocks; and that areas of substantial talc or talc-carbonate development are often found in the hinge areas of infolded portions of the contacts of ultramafics with country rocks. They attributed this to what they called "ponding" or a concentration of solutions in these hinge areas.

Later Investigations

Later investigations of Vermont ultramafic bodies (Jahns, 1967; Chidester, 1962, 1968; Chidester and Cady, 1972) provided more detailed descriptions of the rocks themselves and attempted explanations of the emplacement and deformational history of these bodies. Ideas pertinent to this thesis, from two of these later papers (Jahns, 1967; Chidester, 1968), are summarized below.

Jahns (1967) described in detail the small ultramafic bodies at Roxbury in central Vermont. Some of his observations and conclusions were:

1. assuming that the two deformational events visible in the country rocks (two generations of folding) are both Devonian in age, and believing that the ultramafics display evidence of only the last event, Jahns concludes that the ultramafics were emplaced in the Devonian;
2. the predominant serpentine mineral is antigorite;
3. no evidence of original pyroxene is visible in the Roxbury ultramafics;
4. the gross structure of the bodies is dominated by the presence of "shear polyhedra" (fig. 3, adapted from Jahns, 1967, fig. 5.4), which represent essentially a gradation from unsheared, massive serpentinized ultramafics (often with a core of dunite) through more intensely sheared, foliated and less massive serpentinized rock at the contacts.

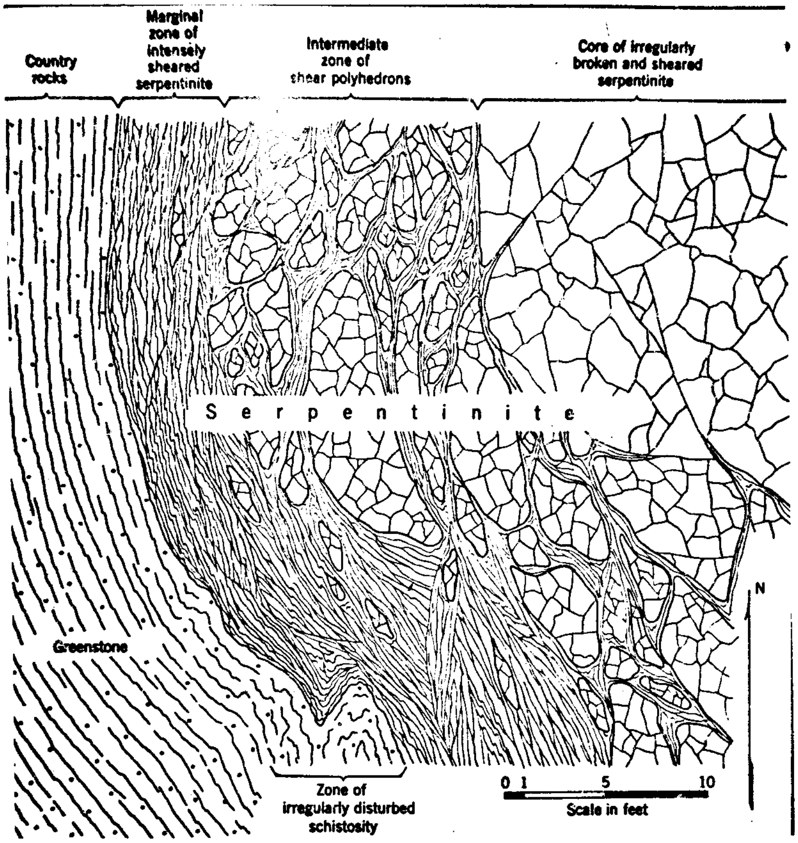


Fig. 3: development of shear polyhedra structures. Figure is taken from Jahns (1967). This feature is not identically developed at East Dover (see text).

Jahns also presented a detailed chemical and petrologic study of the metasomatic zones surrounding the Roxbury bodies.

Chidester (1968) reviewed the geology of the entire belt of ultramafics in New England and some of his observations and conclusions were:

1. the contacts of the ultramafic rocks are mainly concordant with the dominant regional schistosity, which itself is axial plane to the older folds in the country rocks;
2. the largest bodies of ultramafic rocks are limited to northern and southern Vermont, where erosion has exposed deeper parts of the pre-Silurian section;
3. layering of dunite and peridotite, where developed, is on a scale of a few feet or less and is generally subparallel to the contacts;
4. pervasive serpentinization occurred before emplacement;
5. septa and inclusions of country rocks in the ultramafic rocks are common.

Chidester also presented his ideas on the origin and emplacement history of the bodies, and the genesis of and differences in the metasomatic zones surrounding the bodies.

In summary, it can be said that in almost all cases these investigations of Vermont ultramafic bodies have emphasized serpentinization and metasomatic processes, and average or typical descriptive aspects of the entire belt of ultramafic bodies.

A REVIEW OF PREVIOUS INVESTIGATIONS OF THE ULTRAMAFIC ROCKS AT EAST DOVER, VERMONT

It is the purpose of this section to review and not criticize the work of others at East Dover. However, in the light of new data presented in this thesis it is apparent that many of the older ideas will have to be discarded.

The two earliest accounts dealing wholly or in part with the East Dover ultramafic body are found in "The Report of the Vermont State Geologist, 1915-1916" (Jacobs, 1916; Wigglesworth, 1916).

Jacobs (1916), through petrographic investigation, recognized that the ultramafic rocks at East Dover were, mineralogically, serpentinized dunites. He also reported finding a small amount of an unspecified pyroxene.

Wigglesworth, in his paper "The Serpentines of Vermont" (1916), recognized just over twenty locations in Vermont where serpentine is found, the most southern of which was at East Dover.

Commenting on the entire belt of ultramafic rocks in Vermont, Wigglesworth (1916) noted:

1. "In most cases the serpentine forms a small hill, while surrounding schist is covered by swampy ground." p. 283;
2. foliations in the country rocks follow the outlines of the ultramafic bodies;
3. the shape of small serpentine outcrops is lenticular;
4. in southern Vermont the ultramafics are associated with amphibolites;
5. ultramafics in Vermont are mineralogically and chemically similar to those south of Vermont and in Canada;

6. a greater degree of "alteration" of Vermont "serpentines" is evident than in the ultramafic rocks to the south, or in Canada, there being no completely unaltered peridotites in Vermont;
7. that assignment of age of "intrusion" is difficult, although he personally would assign an Ordovician age to these "intrusions." Wigglesworth also postulated that part of the deformation visible in these ultramafic rocks was Permian in age.

Wigglesworth (1916) presented the first chemical analysis of ultramafic rocks from East Dover. His chemical data is reproduced here for future reference.

SiO_2	38.10	K_2O	0.15
Al_2O_3	2.31	Na_2O	0.19
Fe_2O_3	2.70	CaO	----
FeO	3.48	H_2O	11.45
MnO	0.11	NiO	----
MgO	42.04		
		Total	100.53

No further information is given and it is presumed that the data are in weight percent.

Wigglesworth (1916) reported that, compared with analyses from other ultramafic rocks in Vermont, East Dover rocks are lower in silica, higher in magnesia, and lacking in lime.

When Jacobs and Wigglesworth wrote their reports, the ultramafic bodies in Vermont were considered pipe-like intrusions (apophyses) from a buried sheet of ultramafic rocks located somewhere east of the Green Mountains.

In Bain's (1936) paper, "Serpentinization of Vermont Ultrabasics," Vermont ultramafic bodies were divided into two groups on the basis of their physical (and what Bain believed to be chemical and genetic) differences, i.e. a white-weathering type, called verde-antique; and a red-weathering type.

Composite types, consisting of varying proportions of each principal type were also recognized. Bain ascribed the differences between the two types ultimately to differences in serpentine genesis. He considered the white-weathering type to represent serpentinization by hydrothermal solutions which entered the ultramafic bodies along shear or fracture systems, the serpentinization being confined to the proximity of these systems. The red-weathering type was considered to represent Hess' autometamorphic serpentinization.

East Dover was Bain's type red-weathering locality, although he considered the northern periphery of the ultramafic body to be a composite type. Bain's investigations at East Dover resulted in the following observations:

1. the presence of what he called a "primary horizontal-sheeted structure, such as forms in many orthotectic gneisses, attributed usually to flowage of a semi-crystalline magma" (Bain, 1936 p. 1973). This sheeted structure Bain defines as alternating olivine and serpentine rich domains. Olivine grains appear to be elongate parallel to this sheeting;
2. "minor veinlets" of serpentine were observed sub-normal to the "primary" sheeted structure;
3. a conjugate system of joints, forming parallelogram-shaped domains, is prominent in the ultramafic

rocks at East Dover. Bain believed that "tectonic flow" or movement could be deduced from a study of these joints;

4. ultramafic outcrops are typically bordered by abrupt cliffs, which are conspicuous features of the landscape.

The next investigation dealing with East Dover was that of Skehan (1961) who mapped the Willmington quadrangle in Vermont; the East Dover area occupying approximately 20 square km of the northeastern corner of that quadrangle.

Skehan (oral communication, 1974), however, spent very little time in the East Dover area and relied for the most part on field assistants to do the mapping in that area. Errors were made in transferring structural data from the base maps to the available topographic sheets, which resulted in mislocating the southern contact approximately 0.4 km too far east (Skehan, oral communication, 1974; see my comparative interpretations, fig. 4).

Skehan's map of the East Dover ultramafic body (fig. 4A) shows it to be zoned with respect to the amount of serpentine and talc-carbonate which is developed. The zonation is represented as nearly concentric, proceeding from an unaltered dunite core outward to a zone of 100 percent serpentine and talc-carbonate at the margins. Skehan also notes the following:

1. the presence of horizontal "banding" like that described by Bain (1936);
2. a "dike-like" body of talc near the center of his "least altered" zone, interpreted as evidence for the migration of solutions along a large fracture zone;

Fig. 4: comparative interpretations of the mapped boundaries of the ultramafic rocks at East Dover.

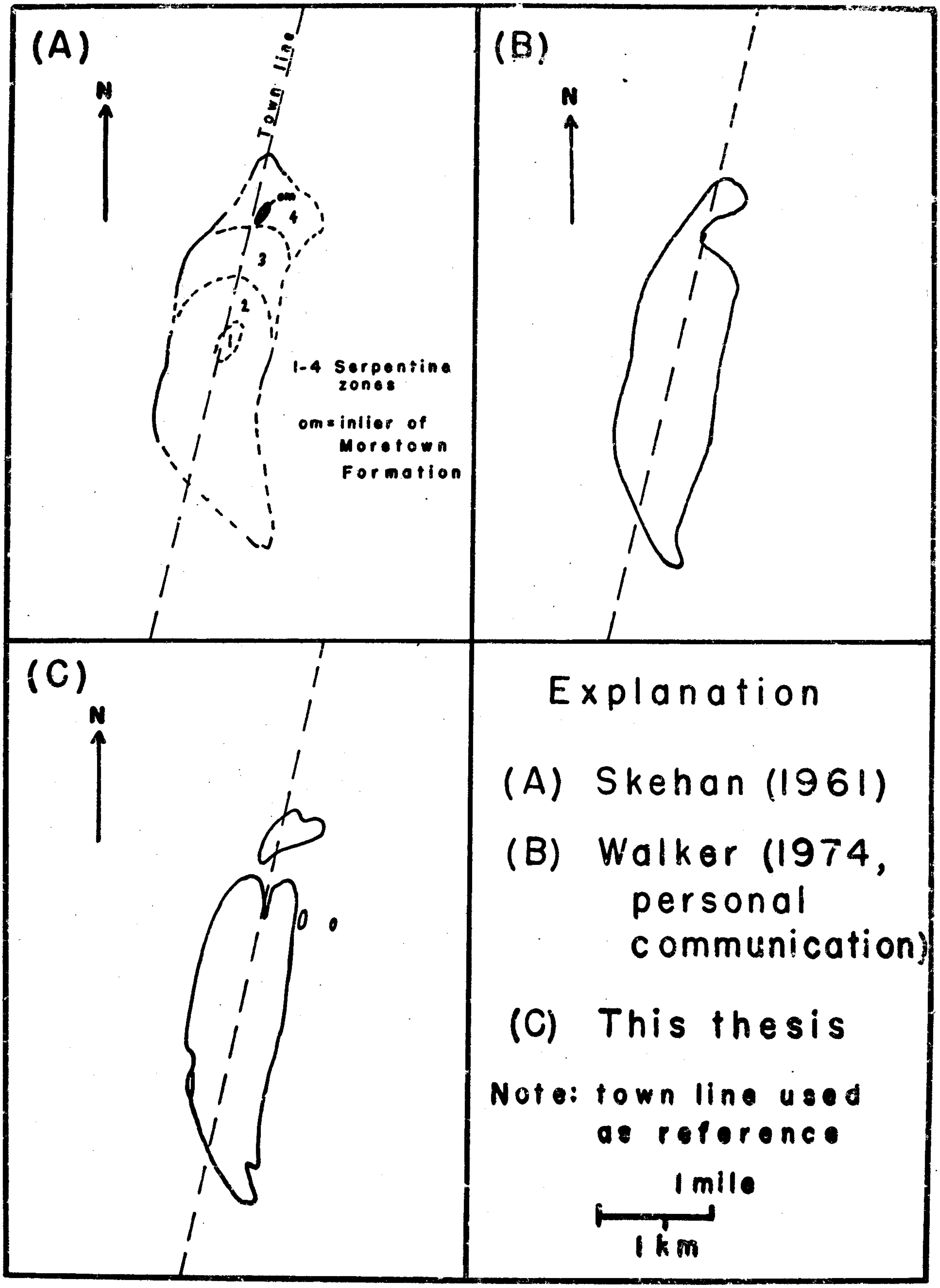

(A)
Town line
N
om
4
3
2
1
1-4 Serpentine zones
om=inlier of Moretown Formation
(B)
N
(C)
N
Explanation
(A) Skehan (1961)
(B) Walker (1974, personal communication)
(C) This thesis
Note: town line used as reference
1 mile
1 km

Fig. 4.

3. epidote-amphibolite everywhere surrounding the ultramafic rocks;
4. the presence of anthophyllite in the ultramafic rocks.

Detailed discussion of these points will be given later, but it should be noted here that in this study conclusive evidence was found that the serpentinization is rather randomly developed and not simply zoned, as Skehan depicted.

The next worker to apply himself to the problems at East Dover was Stuckless (1972, written communication, 1974), and his observations are summarized below:

1. the East Dover body is "keel-shaped," concordant with the "metamorphics," and has no root at depth;
2. serpentinization is parallel to the outlines of the body;
3. high (positive ?) magnetic anomalies are present near largely unaltered masses of dunite;
4. two compositionally distinct olivines are occasionally encountered in X-ray patterns;
5. two generations of serpentine are present in some portions of the body;
6. a tremolite alteration zone is present near the northern contact with the country rocks.

D. Walker at Harvard University (oral communication, 1974) has recently mapped the East Dover body, and his interpretation is presented in figure 4B. The structure in the northern half of the body is extremely complex and Walker based his interpretation of that part of the body on new magnetic data, which was not available to me at the time of this writing.

Presently, as far as I am aware, there is only one other person, R. DeFillippo (Boston College), working in the area, and some of his observations are reviewed below (written and oral communication, 1974).

1. the body is mainly composed of shear polyhedra ranging in size from microscopic to approximately 2000 feet long, the larger of which trend north-south;
2. two generations of serpentine and olivine are present in many places;
3. there is a "correlation of relatively unaltered areas with high magnetic anomalies...;"
4. chemical (X-ray spectrometry) analysis of the clinozoisite-hornblende "body" west of the ultramafic body shows it to be approximately 38 percent SiO_2.

The above compilation of observations at East Dover by various workers does not correspond wholly with the results presented in this thesis. Such points of disagreement as are present are pointed out and subsequently discussed in this text.

MEGASCOPIC APPEARANCE OF THE ROCKS AT EAST DOVER

Country Rocks

In general two types of country rocks are visible in outcrop at East Dover (see petrography section for detailed description):

1. light colored metapelites of the Moretown Formation (Ordovician);
2. dark colored quartz-amphibolites, usually thought to be volcanics of the Barnard group of the Ammonoosuc volcanics (Skehan, oral communication, 1974).

A layering of these two types is commonly observed (fig. 5) and may represent primary layering. Both rock types contain a well developed foliation (S_2, see below) at an angle to this layering.

Grain size in both rock types is highly variable from submegascopic up to 3 mm in diameter. Hornblende crystals are occasionally observed 1-3 cm long in the plane of S_2.

The degree and type of weathering of these rocks is also variable but generally takes the form of an orange-red iron staining and increased ease of parting along S_2.

Ultramafic Rocks

Megascopically the serpentinized ultramafic rocks are characterized by a charcoal gray to gray-green color on freshly broken surfaces. In general, the higher the olivine content the more green the rock appears. Most samples have a weathered surface varying from about 1 mm to 2-4 cm in thickness. This surface is generally various shades of yellow, red and brown in color and is probably composed of clay minerals (smectites,

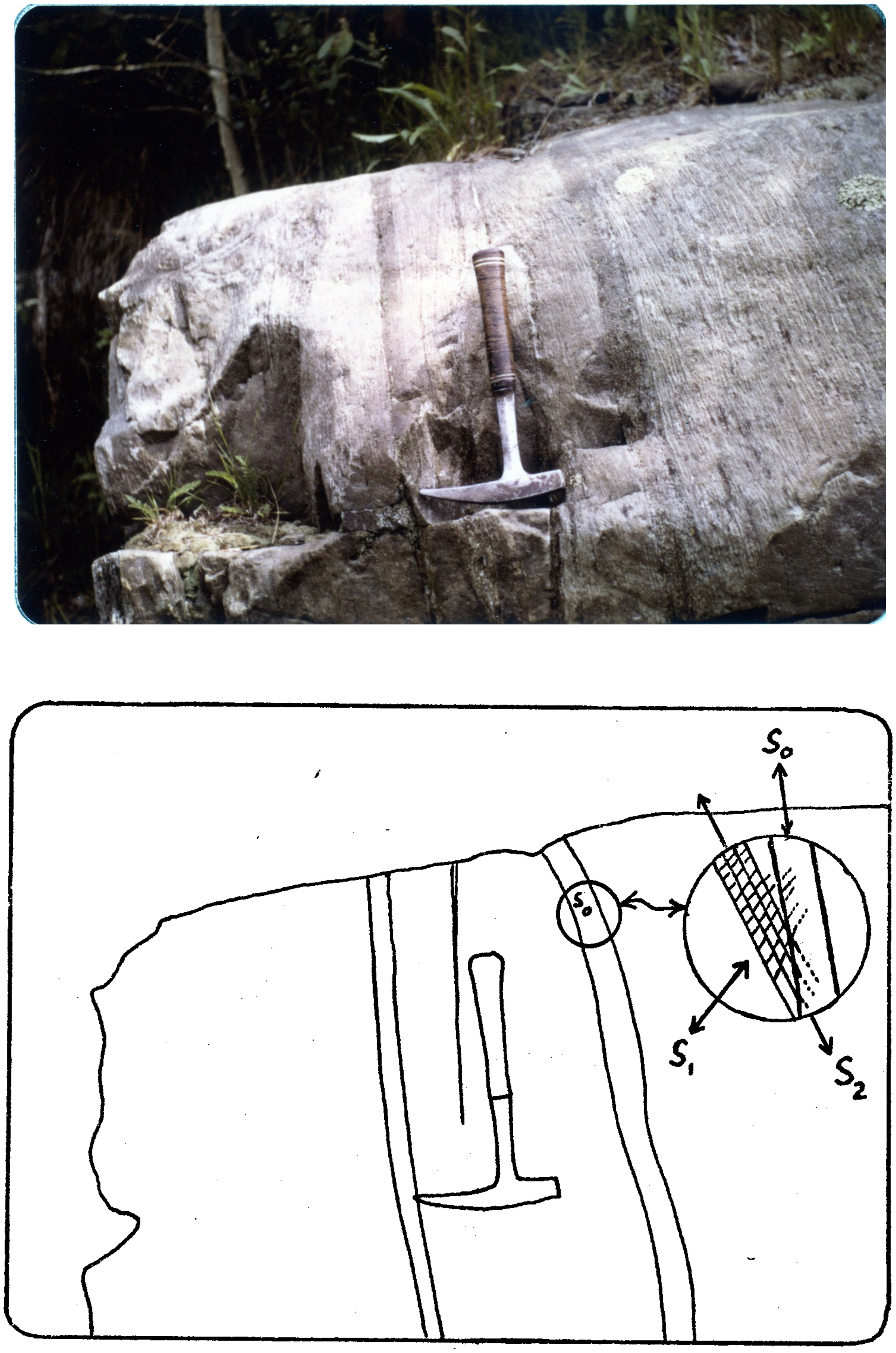


Fig. 5: outcrop on the Main Road east of the intersection with Adams Hill Road. Lower drawing and inset show relationship of various layerings visible. S_1 is not easily detected.

see petrography section).

Individual grains of olivine around 1 mm in diameter are rarely visible on broken surfaces while magnetite "blebs" of from $<$1 mm to 1-2 cm in diameter are commonly observed. Carbonate (magnesite mostly) occurs occasionally as rounded white patches and commonly as small veinlets. If this carbonate is present in large enough amounts (greater than about 10%) the rock as a whole may appear whitish in outcrop.

A pseudo-layering is sometimes observed on outcrops which have been "polished" by stream action. This "layering" is defined by smooth (surfaced) orange colored layers (4-6 cm) which alternate with rough (surfaced) whitish colored layers (4-6 cm). This layering, however, is not visible below the surface weathered layer of the rock and has no expression in thin section. It is thus attributed to differential weathering. However, it should be noted that this weathering may be accentuating a real but subtle difference in the rock chemistry and therefore may actually be an expression of an earlier layering.

Joints are the most prominent structural feature in outcrop. Joint frequency and spacing are highly variable and probably related to the development of shear polyhedra as described by Chidester (1962) and Jahns (1967) (see below).

The clinozoisite-hornblende unit is distinctive in the field due to its very dark brown-black color (darker than the amphibolites due to its lack of quartz) and orange-green colored banding (clinozoisite layers).

STRUCTURAL ASPECTS OF THE EAST DOVER ULTRAMAFIC BODIES AND SURROUNDING COUNTRY ROCKS

Foliations Visible in the Country Rocks Surrounding the Ultramafic Body

Five foliations are readily recognized in the country rocks surrounding the ultramafic body. Three of these can be ascribed relative ages on the basis of crosscutting relationships (S_0, S_1, S_2). The remaining two foliations can only be said to be younger than S_2.

S_0, the earliest layering visible in the area, is defined by thin, less than 10 cm wide, layers of generally darker rock in the more pelitic members of the Moretown Formation. This layering was not identified in any amphibolites near the ultramafic bodies and, indeed, was only recognized at two localities in the metapelites. These two localities are briefly described:

1. On the main road approximately 400 meters east of the intersection with Adams Hill Road is an outcrop of the Moretown Formation which displays S_0, S_1, and S_2 foliations (fig. 5). At this location S_0 is defined by darker layers in a lighter, "pinstriped" member of the Moretown Formation. S_2 is at about 5° to S_0. S_1 and S_2 foliations can be seen to penetrate the S_0 layering, but individual S_1 or S_2 foliation planes could not be traced completely through the darker layers defining S_0.

2. The other exposure of Moretown Formation S_0 is located about 800 meters due north of outcrop number 1. S_0 here differs from that at number 1 in that the alternating layers defining the foliation appear to be mineralogically indistinguishable, showing differences only in grain size and mode. Thin quartz-rich domains with fine-grained biotite alternate with domains containing less quartz and more,

coarser-grained, biotite. Both S_1 and S_2 can be seen to completely crosscut S_0 at this location. S_2 is at a larger angle to S_0 here than at location number 1 (fig. 6).

S_1 is defined by thin, generally less than 3 mm wide, quartz-rich layers alternating with thinner mica-rich layers. S_1 is visible in about 10 percent of the outcrops and S_2 always crosscuts it at a high angle. "Trains" of garnets (fig. 7) are commonly observed parallel to S_1.

S_2 is the most prominent foliation visible in the area. In the metapelitic members of the Moretown Formation, S_2 is defined primarily by thin, alternating quartz-rich and mica-rich domains, and has commonly been referred to as "pinstriping." S_2 is more uniformly and strongly developed than S_1 and mineralogically it appears as though S_2 is defined more by biotite and muscovite while S_1 is defined by muscovite (without biotite). In the amphibolitic members of the Moretown Formation, S_2 is defined by alternating layers of somewhat more complex mineralogy. Where alternating quartz-rich and hornblende-rich layers define S_2 in the amphibolites (by far the most common development of S_2 in these amphibolites), hornblende grains show a preferred orientation as sketched in figure 8.

In thin section, S_2 appears to be a differentiated crenulation cleavage formed at the expense of S_1 (fig. 7). Garnets containing S_1, now rotated parallel to S_2, are common (fig. 9). These garnets also show what might be interpreted as two stages of growth (fig. 9). The cores of some garnets possess a good rotated foliation while the margins of the same grains are free of foliations and, indeed, seem to deform the surrounding S_2 foliation (augen structure ?). Large

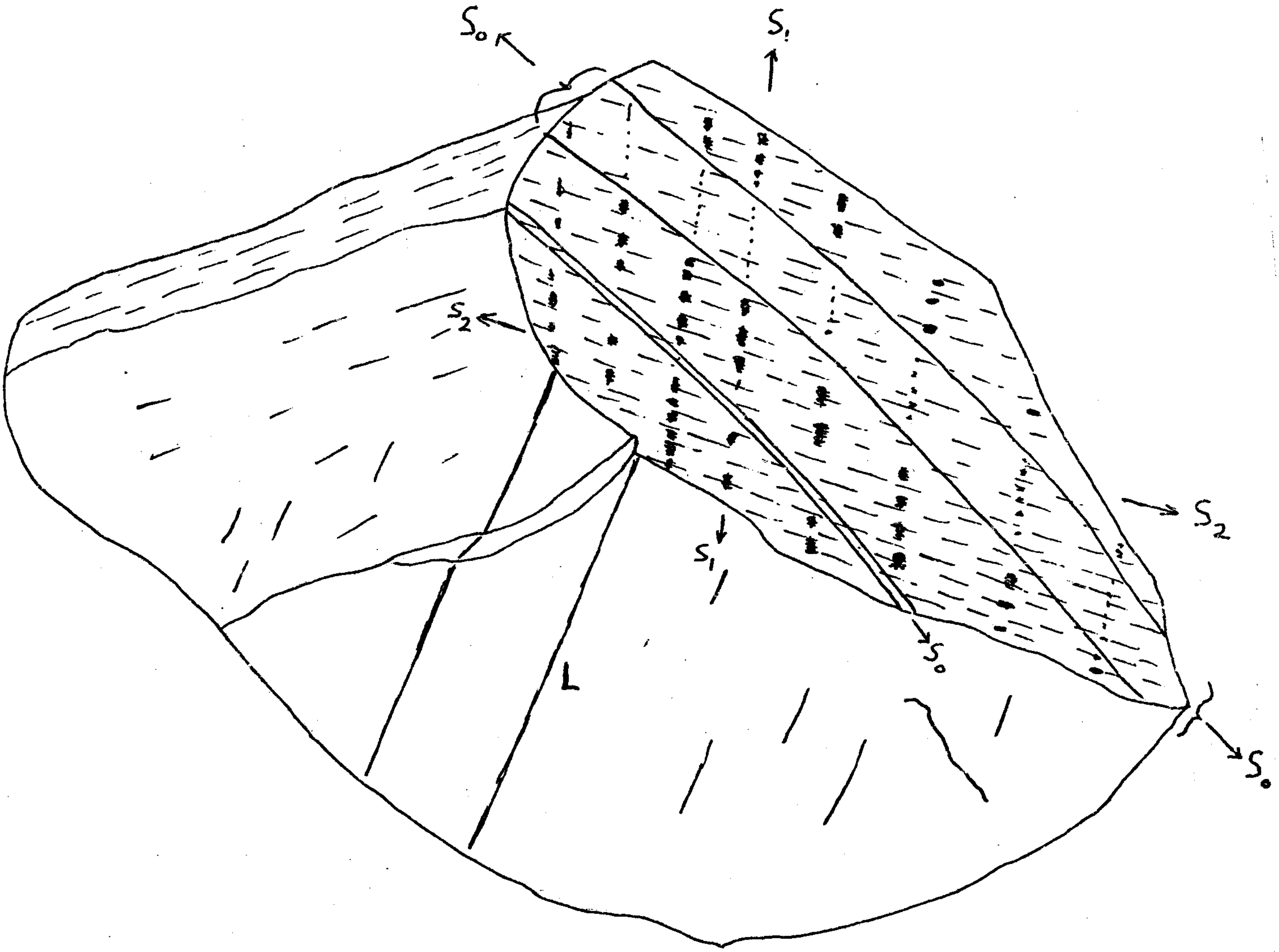


Fig. 6: hand specimen of biotite-muscovite-garnet-quartz schist (actual size). S_0 is defined by layers of fine-grained biotite and garnet, with abundant quartz, alternating with layers of coarse biotite and garnet which contain less quartz. S_1 is defined by coarse biotite and S_2 is a crenulation cleavage. Garnets are not shown in this sketch but may reach 3-4mm. Figure 9 is a garnet from this specimen.

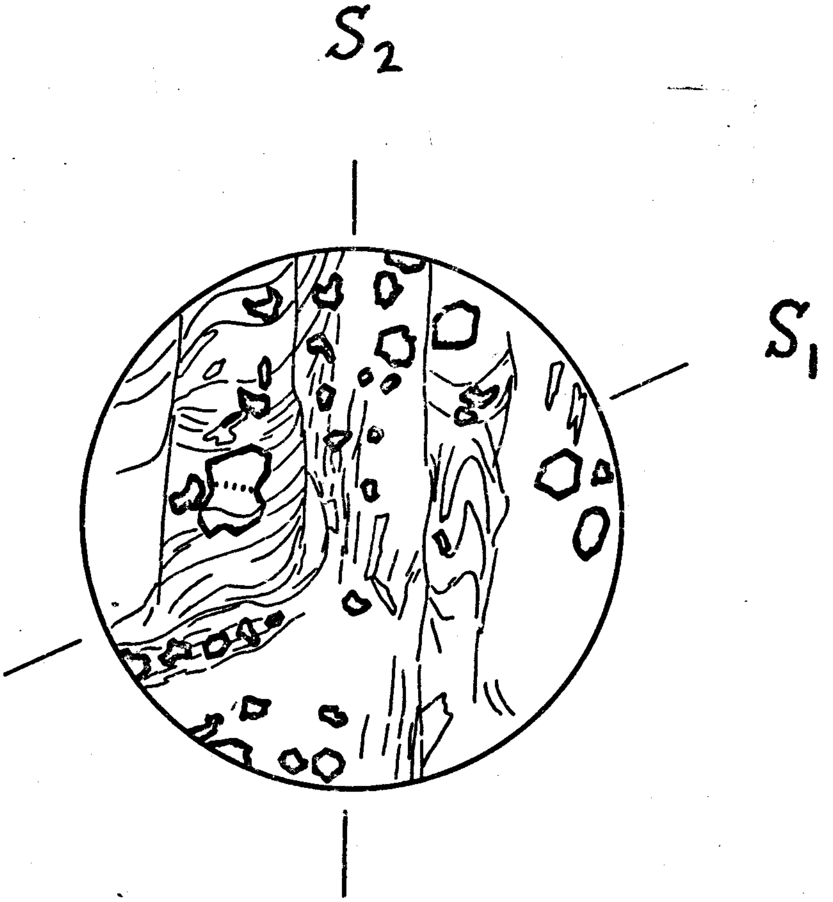


Fig. 7: garnet "trains" aligned in S_1 foliation. Garnets are grains with heavy black borders in sketch. S_2 is a differentiated crenulation cleavage. Sketch made at 40x in plane polarized light.

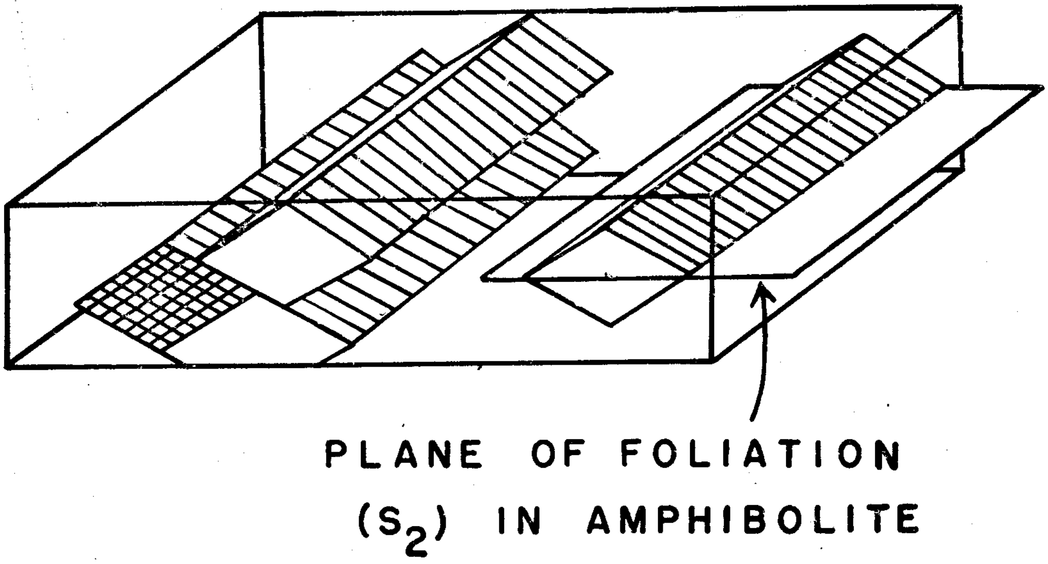


Fig. 8: orientation of metamorphic hornblende in amphibolitic country rocks. Long dimension of hornblende crystals are not observed to have any consistant orientation relative to observed structural elements in the country rocks.

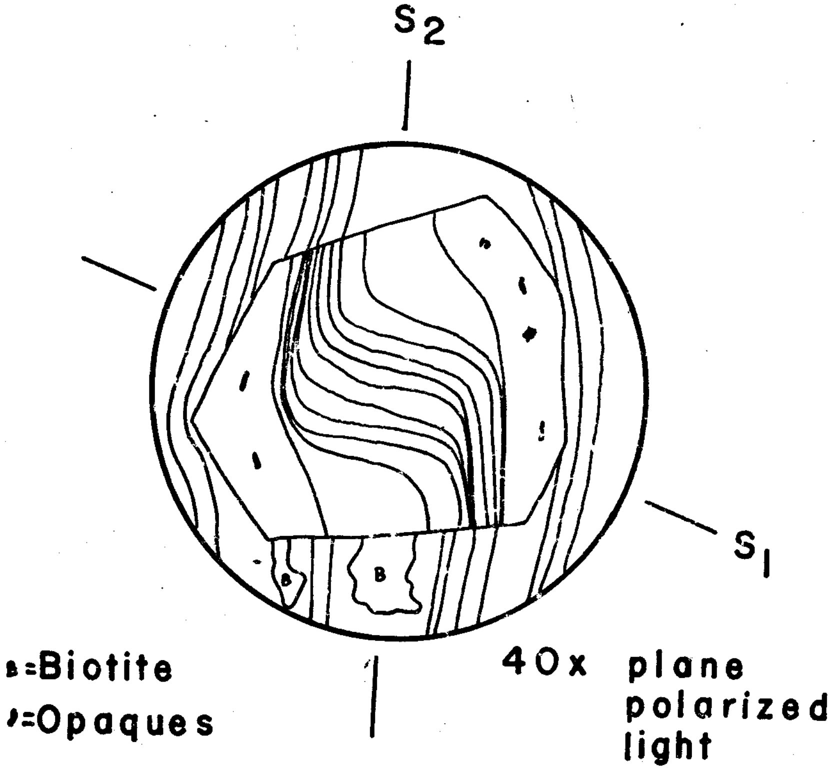


Fig. 9: "rotated" garnet. Garnets appear to display two stages of growth. Large biotite grains terminate abruptly against the garnet.

biotite grains terminate sharply against these garnets.

"Cross micas" (Spry, 1969, p. 257), here biotites with their basal cleavage approximately perpendicular to S_2, are common in biotite-rich rocks, and probably grew after S_2.

Boudinaged quartz layers are observed parallel to S_2, but occasionally these layers show intrafolial isoclinal fold closures with their axial surfaces parallel to S_2 (fig. 10), suggesting that these quartz layers represent a layering that predates S_2.

S_3 is a closely spaced fracture cleavage, occasionally lined with what may be a smectite and/or an undetermined oxide. S_3 cross-cuts all previously described foliations.

$S_?$ is a coarse (wave length about 1 cm) crenulation cleavage developed after S_2 and observed in only a few outcrops. It could not be determined whether this foliation pre or postdates, or indeed was synchronous with, the development of S_3, although some possibilities will be commented upon in a subsequent section.

Folding Visible in the Country Rocks

B_2 Folds:

The earliest folds visible in the area are tight to more generally isoclinal with wave lengths of less than 2 meters. S_2 appears to be developed as axial plane to these folds, but correlation of the layering folded by B_2 folds with either S_0 or S_1 is uncertain. Hinge lines of B_2 folds plunge approximately NE at shallow to moderate angles (less than 50°), while their axial surfaces strike NNE to ESE and dip vertically to moderately north.

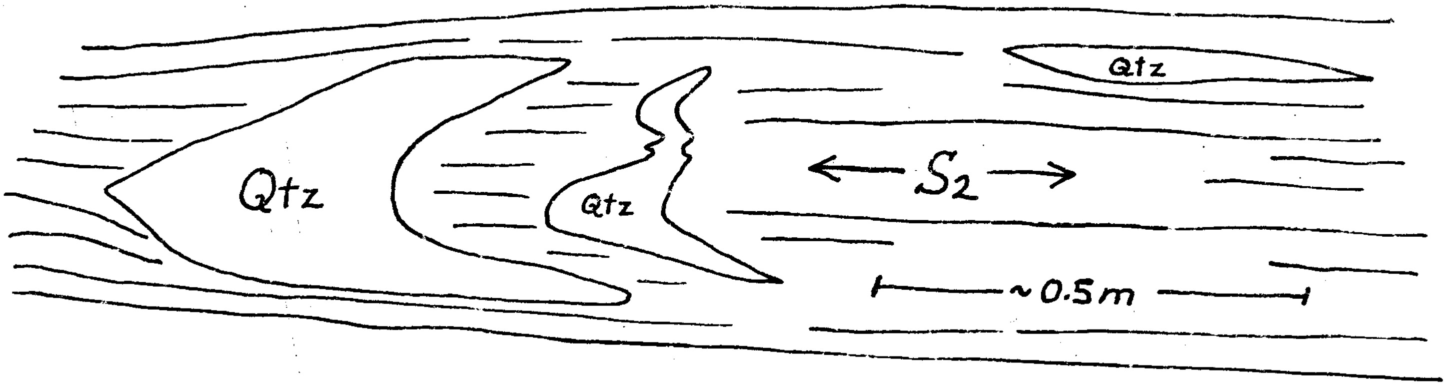


Fig. 10 : folded and boudinaged quartz layers. It is not apparent that S_2 is contained in or passes through the folded quartz layers. Location- atop hill NE of intersection of Adams Hill Road and the Main Road.

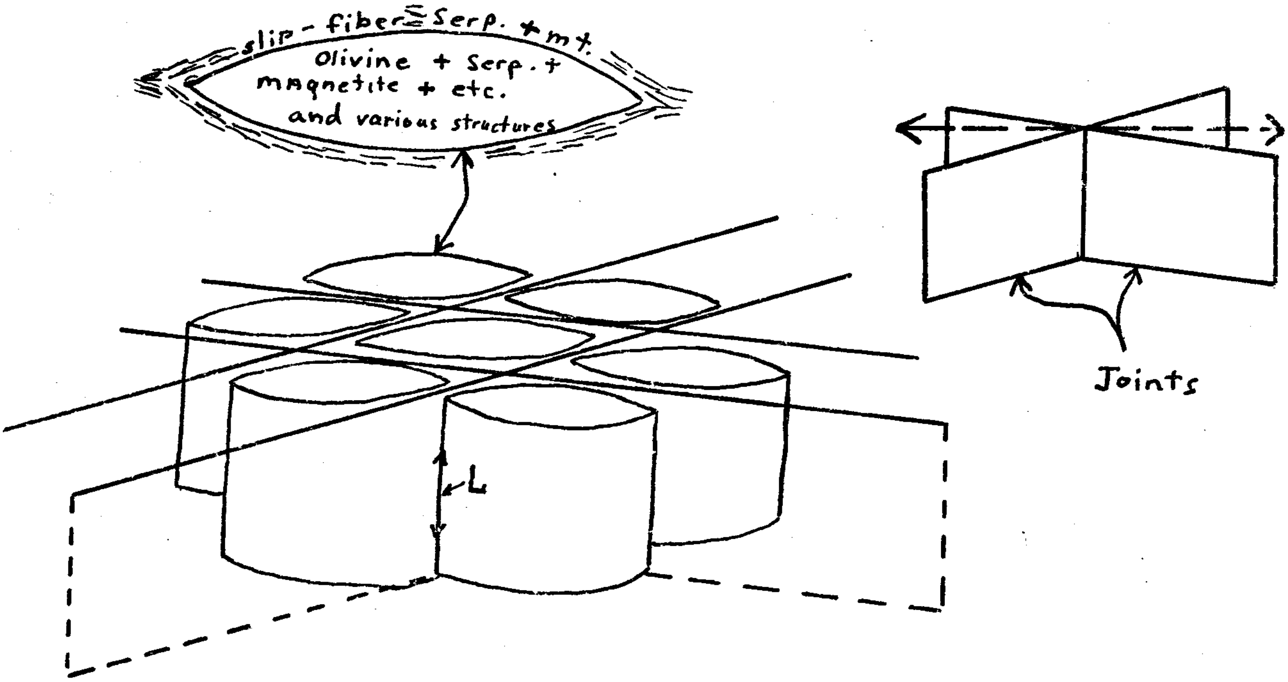


Fig. 11 : anastomosing shearing foliation in ultramafic rocks. Domains may be defined by various combinations of minerals, but slip-fiber serpentine is generally restricted to the areas between individual lenticular-shaped domains. The shape of domains may be controlled by the intersection of two sets of joints as in the inset above right. Lineation "L" does not seem to have a consistant orientation, but the long dimension of the lenticular domains is parallel to the contacts with the country rocks (dashed arrow in inset in upper right).

B_3 Folds:

Folds identified as later than B_2 folds are isoclinal to more generally tight with wave lengths of 4 cm to 2 m. The hinge areas of these folds are typically sharp, almost chevron-like, and show pronounced thickening of the layers in these areas. Hinge lines of B_3 folds typically plunge NNE to ENE at moderate to high angles (40-70°), and where B_2 and B_3 folds can be observed in the same outcrop, B_3 folds commonly have the steeper plunge. Axial surfaces of B_3 folds have orientations that vary from NE to NNE with dips moderately east to vertical. There appears to be a difference in dip of axial surfaces of B_3 on the east and west sides of the ultramafic body, with those on the west side being less steeply inclined.

B_3 folds fold the S_2 foliation and may be tentatively divided into two groups on the basis of their axial surface foliations:

1. those with no axial surface foliation, or a weak S_3 foliation developed parallel to the axial surface;
2. those with a coarse crenulation cleavage, $S_?$, developed as the axial surface foliation.

Nisbet (oral communication, 1974), working near Chester, Vermont, suggests that this difference might be due to the B_3 folds representing two generations of folds (B_3 and B_4) with the same general orientations in this area. Since observations were limited, a conclusion as to this point will have to await further investigation.

Lineations

A pronounced lineation defined by the intersection of S_1 and S_2 is visible in many outcrops (fig. 6).

Foliations Visible in the Ultramafic Rocks

For descriptive purposes, these foliations have been divided into: 1) macroscopic foliations--those best observed on the outcrop scale, and; 2) microscopic foliations--those best observed with a microscope.

Macroscopic Foliations (numbering is not related to relative age):

1. "Shearing foliation." The most prominent foliation visible in ultramafic outcrops and the one most commonly used to delineate the overall map-pattern of the body, is defined by anastomosing domains of olivine + serpentine + magnetite, separated by thin areas of predominently serpentine + magnetite (fig. 11). Individual domains very in size from a few millimeters to a few meters. Toward the interior of the ultramafic body where this foliation is less well developed or absent, it appears as though the anastomosing appearance is due to the intersection of two families of foliation surfaces. Joints are a very prominent feature of the ultramafic rocks and, although no effort was made to study the pattern of joint development, it can be noted that these joints are commonly developed in pairs forming parallelogram-shaped domains.

Microscopic Foliations:

2. This foliation is defined by a rather coarse layering, 2-4 mm wide, of olivine-rich and fine-grained, low birefringent serpentine-rich domains. Individual serpentine grains are equidimensional and olivine-rich layers are commonly discontinuous, occasionally appearing boudinaged. Where olivine-rich layers are boudinaged and kink bands are developed in these olivine grains, the kink band boundaries are typically at a very small angle (less than 25°) to the plane of the foliation.

3. This foliation is defined by thin domains (less than or equal to 1/2 mm) of coarse, elongate (a few mm maximum), bladed serpentine of higher birefringence than that described under number 2 above, alternating with thicker domains of variable mineralogy, usually olivine, fine-grained serpentine and magnetite. This foliation crosscuts, at a high angle, foliation number 2 where the later is developed and has the effect of dividing the olivine-rich domans of number 2 into parallelogram-shaped domains. Occasionally an identical, but weakley developed, foliation is observed at a high angle to foliation number 3. Mutual crosscutting relationships are observed between these latter two foliations, which may imply that they are conjugate shear surfaces.

Foliations number 2 and number 3 are, by far, the most common types observed in thin section. Indeed, number 3 is almost ubiquitous in serpentine-bearing ultramafic rocks. Foliation number 2 is the "sheeted" structure mentioned by Bain (1936) and the "banding" referred to by Skehan (1961). Both authors attributed this layering to some primary feature of the ultramafic rocks. There is, however, no evidence to support this assumption, and, on the contrary, the observations cited before and the fact that much of the mineralogy in the domains defining this foliation is metamorphic in origin (see petrography section), points to a deformational-metamorphic origin for the number 2 foliation.

Other foliations observed in the ultramafic rocks are described below. It is entirely possible that more than one of these foliations originated at the same time and thus reflect varying responses of different parts of the ultramafic body.

4. Small olivine veins occasionally define a foliation (fig. 12). These veins can be seen to cut large, pre-existing olivine grains and are themselves cut by foliation number 3 and clinozoisite +

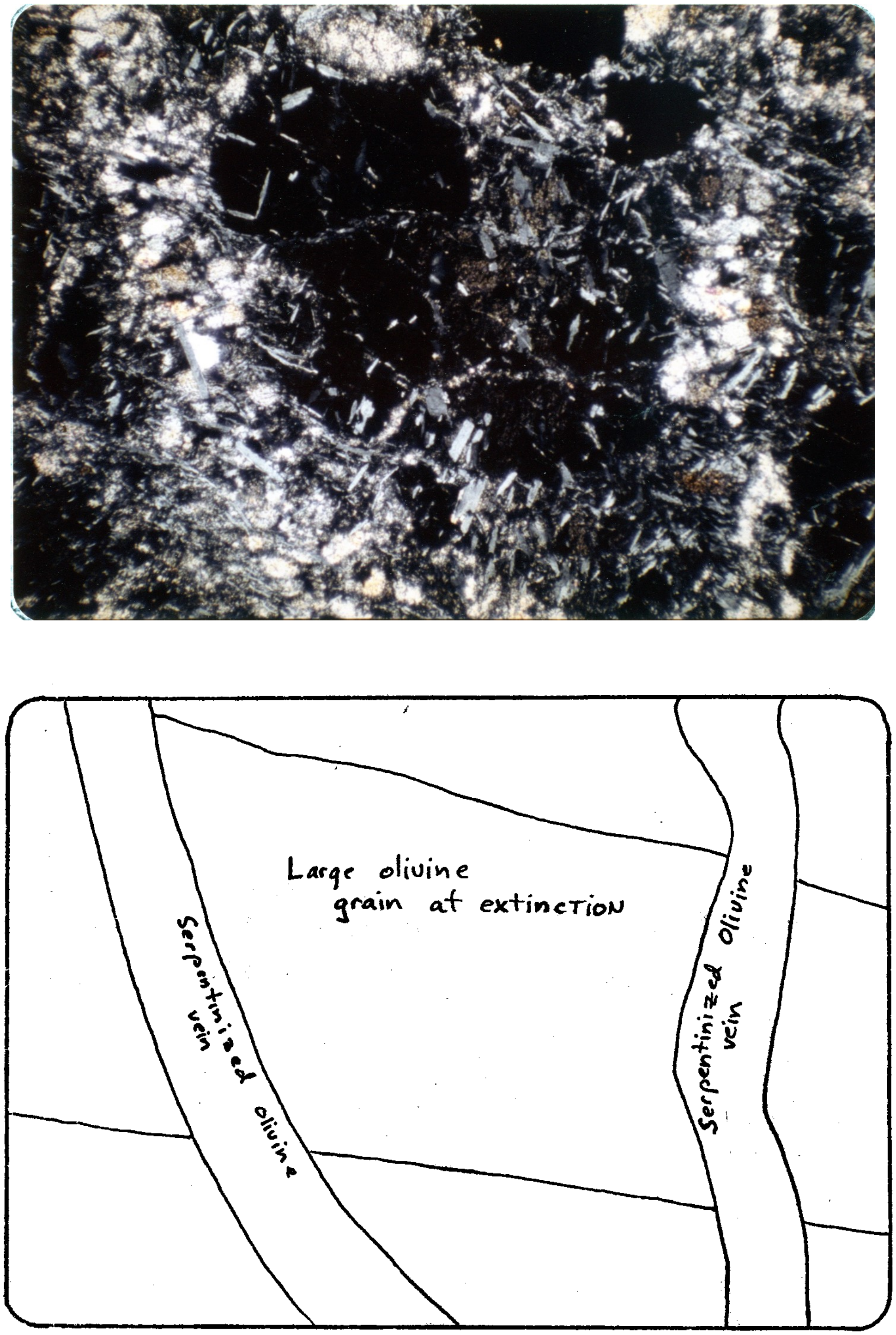


Fig. 12: serpentinized olivine veins crosscutting large serpentinized olivine grain. Length of photo approximately 1.75mm.

carbonate veins from the large clinozoisite-hornblende unit to the west (see subsequent sections). The olivine in these veins has suffered serpentinization to varying degrees, typically 0-20 percent, and shows no evidence of kinking.

5. In the absence of much olivine, and near the contacts, a foliation defined by alternating magnetite and serpentine layers is developed. Individual large magnetite grains are elliptical, boudinaged and occasionally appear flattened in the plane of the foliation. Small isoclinal folds are visible in thin section folding the magnetite layers, the axial surfaces of these folds being more or less parallel to the foliation.

6. Olivine-rich rocks typically display a poorly developed fracture cleavage, with or without serpentine and/or smectite along the fractures. This foliation is similar in many respects (spacing of fractures, degree of development) to the S_3 foliation present in the country rocks. Both foliations cut many earlier foliations implying that both developed late in the deformational history of this area. I suggest that these two foliations, S_3 in the country rocks and number 6 in the ultramafic rocks, may have been contemporaneous.

7. Where olivine grains show the development of kink bands, the kink band boundaries in all grains in the same section are similarly oriented ($\pm$ 25°).

8. In rocks where diopside is developed, there is typically a layering defined by alternating diopside-rich and olivine-rich domains. Individual diopside-rich layers may be up to 4 or 5 mm wide. Further reference will be made to this foliation in the petrography section of this thesis, but it should be mentioned here that diopside is probably

a metamorphic mineral developed after some original pyroxene. This layering, number 8, may then be reflecting a primary layering in the ultramafic body.

9. In the large clinozoisite-hornblende unit west of the main ultramafic body (see map fig. 2 and description in petrography section), a very prominent layering is developed on the scale of a few millimeters. This layering is defined by alternating olive-green clinozoisite-rich layers and black, hornblende-rich layers. Hornblende commonly shows strong undulatory extinction and preferred orientation as shown in figure 8, while clinozoisite has sharp extinction and well developed twins. Quartz veins, derived from quartz-rich amphibolites to the west, penetrate the western margins of this unit, while clinozoisite + carbonate veins from this unit penetrate the serpentinized ultramafic rocks to the east.

There does not appear to be a simple relationship between the macroscopic shearing foliation and any of the microscopic foliations. Occasionally foliation number 3 is seen subparallel to the shear surfaces defining number 1, but this is not always the case.

Folding Visible in the Ultramafic Rocks

Folding in the ultramafic rocks is difficult to observe, but where observed is always on a small scale (wave length typically less than 10 cm) and relatively near mapped contacts with the country rocks. No definite assignment of relative ages of folding episodes can be made, although one instance of overprinting is noted below.

Folds 1:

Small (wave length less than 5 cm) isoclinal folds are visible in the ultramafic rocks where type number 5 foliation is developed, in

Rock River and on the main road near the eastern contact. The folds fold thin magnetite layers and foliation number 5 is developed parallel to the axial plane.

Folds 2:

Small, open to tight folds are visible in a number of outcrops. These folds fold a foliation defined by serpentine and magnetite and in Rock River can be seen refolding the isoclinal folds, number 1, described above.

Discussion of Contact Relationships, Mapped Boundaries of the Ultramafic Bodies and a Review of Previous Workers' Mapped Boundaries

Outcrops where contacts between ultramafic and country rocks can be observed are exceedingly rare, being present at only five locations around the bodies. Therefore, in mapping the ultramafic rocks at East Dover, one important problem is where to place the contacts. In this section a description of the information used to locate the contacts as they appear in figure 2 is presented.

Where contacts can be observed they are of two types:

A. Those with developed metasomatic zones (see Jahns, 1967, for a very good description of these zones);

B. Those with no metasomatic zones. An example of this type of contact occurs at a large outcrop north of East Dover, off Wakelee Road. At this outcrop, highly sheared, carbonate-bearing ultramafic rocks are in contact with massive amphibolite (10-20 cm wide) which is, itself, in contact with well-foliated metapelitic rocks. Walker (personal communication, 1974) has suggested that this second type of contact might be attributed to faulting. It is possible that some of the metasomatic zones were removed during late movements, or rotation, of the ultramafic bodies, possibly the same movements that produced the shearing foliations.

Near the margins of the ultramafic bodies where contacts are not exposed, in many instances the following can be observed:

A. The shearing foliation, number 1 above, increases in intensity of development as the margins of the ultramafic bodies are approached (i.e. the number of lenticular, olivine-rich domains per unit area of outcrop increases). This observation is in agreement with those of Chidester (1968) and Jahns (1967) with respect to the increased development of "shear polyhedra" as contacts with country rocks are approached.

B. There is generally observed a modal increase in carbonate developed in ultramafic rocks near contacts as opposed to those further from contacts.

C. Almost ubiquitously separating the ultramafic rocks from the metapelitic rocks is a quartz-hornblende amphibolite (see petrography section), generally less than 2 m wide and typically only a few tens of cm wide. This "border" unit is also present between the clinozoisite-hornblende unit and the country rocks. Nowhere were metapelitic rocks observed in direct contact with serpentinized ultramafics.

D. Generally, ultramafic rocks are separated from country rocks by at least 5 m, the intervening space usually of lower elevation than the rocks on either side. Where the distance between rock types is greater, it is common to find a swamp or marsh.

E. Folding is more evident near the margins of the ultramafic bodies than in the interior. The only good examples (ones that could be measured with confidence) of folds in the ultramafic rocks at East Dover were observed within 60 m of the contacts.

The above observations agree well with those of previous workers in other ultramafic bodies in Vermont (see history section). I have found, as they did, that although contacts may not be exposed around ultramafic bodies, reasonable inferences as to the locations of these contacts can be made on the basis of the above observations.

The orientation of foliations in the ultramafic rocks also tends to support the interpretation adopted here as to the shape of these bodies. The shearing foliation, number 1, is always observed to be parallel to the contacts, and was the foliation measured in the field and plotted in figure 2.

Comparison of the shape of the ultramafics, as interpreted here, and those of other authors is presented in figure 4. Major differences in interpretation can be seen to be mostly confined to the northern third of the mapped area, where critical outcrop is most lacking.

Walker (personal communication, 1974) relied on new magnetic data in interpreting the shape of the northern area, while Skehan's map is based mostly on reconnaissance field mapping. The interpretation made here for this northern area is based on, besides the observations described above, the following:

1. The area between the two largest exposed ultramafic units is a swamp, lower in elevation that the surrounding rocks.

2. The rock float between the two largest ultramafic units is predominently country rock (mostly pelitic schist).

3. The distribution of various rock textures and the available magnetic data are remarkably consistent with the interpretation used here.

4. The orientation of the shearing foliation and the location of talc and carbonate bearing ultramafic rocks (see fig. 2) supports this interpretation.

The data that have been collected for the northern part of this area tends to support the idea of two separate ultramafic units, as has been mapped here. However, with the available data, Walker's (personal communication, 1974) interpretation is equally valid.

A Discussion of Some Specific Structural Aspects of the Ultramafic Bodies at East Dover

1. The location of the large talc-carbonate deposit in the northern part of the mapped area is consistent in location with the observations of Phillips and Hess (1936). These authors find talc-carbonate deposits commonly developed in what they describe as "infolded" contacts. At East Dover the large talc-carbonate deposit is bordered to the south by serpentinite, with carbonate bearing rocks extending both NE and NW from the most northern outcrop of talc bearing rocks. The long dimension of the talc-carbonate deposit strikes into the swamp separating the two large ultramafic units (see fig. 2). These observations, and the fact that the ultramafic rocks that do border this deposit do not show evidence of unusually severe deformation, suggest that Skehan's (1961) idea of the deposit being a "dike" formed along a fracture system, is not valid.

2. Jahns (1967) describes inclusions of country rocks in the ultramafic bodies at Roxbury, Vermont, and Skehan originally mapped a large inclusion of the Moretown Formation within the ultramafic body at East Dover. The only outcrop of country rocks at East Dover that could be entirely contained in ultramafic rocks is briefly described below.

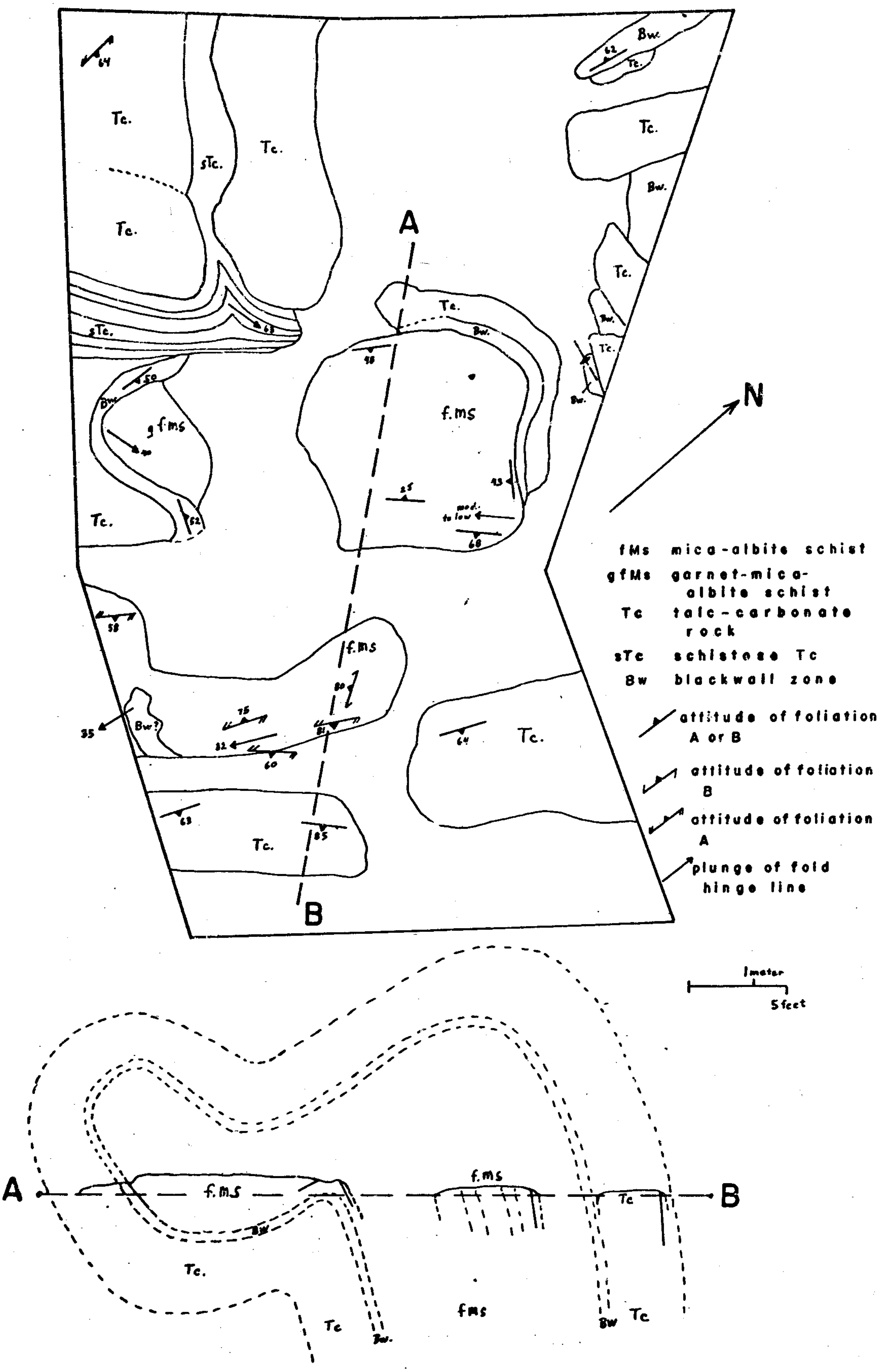
This outcrop is located in Adams Brook near the western contact and is very small in size, measuring less than 20 x 20 meters. It is especially unusual in one respect, in that it is the only rock type in the area with more than minor amounts of feldspar. This outcrop is surrounded by ultramafic rocks with partially developed metasomatic contact zones on all but the southwest margin, where the nearest outcrop is of ultramafic rocks some 400 meters distant. Mapping of a small area including this "inclusion" (fig. 13) indicates that its cross section is that of a refolded isoclinal fold. The unique mineralogy (see petrography section), severely deformed aspect, and location within the ultramafic body (as the contacts are located here) suggest that this outcrop may indeed be an inclusion. However, the lack of outcrop to the southwest leaves this question open to debate.

3. The large clinozoisite-hornblende unit possesses a shearing foliation identical in every respect (except mineralogically) to the shearing foliation developed in the serpentinized ultramafic rocks.

4. Stuckless (personal communication, 1974) mentions a tremolite alteration zone near the northwest contact with the country rocks. However, no evidence of such a zone was found in this study.

5. Bain's (1936) observation that ultramafic outcrops were typically bordered by abrupt, steep cliffs agrees well with observations made here. At East Dover, cliffs range from 2 to 30 m in height. In all cases these cliffs are east facing and nearly vertical. The cliffs at East Dover have their faces parallel to the shearing foliation, and an explanation of their occurrence might be related to this foliation or the direction of glacial movement.

Fig. 13: small outcrop of albite-porphyroblast rock located in Adams Brook about 0.6 km downstream from contact with country rocks.


fMs mica-albite schist
gfMs garnet-mica-albite schist
Tc talc-carbonate rock
sTc schistose Tc
Bw blackwall zone
attitude of foliation A or B
attitude of foliation B
attitude of foliation A
plunge of fold hinge line
N
1meter
5feet
A
B
Tc.
sTc.
Bw.
f.ms
gf.ms
Bw?
mod. to low
64
62
63
50
40
52
98
25
43
68
58
35
75
32
60
80
81
64
63
85
Tc
Bw
fms

Correlation of Structural Elements Between Country Rocks and the Ultramafic Rocks

The nature of this study at East Dover did not allow a definite correlation of structural elements between country rocks and ultramafic rocks. However, (table 1) a very tentative and interpretive correlation based on the following criteria has been compiled:

1. A relative age can be assigned to many of the foliations visible in each rock type.

2. Both country rocks and the marginal areas of ultramafic rocks show evidence of two folding episodes and the style of folding in each rock type is approximately the same.

3. The most intense and pervasive foliations in each rocks type have characteristics in common, such as spacing, a relative late development in relation to the other foliations developed in the area, and the intensity of development.

4. Both rock types have experienced three (at least) metamorphic events.

Table 1 implies that the ultramafic rocks at East Dover were emplaced prior to, or at the same time as, the development of the first metamorphic foliation in the country rocks. If this foliation represents Ordovician deformation (see history section) than it might be inferred that emplacement occurred also during the Ordovician.

Concluding Remarks

What I have attempted to do with my structural study in the East Dover area is describe some of the types of foliations and structures visible in the ultramafic rocks, and to show that a correlation of these elements with similar elements in the country

COUNTRY ROCKS			ULTRAMAFIC ROCKS		
FOLIATIONS	FOLDING	COMMENTS	FOLIATIONS *	FOLDING	COMMENTS
S_0		primary layering (?)	no. 8		primary layering
S_1	?	garnet-grade metamorphism	nos. 2,7	?	serpentinization of olivines, uralitization of pyroxenes
S_2	B_2	garnet-grade to epidote-amphibolite grade metamorphism	nos. 3,4, 5(?),9	isoclinal	recrystallization of olivines, generation of diopside, alteration of chrome spinels, serpentinization (antigorite)
S_3 or $S_?(S_4)$	B_3 or B_4	chlorite grade metamorphism (?)	nos. 1, 6	tight	serpentinization

* see text for explanation

NOTE: this table is very speculative and is not intended to imply any definite structural correlations between the ultramafic and country rocks.

Table 1

rocks is possible. This correlation is, of course, tentative and, undoubtedly, further work would allow a more definitive or conclusive result.

PETROLOGIC ASPECTS OF THE EAST DOVER ULTRAMAFIC BODIES AND SURROUNDING COUNTRY ROCKS

Petrography of the Country Rocks Surrounding And Contained Within the Ultramafic Rocks

There are three rock types defined on the basis of major mineralogy surrounding and/or contained within the ultramafic rocks:

1. quartz-mica schists, in places gneissic;
2. quartz-hornblende epidote amphibolites;
3. mica-albite (porphyroblast) schist.

Quartz-mica Schists (Metapelitic Rocks):

These are by far the most abundant of the country rocks, comprising approximately 80-85 percent of the exposures (Skehan, 1961). Typically three micas--muscovite, biotite, and chlorite--are present. Modal amounts of garnet vary from trace to nearly 6 percent, while magnetite, zircon, apatite, and clinozoisite are common accessories. No feldspar or amphibole has been found in these rocks.

These rocks have a well developed crenulation cleavage, (see structure section), muscovite, defining the earlier, and biotite, the later foliations, respectively. Quartz is typically between 35 and 45 modal percent.

Chlorite appears as an alteration product of biotite and/or garnet. Anomalous violet and brown interference colors are often observed for these chlorites, which suggests a composition near penninite (Albee, 1962).

Biotite is sometimes observed enclosing laths of muscovite in a pseudo-ophitic manner. Garnet "trains" are aligned in the S_1 plane (parallel to 001 of muscovite) and individual larger garnet grains typically contain traces of that foliation which is now rotated parallel to S_2.

Structural and petrologic observations suggest that these rocks have suffered at least two deformational/metamorphic events. The earlier event, producing S_1 formed some garnet (the garnet in the "trails" in S_1) and muscovite, while the later event, producing S_2, formed garnet (overgrowths and garnet with included fabrics) and biotite. Biotite also probably formed after the development of S_2. (cross micas). Chlorite alteration affected both biotite and garnet.

Quartz-epidote Amphibolites:

The major mineralogy of this rock type is hornblende and quartz, with however, an extreme range in grain size and modal percentage of these two minerals being observed. To facilitate mapping and discussion it was found convenient to include within this rock type the following two variations:

1. rocks with 90-95 percent hornblende, approximately 5 percent quartz and accessories (hornblendites); and
2. rocks containing little or no hornblende but which are intimately interlayered with the more normal amphibolites. These rocks may be distinguished from the metapelitic rocks by the presence of abundant chlorite and what appears to be a rimming relationship between two epidote group minerals: a dark yellow-brown core in sharp contact with a light clear to yellowish rim.

Typically, however, these amphibolites have quartz and hornblende in roughly similar amounts, generally greater than 25 modal percent. Accessory mineralogy is complex: chlorite (up to 22%), garnet, albite, epidote group minerals, muscovite, magnetite and apatite are present in varying amounts and combinations.

Hornblende may be developed as crystals up to 3 cm long. "Rosettes" of these large crystals are common, close to the contacts with ultramafic rocks. Most of the hornblende observed has a striking blue-green axial (Z) color and is the main mineral defining foliation.

Garnets show no evidence of rotation or two growth stages, as do some of the garnets in the metapelitic rocks. Albite, if present, is always less than 5 modal percent and albite twinning is sometimes poorly developed or absent.

The occurrences of quartz-epidote amphibolites are especially interesting. They are invariably found separating ultramafic rocks from metapelitic rocks and in this respect constitute a distinct border unit to the ultramafic bodies. In some instances they are useful in locating contacts. It should be noted, however, that visible contacts of ultramafic rock with country rock are rare, but, in every instance where contacts are observed or closely inferred, quartz amphibolites are present.

These amphibolites are also found as thin interlayered units and small pod-like units within the metapelitic rocks. The relationship of these amphibolites to the "border" unit is not clear.

Quartz veins originating in quartz-hornblende amphibolites adjacent to the large clinozoisite-hornblende unit (described subsequently) penetrate for a few meters eastward into the clinozoisite-hornblende unit. No similar quartz veins are found anywhere penetrating the serpentinized ultramafic rocks.

Mica-albite (Porphyroblast) Schist:

It is estimated that this rock type is comprised of 70-80 percent albite, 15-25 percent micas (biotite, chlorite, muscovite), 2-5 percent clinozoisite, minor quartz and less than 1 percent opaques. Albite is developed as porphyroblasts, some as large as 3-5 cm in diameter. Schistosity is weakly developed and defined by biotite, for the most part.

In the East Dover area this rock type is found at only one location, believed to be an inclusion within the ultramafic body (a description of the structure at this location has been given on page 41 and fig. 13).

Chidester (1961) has described an "albite porphyroblast rock" found at the margins of ultramafic bodies in North-Central Vermont. His observations agree well with those of this study except for two points:

1. biotite is more abundant than chlorite in these rocks at East Dover, whereas Chidester (1961) made no mention of biotite as a major constituent of the rocks he described;
2. Chidester (1961) reported a thickness of 3-5 inches for albite porphyroblast rock bordering ultramafic bodies in North-Central Vermont, while at the occurrence of this rock at East Dover a thickness of 30 cm (12 inches) is not uncommon.

That the albite in this rock is metasomatic in origin is probably unquestionable (Chidester, 1961). However, these albite porphyroblasts show well developed albite twins and any hypothesis as to their origin would have to account for this twinning, possibly as either growth or deformational twins.

Chidester (1961) believes that the formation of the albite porphyroblast rocks is related to the formation of the "blackwall" zone and therefore a metasomatic process. At East Dover it is not clear whether or not this entire unit can be ascribed a metasomatic origin.

Petrography of the Ultramafic Rocks

Three ultramafic rock types are encountered in the field:

1. serpentinized dunite, composing the largest ultramafic units;
2. a "clinozoisite-hornblende," a small lenticular unit outcropping between, and in contact with, serpentinized dunite and quartz-hornblende amphibolites;
3. an ultramafic "breccia," observed at only one location in Rock River.

The mineralogy of each of these rock types is described below. Petrologic aspects are introduced and discussed where appropriate. Methods of optical and chemical analysis are described in Appendicies I and II.

Mineralogy of the Serpentinized Dunites:

Serpentine - optically two types of serpentine are recognized:

1. a very fine-grained, equidimensional serpentine with extremely low birefringence;
2. a coarse, bladed variety with higher birefringence than the first type.

Relationships of these two types of serpentine to foliations have been previously described.

Recently it has been reported that three polymorphs of serpentine have been identified in thin section by differences in birefringence and morphology (Rao et al., 1974). No detailed investigation of serpentine mineralogy was undertaken for this thesis and it is not known whether the difference in optical properties observed reflects the presence of two serpentine polymorphs.

The percentage of serpentinization observed in these ultramafic rocks varies from 5 percent to 100 percent (true serpentinite) and averages 45-55 modal percent (fig. 14). The following observations were made with respect to the distribution of serpentinization in these ultramafic bodies:

1. Areas interpreted as being at, or very close to, mapped contacts with country rocks generally have the highest percentage of serpentinization.

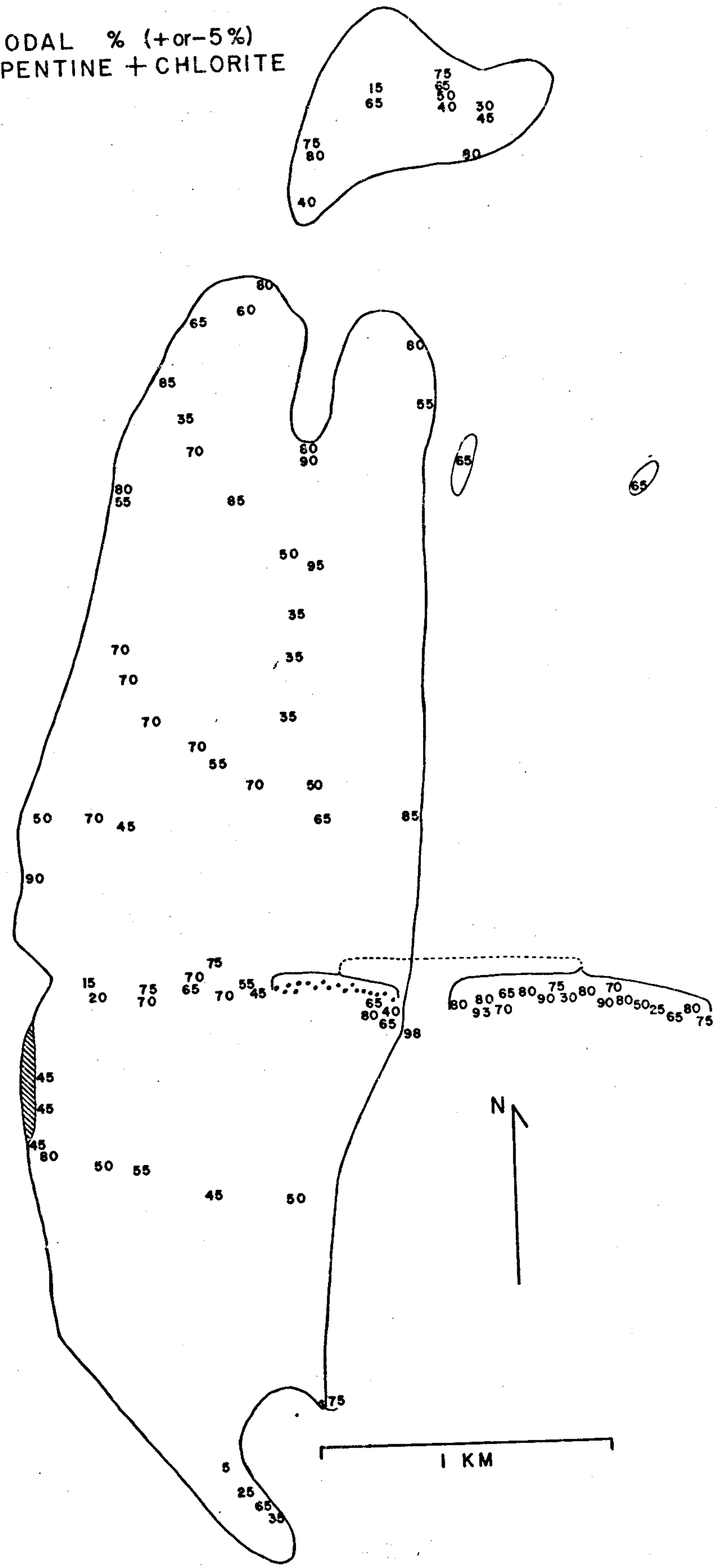
2. With the exception of the areas described above there is no regular distribution of serpentinization within these ultramafic bodies (fig. 14). A look at the distribution of serpentinization in ultramafic rocks along the Main Road at East Dover (fig. 14 enlargement) illustrates the complexities to be encountered in attempts to postulate an orderly arrangement of serpentinization (Skehan, 1961; Stuckless, 1972).

3. Overall, areas south of the Main Road in East Dover show less serpentinization (average 50%) than areas north of the Main Road (average 65%). The significance of this observation is not yet apparent.

4. On an outcrop scale, highly deformed, foliated, linear "zones" with a high percentage of serpentine are observed bordering "massive," less serpentinized rock. These zones dip steeply, trend north-south to north-northeast and are observed in almost all parts of the ultramafic bodies. Petrographic investigation of these zones reveals a high proportion of "slip-fiber" serpentine (Coleman and Keith, 1970) oriented parallel to the strike of the large zones. These zones are here interpreted as shear zones that may have developed prior to or contemporaneously with the development of the

Fig. 14: modal percent serpentine + chlorite (+ or - 5%). An area along the Main Road in East Dover has been enlarged 2 times. The diagonally ruled area is the clinozoisite-hornblende unit.

MODAL % (+or-5%)
SERPENTINE + CHLORITE



"shear polyhedra" structures already described.

Discussion of serpentine distribution - Hess (1933) argued that the distribution of serpentinization in Vermont ultramafic bodies is "haphazard" and generally unrelated to the margins of the bodies. Skehan (1961) and Stuckless (1972) report a zonal arrangement of serpentinization for the East Dover body; a highly serpentinized margin grading to an "unaltered" dunite core.

The results of this study are most nearly in agreement with those of Hess (1933). Serpentinization is uniform over large areas of the East Dover ultramafic bodies but is randomly disposed with respect to the margins. The configuration of serpentinization in these bodies might be represented by the arrangement of structures similar to the "shear polyhedra" described by Chidester (1968) and Jahns (1967), but no large scale structures of this nature were delineated in this study.

Chlorite - chlorite and serpentine are generally intimately intermixed in the rocks at East Dover, making optical discrimination at times difficult. For this reason, and because serpentine and chlorite are structurally and chemically similar, the plot of percent serpentinization in these rocks (fig. 14) is actually the plot of total serpentine + chlorite.

Different interference colors for chlorites with different occurrences are observed:

A. Most chlorites show typical green to grey-green interference colors and are difficult to distinguish from the non-bladed variety of serpentine.

B. Chlorite with anomalous brown and violet interference colors is observed associated with magnetite and chrome spinels. This association takes the form of "inclusions" of chlorite in magnetite and chrome spinels, partial to complete rims of chlorite on magnetite and chlorite "linings" along the interfaces separating magnetite rims from chrome spinel cores (see below). These anomalous interference colors indicate a $(Fe^t + Mn + Cr)/(Fe^t + Mg + Mn + Cr)$ ratio of about 50-55 atomic percent (Albee, 1962), while normal interference colors probably indicate a lower value for this ratio (Albee, 1962). It is suggested that the higher value of this ratio for chlorites associated with magnetite and chrome spinel could be explained by a reaction with or alteration of these minerals which enriches the chlorites in Fe^t and/or Cr relative to Mg.

Olivine - olivine is present in a large majority of the thin sections observed, and modally it may compose 95 percent of an individual section. Optically it is possible to separate olivine grains into two textural types on the basis of their appearance in thin section. These two types are defined and discussed below.

Type 1 (T_1) olivines - have well developed kink bands and/or strong undulose extinction (fig. 15). There is no optical evidence of recrystallization (see below). Typically, numerous small (<1 mm) olivine grains, separated by serpentine, are optically continuous (have identical or similar extinction positions). This implies the former presence of much larger grains, some originally a centimeter or more in diameter.

Type 2 (T_2) olivines - no kink bands are visible in these olivine grains, which generally show very sharp extinction. Recrystallization textures are dominant, the following being interpreted as recrystallization phenomena:

1. Overgrowth or corona structures (fig. 16). Olivine grains form complete or partial coronas around magnetite grains.

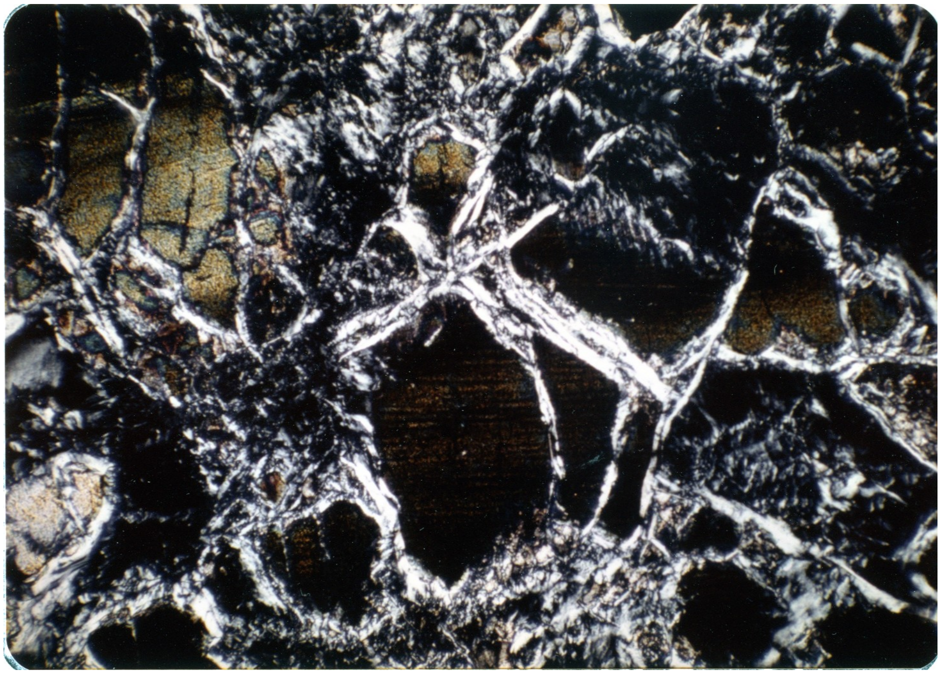


Fig. 15: typical development of kink-bands in olivine. Kink-band boundaries are oriented approximately horizontally in this photograph. Long dimension of photograph is about 1.75mm.

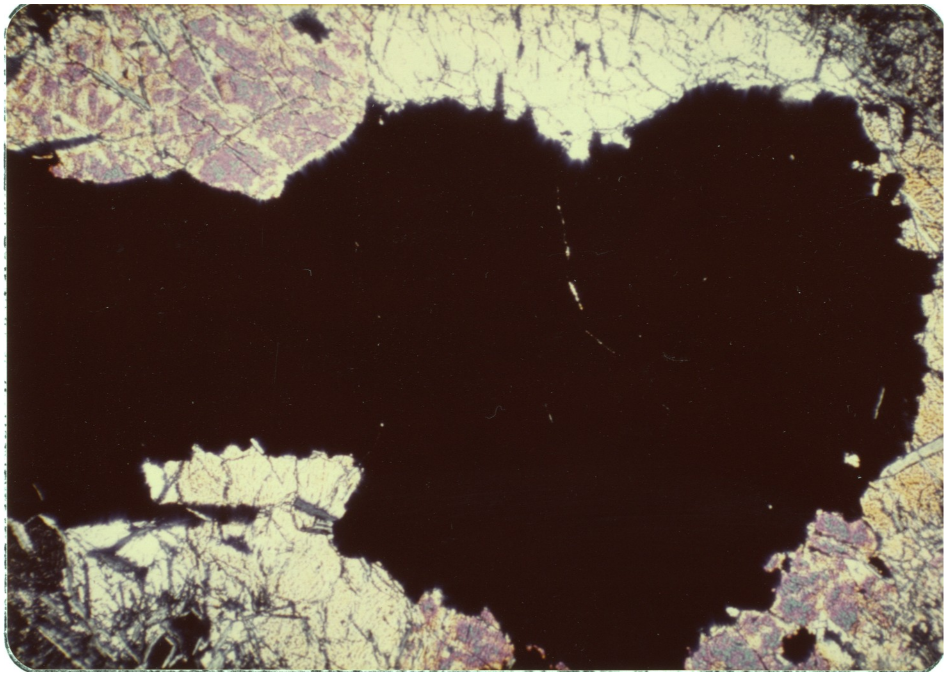


Fig. 16: "Corona growth" of olivine around opaque. Long dimension of photograph is about 1.75mm.

These coronas are usually observed as numerous randomly oriented olivine grains surrounding a magnetite core, but occasionally a small magnetite grain is observed completely enclosed in a single olivine grain.

2. Annealed texture (fig. 17). Ragan (1969) and Kretz (1966) have shown that recrystallization of olivine under hydrostatic stress (annealing) produced a characteristic texture dominated by 120° triple junctions between adjacent olivine grains. This texture is poorly to moderately well developed in a number of thin sections. At one locality, near the southern margin of the largest ultramafic unit, however, it is the only prominent textural feature observed (fig. 17).

3. "Interfingering" and interlocking texture (fig. 18). Numerous elongate olivine grains with sharp extinction are observed "interfingering" with each other. Occasionally a less elongate olivine grain is observed enclosed within a single elongate grain. Serpentinization of grains showing this textural feature is absent to minimal, while serpentinization of other olivine grains in the same thin section may be well advanced.

The following features, where observed, are interpreted as representing incipient recrystallization phenomena:

4. Replacement textures (fig. 19). Small elongate olivine grains are observed cutting, or developed along the margins of, larger olivine grains. Measurement of the optic orientation of host and "new" grains suggests that there is some control exerted by the host grain on the optic orientation of the Z-axis of the "new" grains. Avé Lallemant and Carter (1970) have recognized "host control," by relict grains, of the optic orientation of

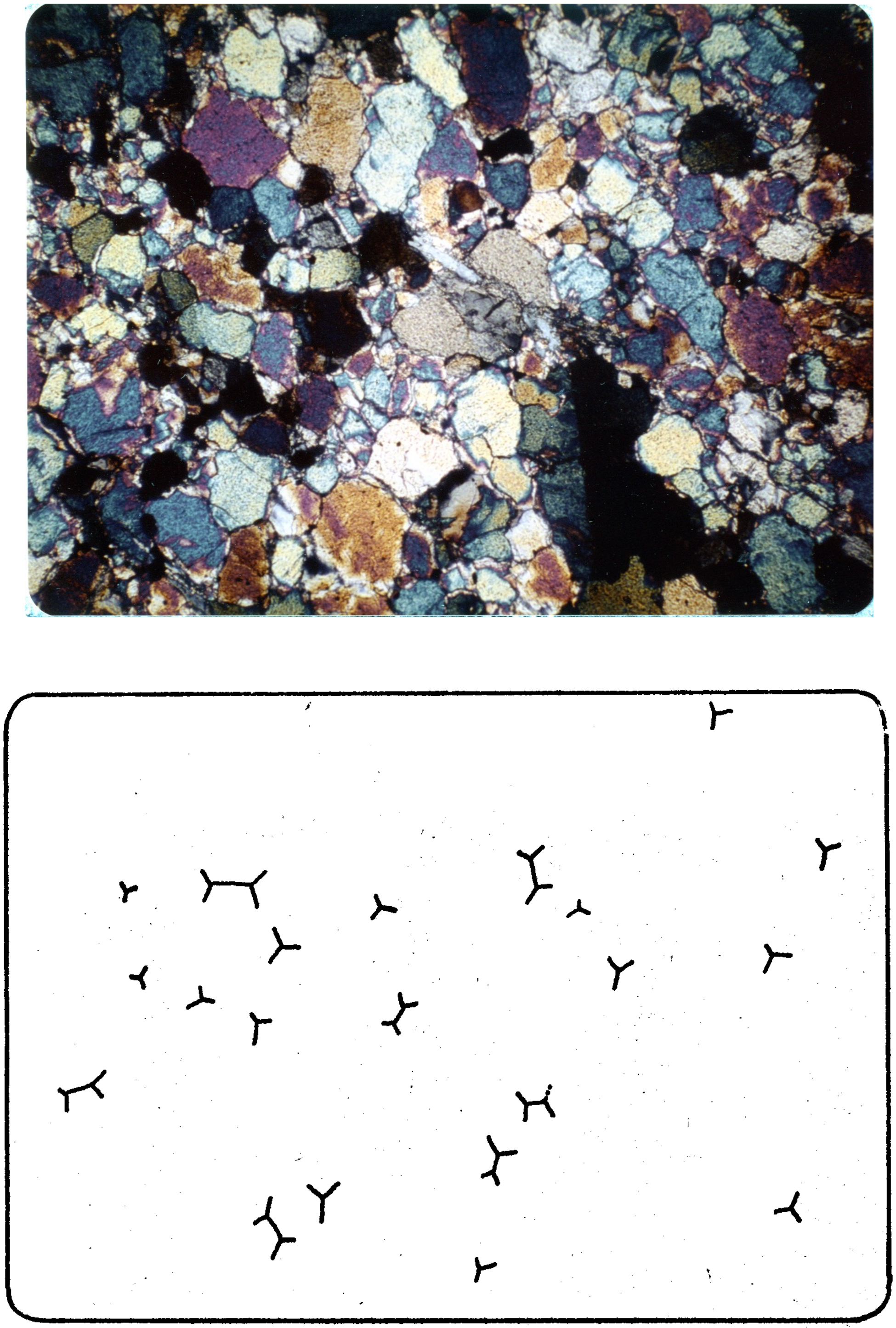
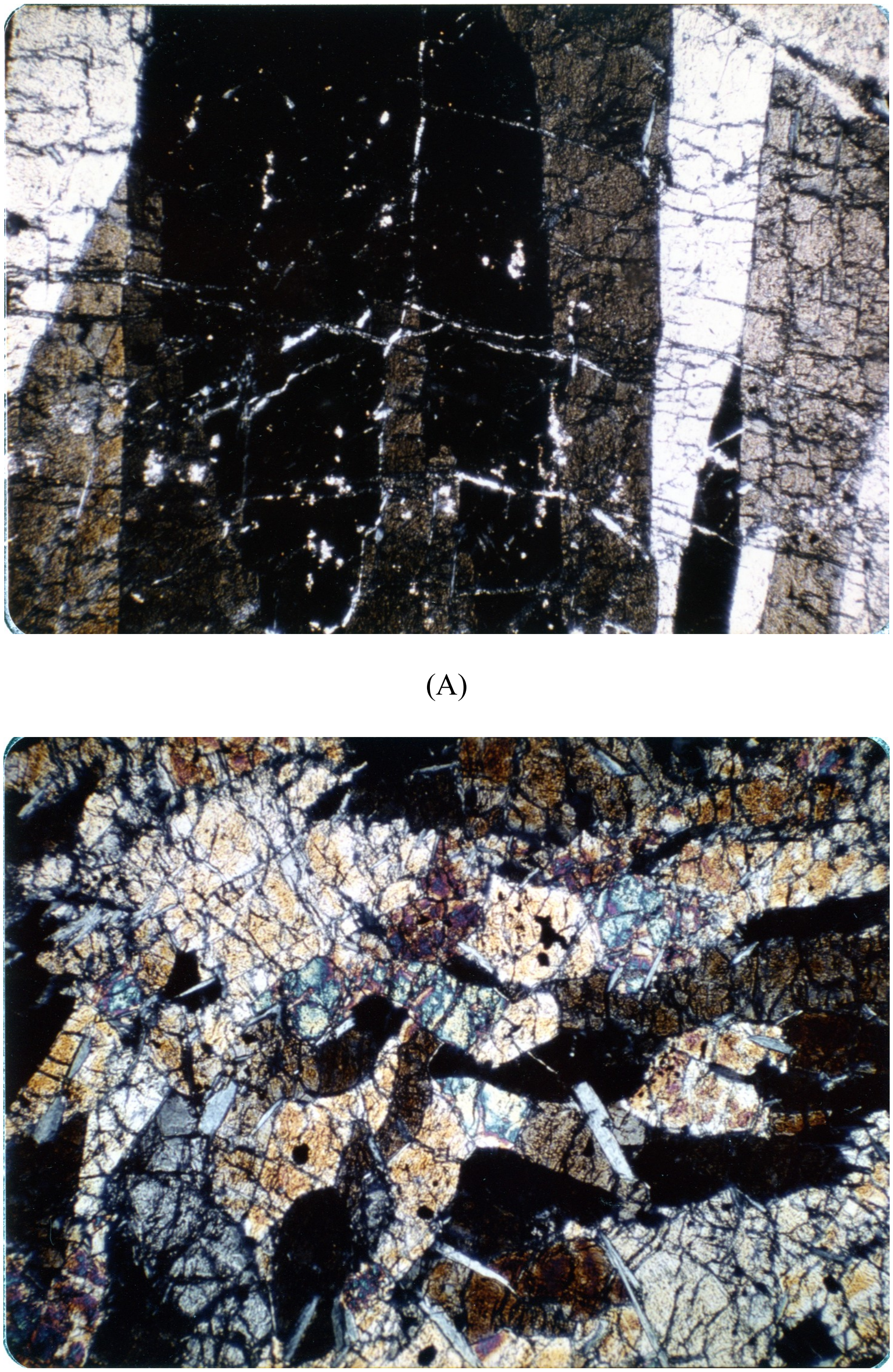


Fig. 17: the development of 120° triple grain boundaries in olivine. Lower figure is position of some of these triple boundaries in the above photograph. This sample is from olivine Zone 2 (it contains some kink-bands, not visible) and is interpreted as representing incipient recrystallization under hydrostatic stress (annealing). Length of photo approximately 1.75mm.

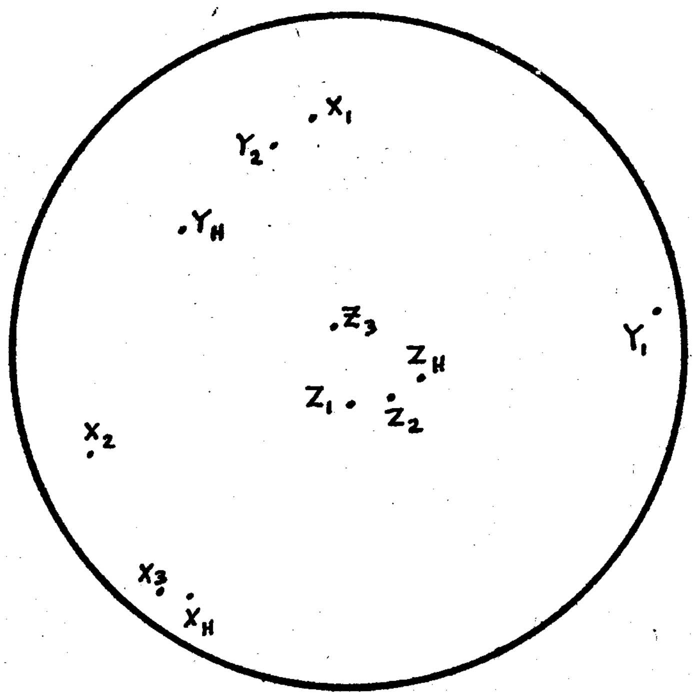


(A)

(B)

Fig. 18: (A) Interfingering texture of olivine grains. (B) Interlocking texture of olivine grains. In both examples individual olivine grains show very sharp extinction. Long dimension of photographs is approximately 1.75mm.

(A)



(B)

Fig. 19: A) olivine replacement texture. Three small elongate olivine grains are seen penetrating larger (at extinction) olivine grain (host).

B) optic orientation of host olivine grain (Z_H,X_H,Y_H) and new olivine grains (Z_1, etc.).

Host control of the orientation of the Z-axes of the new grains is implied.

recrystallized olivine grains.

5. Grain boundary recrystallization and embayment features. Very small olivine grains with sharp extinction are observed along the grain boundaries and internal surfaces (cracks ?) of large olivine grains. These large olivine grains occasionally show undulose extinction or poorly developed kink bands. Avé Lallemant and Carter (1970) and Sylvester and Christie (1968) suggest that features such as this represent incipient recrystallization.

6. Olivine veins (fig. 12). Small veins of olivine are observed cutting larger "relict" olivine grains. These veins are serpentinized to varying degrees and not readily recognized in the field.

All olivine-bearing rocks at East Dover were classified on the basis of the olivine textural type that was most abundant in thin section. The effect of the orientation of the thin sections on the determination of this classification was found to be minimal. Three zones, gradational in all respects, were recognized:

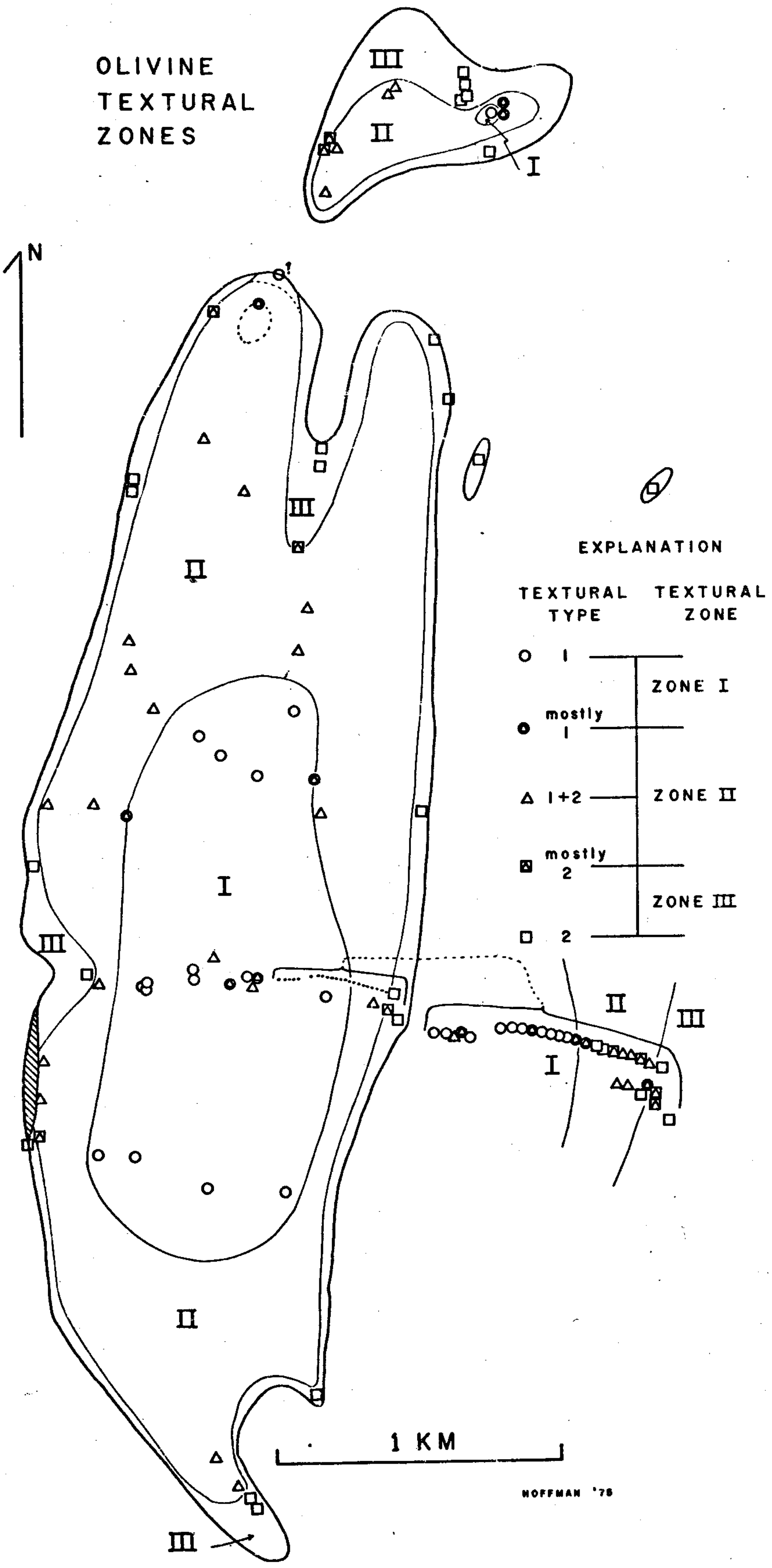
Zone 1 - over 90 percent of the olivine grains in thin section are textural type 1. No type 2 features are observed, with the possible exception of a very minor amount of grain boundary recrystallization.

Zone 2 - type 1 and type 2 olivines are intermixed. This means that olivine grains showing recrystallization features are present in the same thin section as those displaying well developed kink bands.

Zone 3 - over 90 percent of the olivine grains in a thin section display type 2 recrystallization features.

The relationship of these zones to olivine textural types and the geographic distribution of these zones over the ultramafic bodies is shown in figure 20.

Fig. 20: distribution of different olivine textures. The boundaries between zones are not intended to indicate exact limits but rather to show the manner in which olivine textures vary. An area along the Main Road has been enlarged 2 times.


OLIVINE TEXTURAL ZONES
N
I
II
III
1 KM
EXPLANATION
TEXTURAL TYPE
TEXTURAL ZONE
○ 1
ZONE I
● mostly 1
△ 1+2
ZONE II
⊠ mostly 2
ZONE III
□ 2
HOFFMAN '78

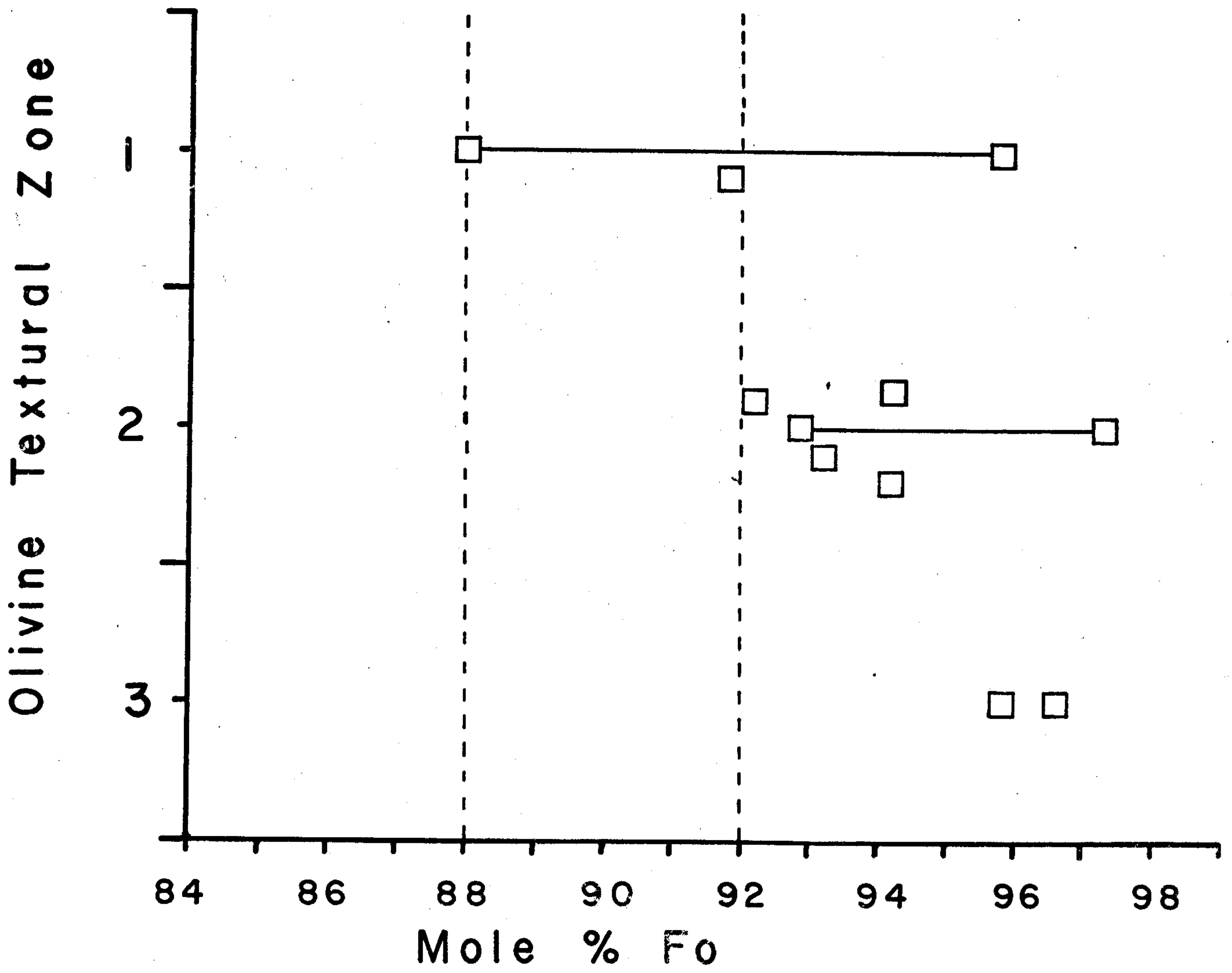
Chemical variations of olivines - samples of olivine from each of the above zones were analyzed by X-ray diffraction (method discussed in Appendix I) to determine the Fo content. Figure 21 shows the results of these analyses plotted as a function of olivine textural zone. A number of conclusions can be drawn from this figure:

1. the lowest Fo olivine (Fo_{88}) is present only in Zone 1;
2. two olivine compositions coexist in Zone 1 and 2 but not in Zone 3;
3. all three zones have some Fo-rich olivine (Fo_{96}) but Zone 3 is entirely Fo-rich olivine;
4. the range of olivine compositions varies from 8 modal percent Fo in Zone 1 to a restricted range of $Fo_{96 \pm 1}$ in Zone 3.

Discussion of olivine textural and chemical variations - the observation of kink bands in olivines of Alpine-type peridotites is common (Loney et al., 1971; Avé Lallemant and Carter, 1970; Ragan, 1967). In the East Dover rocks, however, previous workers (Skehan, 1961; Stuckless, 1972) have not reported kink bands in olivine. The geographic disposition of zones defined by olivine textural types (fig. 20) implies that the degree of recrystallization has proceeded (decreased) in a regular way from the margins of the bodies (Zone 3) toward the interiors (Zone 1).

A bimodal distribution of olivine compositions in the East Dover bodies was initially reported by Stuckless (1972). This study shows that a definite correlation exists between olivine composition and textural type. It may then be concluded that there is a direct correlation between composition and degree or intensity of recrystallization. The geographic distribution of olivine compositions further

Fig. 21: percent Fo of olivines in different textural zones. Vertical scale is not gradational (does not indicate differences in individual textural zones). The dashed lines at Fo_{88} and Fo_{92} represent the average Fo content of olivines in peridotites and dunites respectively.


Olivine Textural Zone
1
2
3
84
86
88
90
92
94
96
98
Mole % Fo

suggests that:

1. all the ultramafic rocks in the area have suffered some degree of recrystallization;
2. the fraction of total olivine that has suffered recrystallization increases gradationally from a few percent in the core areas to nearly 100 percent at the margins of the largest ultramafic bodies. This change is accompanied by a "homogenization" of the olivine compositions to around Fo_{96};
3. Zone 1 has olivine of the lowest Fo content in the area; furthermore, Skehan (1961) reports finding Fo_{87} olivine in rocks within Zone 1. It is suggested here that $Fo_{88 \pm 1}$ represents the "primary" or original composition of olivine in these rocks. Furthermore, it is reasonable to assume that the Fo_{95-97} olivine detected in a few rocks of Zone 1 is the product of incipient grain boundary recrystallization, which was indeed observed in a number of thin sections.

Chrome spinel and magnetite - it is possible to define three textural types of chrome spinel based on a gradational change in the appearance of chrome spinel grains. With one exception, commented on below, chrome spinels are ubiquitously rimmed by magnetite. The thickness of these rims and the shape of the chrome spinel cores (euhedral to anhedral) form the basis for this textural classification. Textural types composing the end members and midpoints of this gradational series are defined below:

Type 1 (T_1) - chrome spinel grains are euhedral, (rarely subhedral) and have extremely thin magnetite rims. Internal cracks in these grains, if present, show no evidence of alteration to other minerals such as chlorite or magnetite.

Type 2 (T_2) - chrome spinel grains are generally subhedral (rarely euhedral or anhedral) and have moderate to thick magnetite rims. Internal cracks are altered to opaques (magnetite ?).

Type 3 (T_3) - chrome spinel grains are completely anhedral and have very thick magnetite rims.

Examples of these textural types are shown in figures 22 and 24. Three geographic zones are delineated (fig. 23) on the basis of the occurrence of these textural types. In contrast to olivine textural variations, chrome spinel textural types are not intermixed and the change in textural type is gradational in all respects. The similarity in geographic distribution of these zones and those defined for olivine is striking (compare figs. 20 and 23). With respect to the two largest ultramafic bodies, a core with Type 1 chrome spinels grades outward to a margin with Type 3 chrome spinels.

Accompanying this textural change is a change in the intensity of color of the chrome spinel cores (fig. 24). Type 1 chrome spinel grains are generally dark red-brown to opaque, translucency being often difficult to detect (fig. 24a). Type 2 chrome spinel grains are generally lighter in color (more yellow-orange) and translucency is greater than that of Type 1 (fig. 24b). Type 3 chrome spinel grains are usually even lighter colored than Type 2; yellow and orange colors are typical and translucency is very apparent (fig. 24c). As figure 25 shows, however, this color change is neither universal, nor strictly uniform.

Fig. 22: typical chrome spinel textural variations (see also fig. 24). Drawings represent opaque rims and translucent cores. A) Type 1 chrome spinels; B) Type 2 chrome spinels; C) Type 3 chrome spinels.

The black linear segments in A and C represent chlorite (see text).

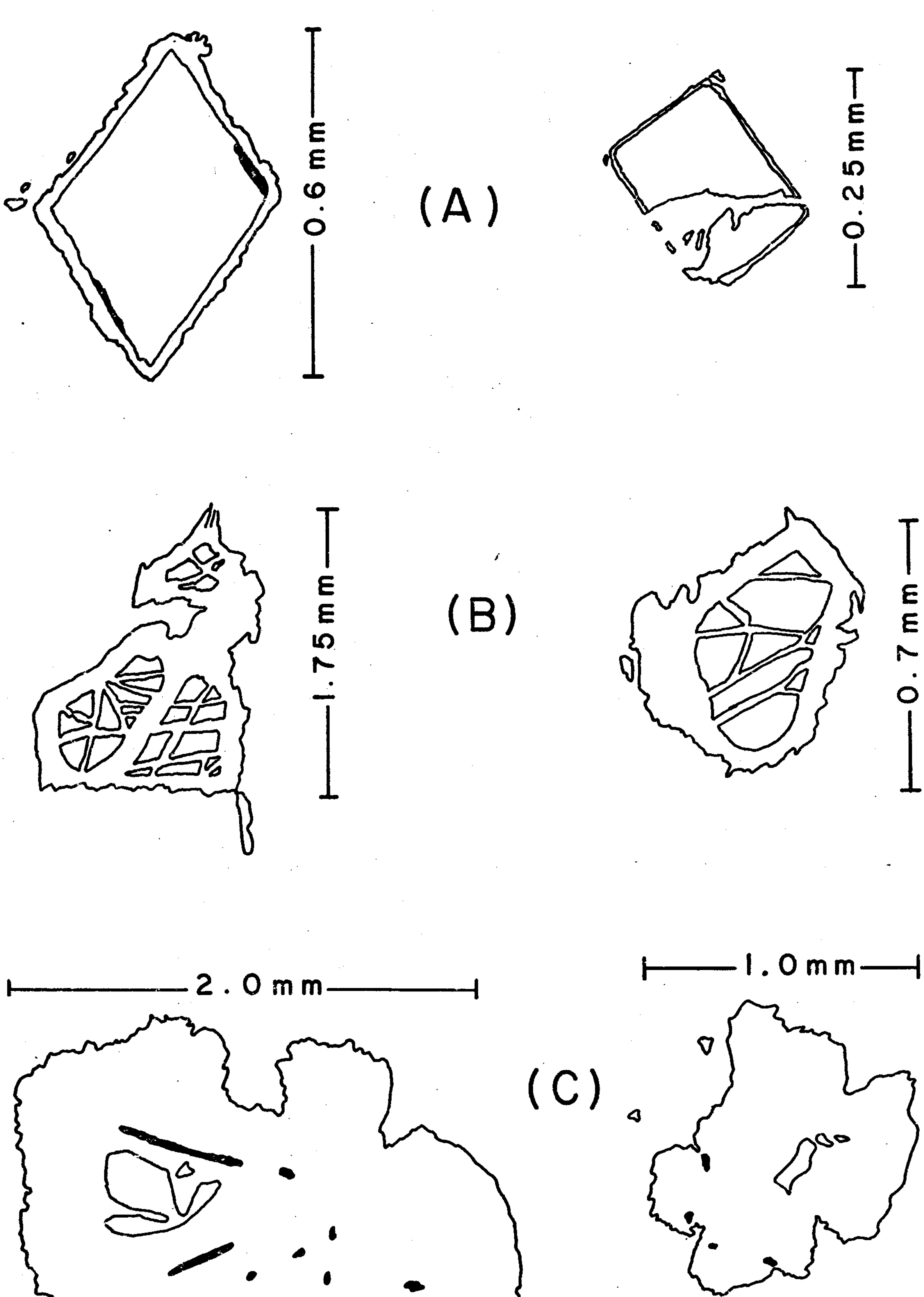
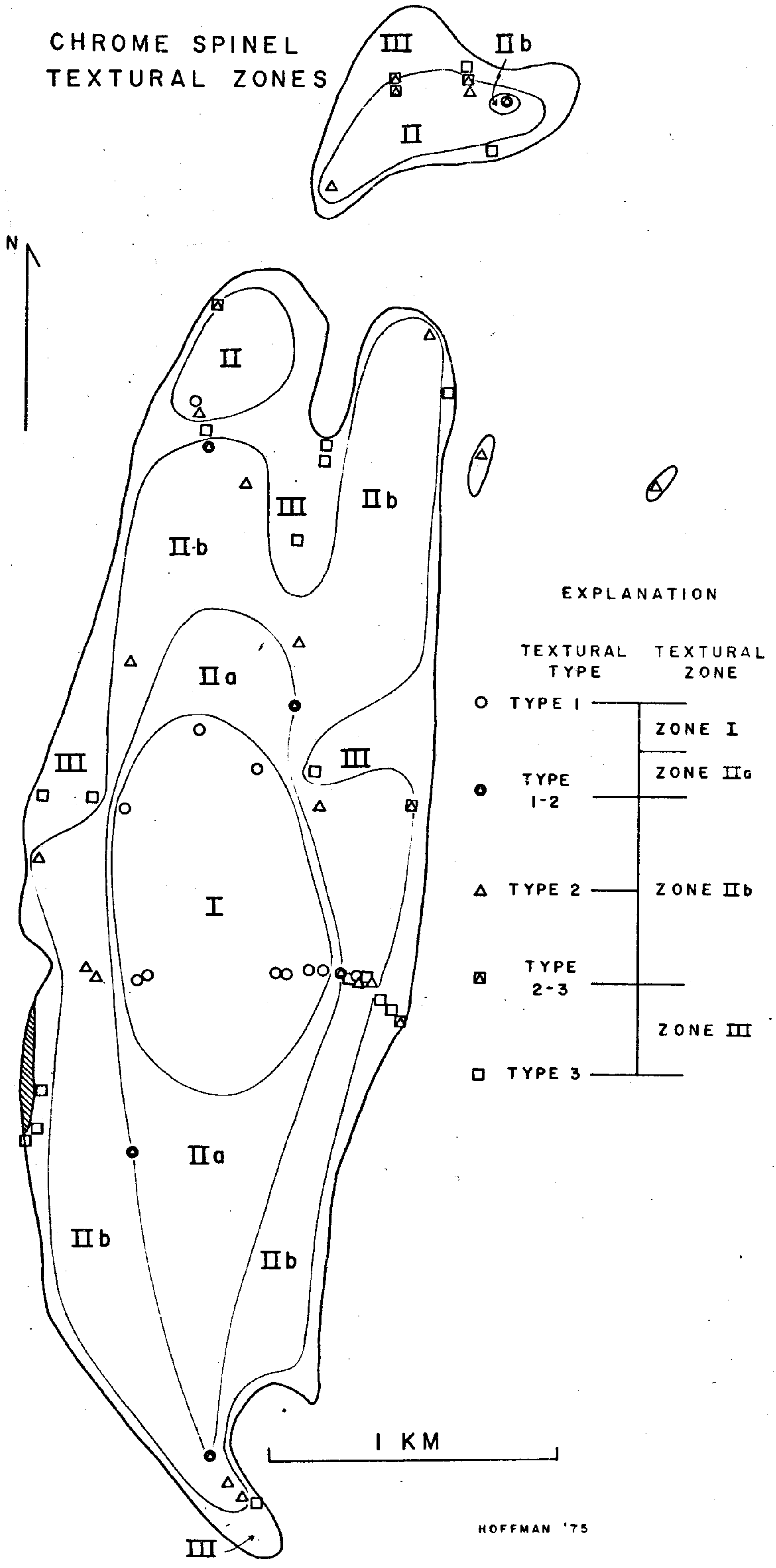
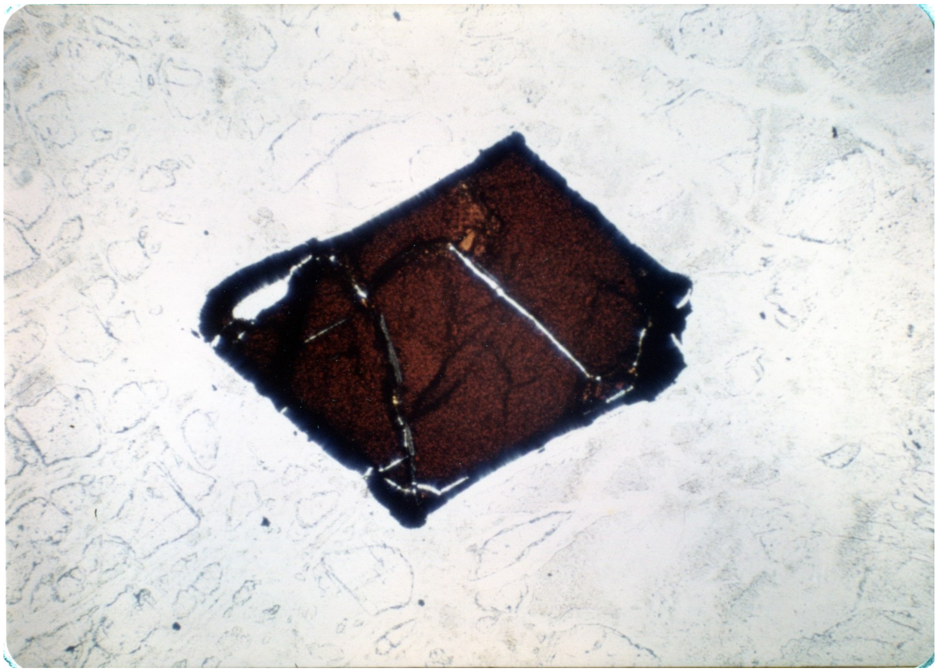

0.6 mm
(A)
0.25 mm
1.75 mm
(B)
0.7 mm
2.0 mm
1.0 mm
(C)

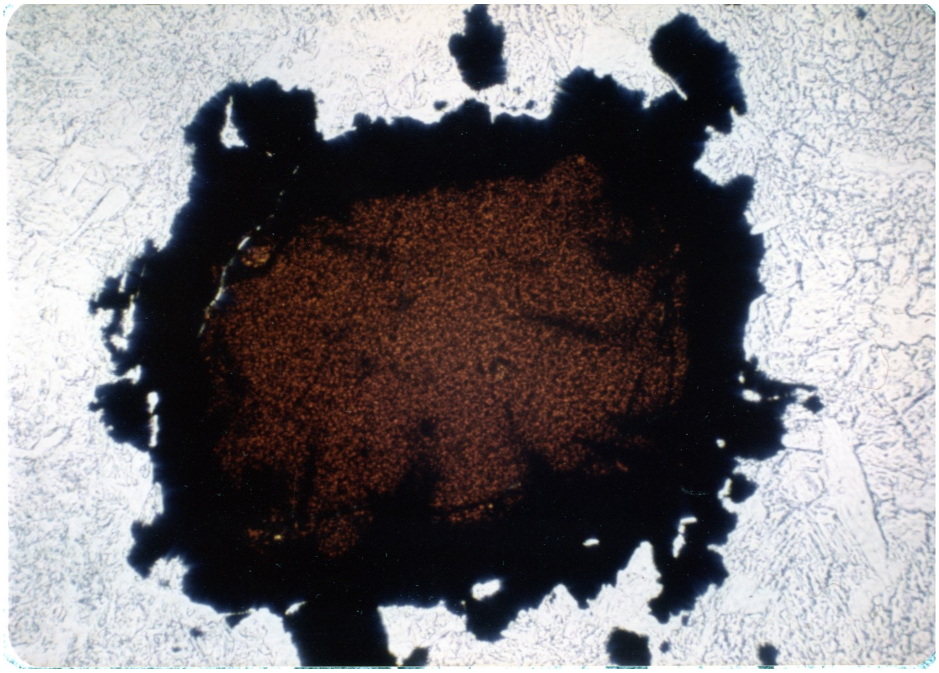
Fig. 23: chrome spinel textural zones. The boundaries between zones are not intended to represent exact limits but rather to indicate the manner in which chrome spinel textures vary with respect to the shape of the bodies.

Note: Zone IIa could be extended further north but the occurrence of the Type 1-2 chrome spinel at that location is unusual (in talc-carbonate rock, see text) and may not be a valid indicator of textural variations.


CHROME SPINEL
TEXTURAL ZONES
N
III
IIb
II
III
IIb
III
II-b
IIa
III
III
I
IIa
IIb
IIb
III
1 KM
EXPLANATION
TEXTURAL TYPE
TEXTURAL ZONE
○ TYPE 1
ZONE I
ZONE IIa
● TYPE 1-2
△ TYPE 2
ZONE IIb
☒ TYPE 2-3
ZONE III
□ TYPE 3
HOFFMAN '75



(A)

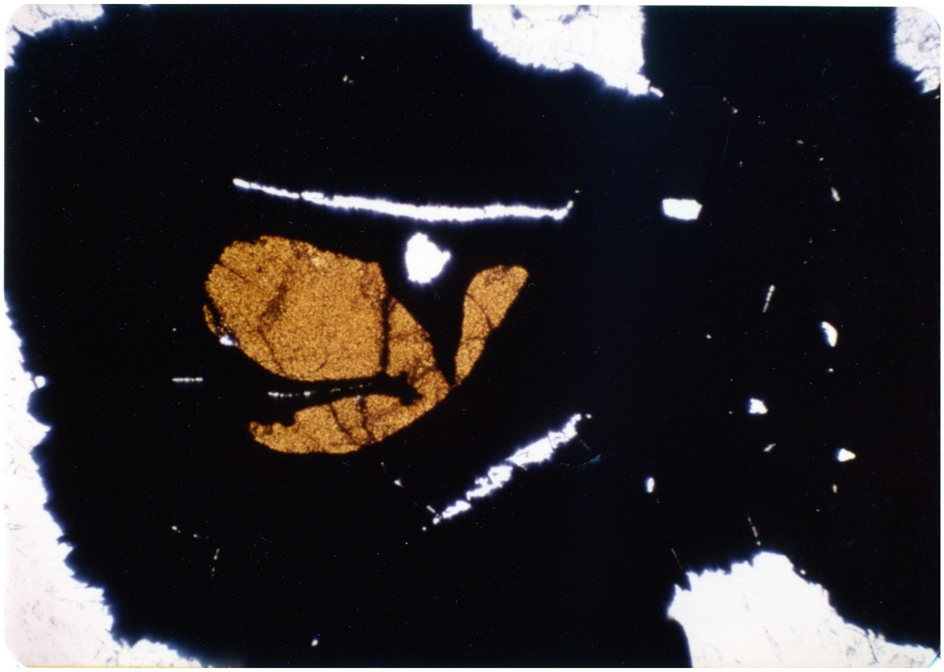


(B)

Fig. 24: textural and color variations of chrome spinels. Length of photographs (A through C) is approximately 1.75mm.

A) Type 1. Photo is overexposed to record nearly opaque core.

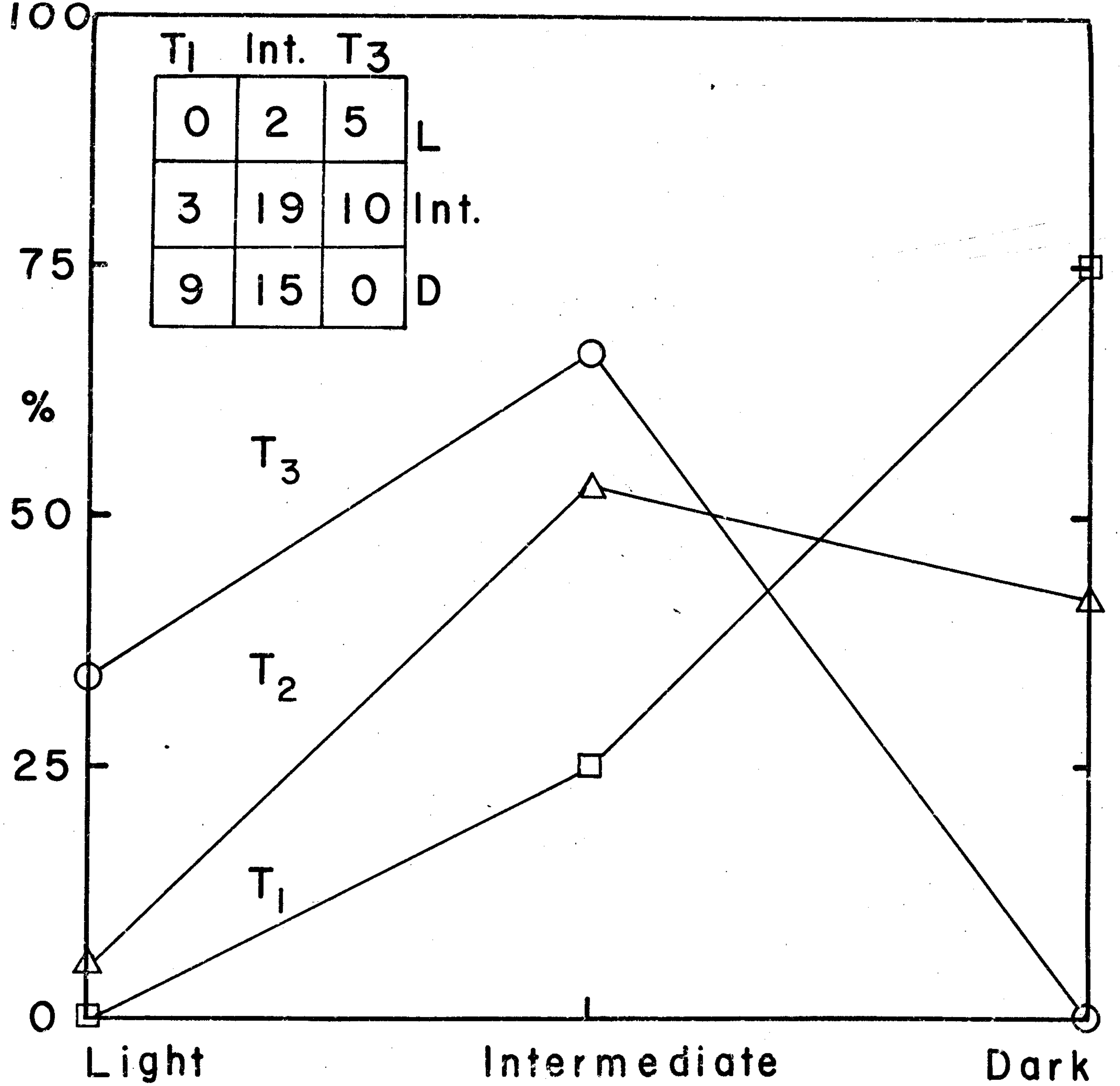
B) Type 2.



(C)

Fig. 24: C) Type 3 chrome spinel.

Fig. 25: percent of chrome spinels which are light, intermediate, and dark in color in each textural type (i.e. about 34% of Type 3 chrome spinels are light colored). Actual numbers of samples of each color are in upper left corner.


T1 Int. T3
0 2 5 L
3 19 10 Int.
9 15 0 D
100
75
%
50
25
0
T3
T2
T1
Light
Intermediate
Dark

Fine-grained chlorite (?) is observed between the core and rim in some Type 1 chrome spinels and as linear segments in Type 3 grains (see fig. 22, a and c). The linear segments in Type 3 are reminiscent of the chlorite observed in Type 1. It is suggested that this chlorite in Type 3 chrome spinel grains might mark the boundary between a magnetite rim overgrowth on an original igneous chrome spinel crystal core. In Type 3 chrome spinels, the opaque mineral (magnetite, ferrichromite ?) between the linear chlorite segments and the relict spinel cores was probably formed during the same reaction that changed the color of the chrome spinel core.

As mentioned previously, there is one occurrence of chrome spinel without a magnetite rim. This chrome spinel is euhedral, dark red-brown, and occurs in talc-carbonate-serpentine rock. Disseminated magnetite occurs as isolated small grains and forms less than 1 percent of the rock. This is a very restricted and unusual occurrence of chrome spinel in these ultramafic rocks, and for this reason, possibly should not be included in the distribution of textural variations of this mineral (fig. 23).

<u>Magnetite</u> - magnetite has three modes of occurrence in the East Dover ultramafic bodies:

1. in thin layers composed of euhedral to compact anhedral magnetite grains;
2. as fine to coarse-grained (<1 mm) disseminated particles, and
3. as rims on chrome spinel cores.

The first type is very rare, being observed in only two thin sections. In these sections the layers of magnetite appear similar to those observed in layered cumulate igneous complexes.

Disseminated magnetite is ubiquitious in these rocks and shows great variations in grain size and shape. There is a remarkable correlation of the modal amount of magnetite (total) with the olivine and chrome spinel textural zones (fig. 26). With respect to olivine zones, the following observations can be made:

1. In Zone 1 magnetite is typically 1% or less.
2. In Zone 2 magnetite is generally between 2-5%.
3. In Zone 3 magnetite is typically between 3-5, but up to 7%.

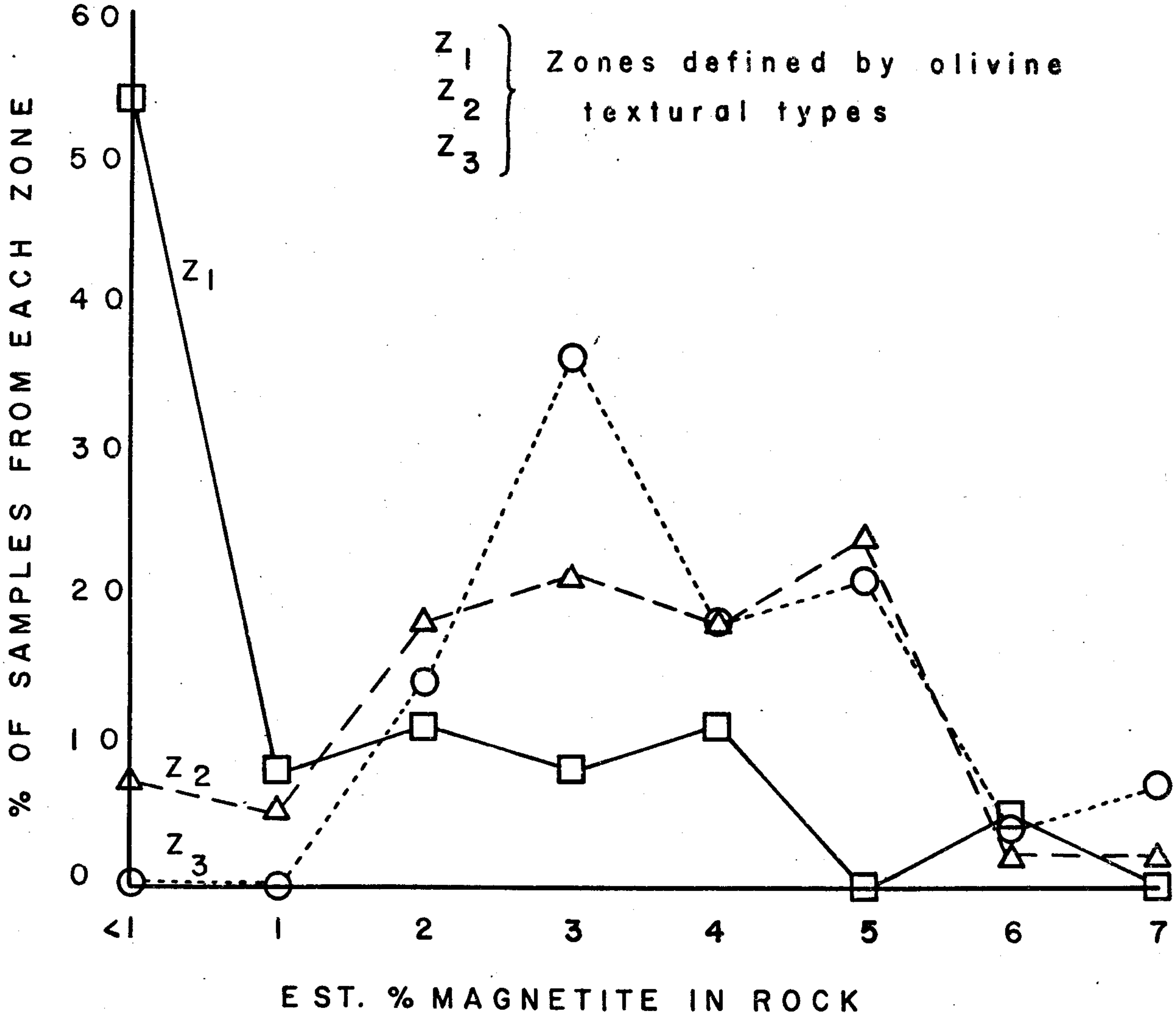
It should be emphasized here that there is no correlation of percent magnetite with present percent of serpentinization, with the possible exception of the immediate contact area.

<u>Discussion of magnetite and chrome spinel textural variations</u> - literature concerned with the alteration of chrome spinel in ultramafic rocks is abundant (den Tex, 1955; Miller, 1953; Lapham, 1964; Beeson and Jackson, 1969; Loney et al., 1971; Fletcher and Carpenter, 1972; Irvine and Findley, 1972; Springer, 1974; Ulmer, 1975). However, as far as the writer is aware, this thesis presents the first documented account of textural variations of chrome spinel which can be directly related to differing intensities of recrystallization of the host rocks.

Loney et al. (1971) attributed differences in texture and composition of chrome spinels to differences in bulk composition of the peridotites. The sequence of subhedral to anhedral grain shapes was interpreted by these authors to be a result of the relative order of crystallization of rock types with slightly different compositions; more euhedral spinels supposedly crystallized earlier than anhedral spinels, relative to the crystallization of silicates (olivine).

Fig. 26: percent of magnetite in each olivine textural zone, i.e. ~36% of the samples from Zone III had ~3% magnetite and ~8% of the samples in Zone I had 3% magnetite. Total percent for each zone = 100.

MAGNETITE CONTENT (modal %) OF SERPENTINIZED ULTRAMAFIC ROCKS



In the present study, the zonal disposition of different chrome spinel textures and the correlation of this arrangement with differences in olivine textures and chemistry leave little doubt as to the cause; the shape of chrome spinel grains and the thickness of the opaque rims reflect differing intensities of recrystallization of the host rocks. This is further emphasized by the color change observed for chrome spinels which is probably the result of a change in chemistry accompanying this recrystallization.

The color and morphology of unaltered chrome spinels from similar Alpine-type peridotites has been described by Irvine and Findley (1970). These authors relate morphology to cell edge dimensions, which are themselves related to composition. What have been interpreted as the least altered chrome spinels in the East Dover bodies correspond to Irvine and Findley's (1970) "opaque to deep-red, Cr-rich, subhedral-euhedral type" with a cell edge dimension of 8.315 Å (approximately). This dimension corresponds to a 100 Cr/(Cr + Al) ratio of about 70.

At East Dover, chlorite is commonly associated with magnetite and chrome spinels. The association of chlorite with the alteration of chrome spinels has been discussed by Beeson and Jackson (1969) and Miller (1957). According to Beeson and Jackson (1969), Al is released by the alteration of chrome spinel and used in the formation of chlorite. The results of the optical study of chlorite associated with chrome spinels of the East Dover rocks also suggested that these chlorites are enriched in Cr and/or Fe^{total} relative to Mg.

Clinopyroxene - 2V and birefringence measurements (fig. 27) indicate that the clinopyroxene locally present in rocks of the ultramafic bodies is nearly pure diopside (Deer, et al., 1972). This diopside is locally abundant (up to 20%) but nowhere can any rocks be called

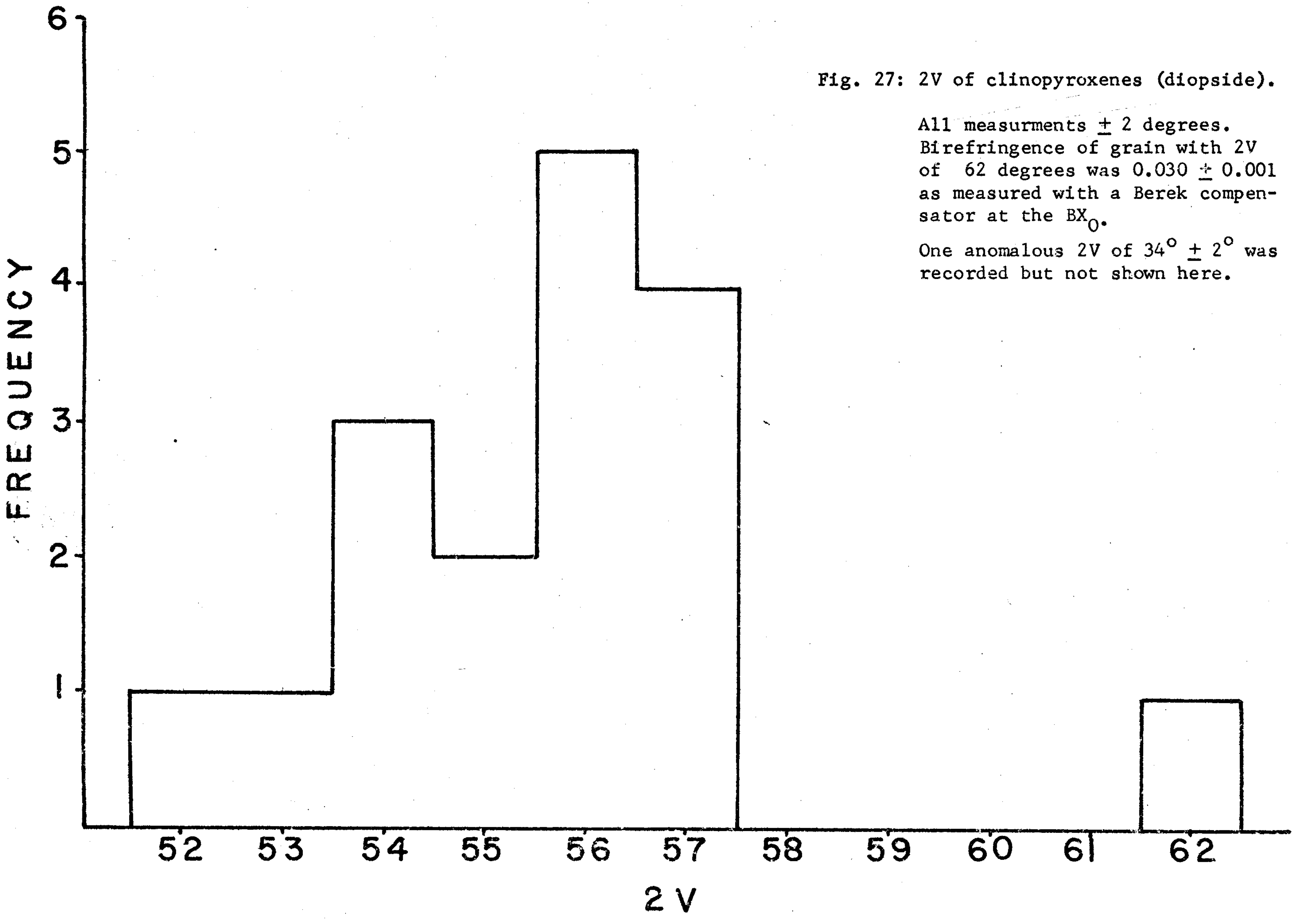


Fig. 27: 2V of clinopyroxenes (diopside).

All measurments ± 2 degrees. Birefringence of grain with 2V of 62 degrees was 0.030 ± 0.001 as measured with a Berek compensator at the BX_O.

One anomalous 2V of 34° ± 2° was recorded but not shown here.

clinopyroxenite. Diopside typically occurs as:

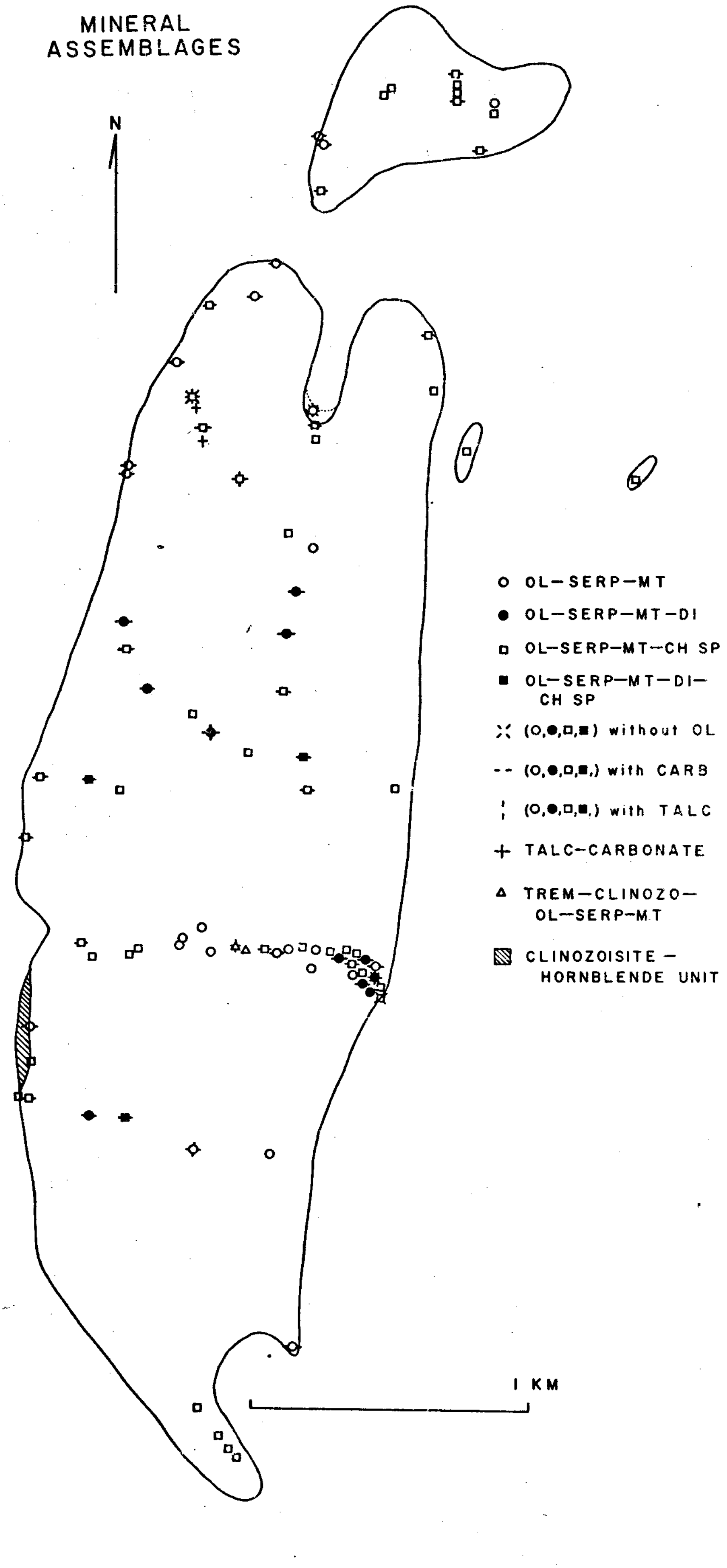
1. isolated large grains (1-2 mm) occasionally euhedral, mostly anhedral;
2. cores to what may be relict grains of another pyroxene or olivine. Cleavage in this diopside is usually at a distinct angle to what is interpreted as relict cleavage in the enclosing grains.

Typical pyroxene cleavage is absent but diallage structure is common. Clinopyroxene coronas on chromite (Loney et al., 1970), similar to olivine coronas, have not been observed, and indeed, chrome spinels are generally absent in diopside bearing rocks. Occasionally, euhedral opaque grains (magnetite after chrome spinel ?) are observed in olivine in diopside bearing rocks in Zone 2.

As mentioned in the structure section, a fine layering, defined by alternating diopside-free and diopside-bearing layers, is developed at a few localities. In two northwest to southeast traverses across the largest ultramafic body, passage from diopside-bearing to diopside-free assemblages was observed a number of times. Not enough data are available now to decide whether this is actually a large-scale layering similar to the small-scale layering visible in thin section.

Too few occurrences of diopside were found to draw any definite conclusions about its geographic distribution, but it is observed that diopside is present around, but not within, the core of the largest ultramafic body, as defined by olivine and chrome spinel textural variations (fig. 28).

Fig. 28: mineral assemblages. These assemblages do not represent stable mineral parageneses or necessarily the actual extent of development of certain minerals (i.e. talc may be developed in more localities than shown).


MINERAL ASSEMBLAGES
N
○ OL—SERP—MT
● OL—SERP—MT—DI
□ OL—SERP—MT—CH SP
■ OL—SERP—MT—DI—CH SP
(○,●,□,■) without OL
-- (○,●,□,■,) with CARB
(○,●,□,■,) with TALC
+ TALC—CARBONATE
△ TREM—CLINOZO—OL—SERP—MT
▨ CLINOZOISITE — HORNBLENDE UNIT
1 KM

The metamorphic assemblage found in diopside bearing rocks--olivine + antigorite + diopside + chlorite + magnetite--is consistent with the observation of upper greenschist (garnet grade) to epidote amphibolite facies mineralogy that is developed in the country rocks (Evans and Trommsdorff, 1974; Trommsdorff and Evans, 1972). (Note: one 2V measurement of a euhedral clinopyroxene grain in one thin section gave a 2V + 34 ± 2°. No explanation of this anomalous measurement is given here, but it is suggested that further study is needed to clarify what may be a significant observation.)

Tremolite - at one locality in the center of the largest ultramafic body, tremolite occurs together with olivine (T_1), serpentine, chlorite, magnetite, and clinozoisite (fig. 28). This tremolite has the following optical properties:

$2V_{(-)}$ 76 ± 3°

extinction angle 18°

colorless

pleochroism absent

fibrous habit with (+) elongation

moderate birefringence

RI low to moderate

Tremolite comprises a maximum 15-25 modal percent of the rock in a limited area less than 20 m in diameter at this locality. The modal amount of this mineral decreases rapidly further from this core area and tremolite is not detected in any other parts of the ultramafic bodies (with the exception of the metasomatic zones).

This tremolite is very fine-grained, uralitic in aspect, and appears to be a replacement of some large pre-existing grains. For example, a euhedral Type 1 olivine and a large clinozoisite grain occur surrounded by uralitic tremolite in one thin section. It is interesting to note that the only tremolite found in these rocks, besides that associated with metasomatic "rinds," is found in the center of what I interpret as the least recrystallized part of the largest ultramafic body. There are at least three explanations for the occurrence of tremolite at this locality:

1. It is a "primary" feature of the ultramafic body, that because of its location was not destroyed by regional metamorphism.

2. It is the product of the same metamorphism that generated Type 2 olivines and diopside.

3. Uralitization of all the "primary" pyroxenes in the body occurred prior to regional metamorphism. By reason of its location, the tremolite in the center of the largest body survived the metamorphic event that generated olivine and diopside (by reason of higher f_{H_2O} ?).

The third possibility is the most attractive for the following reasons:

A. The textural features of uralitic tremolite suggest replacement of some pre-existing mineral.

B. If possibility number 2 is correct and the paragenesis olivine + antigorite + tremolite is of higher metamorphic grade than the paragenesis olivine + antigorite + diopside (Evans and Trommsdorff, 1974), then the zonation represented by a tremolite-bearing core of the largest ultramafic body is opposite to that suggested by the distribution of olivine and chrome spinel textures.

Clinozoisite - only two occurrences of clinozoisite were recognized within the serpentinized dunites:

1. associated with the uralite described above;
2. with calcite in veins originating in the clinozoisite-hornblende unit in contact with the serpentinized dunites. These veins penetrate only a few meters into the dunites.

Carbonate - carbonate (magnesite and locally siderite and calcite) occurs as veins throughout all the ultramafic bodies. Disseminated "patches" of magnesite, not associated with veining, are present in varying amounts, generally increasing toward the margins of the bodies.

Smectite - a very fine-grained, orange to reddish brown alteration product, generally observed after olivine, was tentatively identified as smectite. It is only locally abundant, but some outcrops along the Main Road in East Dover show a striking yellow-orange color which is due to the presence of up to 15 modal percent of this mineral.

Mineralogy of the Clinozoisite-Hornblende Unit:

This unit occurs in contact with the serpentinized dunites on the west side of the largest ultramafic body (fig. 2). The estimated modes of three thin sections from this unit are given in table 2. Both hornblende and clinozoisite occur as coarse subhedral to euhedral grains; their optical properties are reported below:

Hornblende

2V$_{(-)}$35-55
pleochroism:
  Z=blue gray-green
  Y=green brown
  X=yellowish

Clinozoisite

2V$_{(+)}$moderate to large
birefringence 0.031-0.035
colorless with spotty yellow-blue areas
extinction angle 0-40°
pleochroism absent

Sphene is observed as rims on opaque grains (ilmenite ?) and as small inclusions in hornblende. Clinozoisite is also seen included in hornblende.

Table 2

Approximate modes of clinozoisite-hornblende unit rocks

Mineral	Sample 6-11-5	Sample 6-11-6	Sample 6-11-2
Hornblende	30-40%	40-50	35-45
Clinozoisite	35-45	40-50	25-35
Chlorite	5-15	trace(?)	5-10
Sphene	2-4	1	minor
Apatite	1-2	1	1
Biotite			1
Opaques	2-4	1-2	2-4
Quartz	trace		1-3
Unknown			

Two types of chlorite are observed:

1. an alteration product of hornblende occasionally displaying dark brown interference colors;
2. short prismatic crystals with what appear to be polysynthetic twins (like those of plagioclase) and gray-brown interference colors. These chlorite grains define a good foliation.

The minor quartz present in some sections is inferred to be derived from the quartz-hornblende rocks in contact with the unit to the west.

Mineralogical and structural data imply that this unit is completely metamorphic in origin, but additional petrogenesis cannot be inferred from this study.

The Ultramafic "Breccia":

This is observed at one location in Rock River (fig. 29). Small elliptically-shaped pieces of ultramafic rock (centimeter size) in a fine-grained matrix of what appears to be the same material are observed in contact with massive serpentinized ultramafic rock. These elliptical pieces appear to "flow" around the larger massive blocks of serpentinized dunite (fig. 29) and both massive blocks and the "breccia" are cut by the same serpentine veins. The term breccia is used here for lack of a better term.

Discussion and Summary of Petrologic Aspects:

The discussion of the petrology of serpentinized ultramafic rocks at East Dover can be simplified by considering the mineralogy of these rocks to comprise three distinct groups:

1. primary assemblages;
2. metamorphic assemblages;

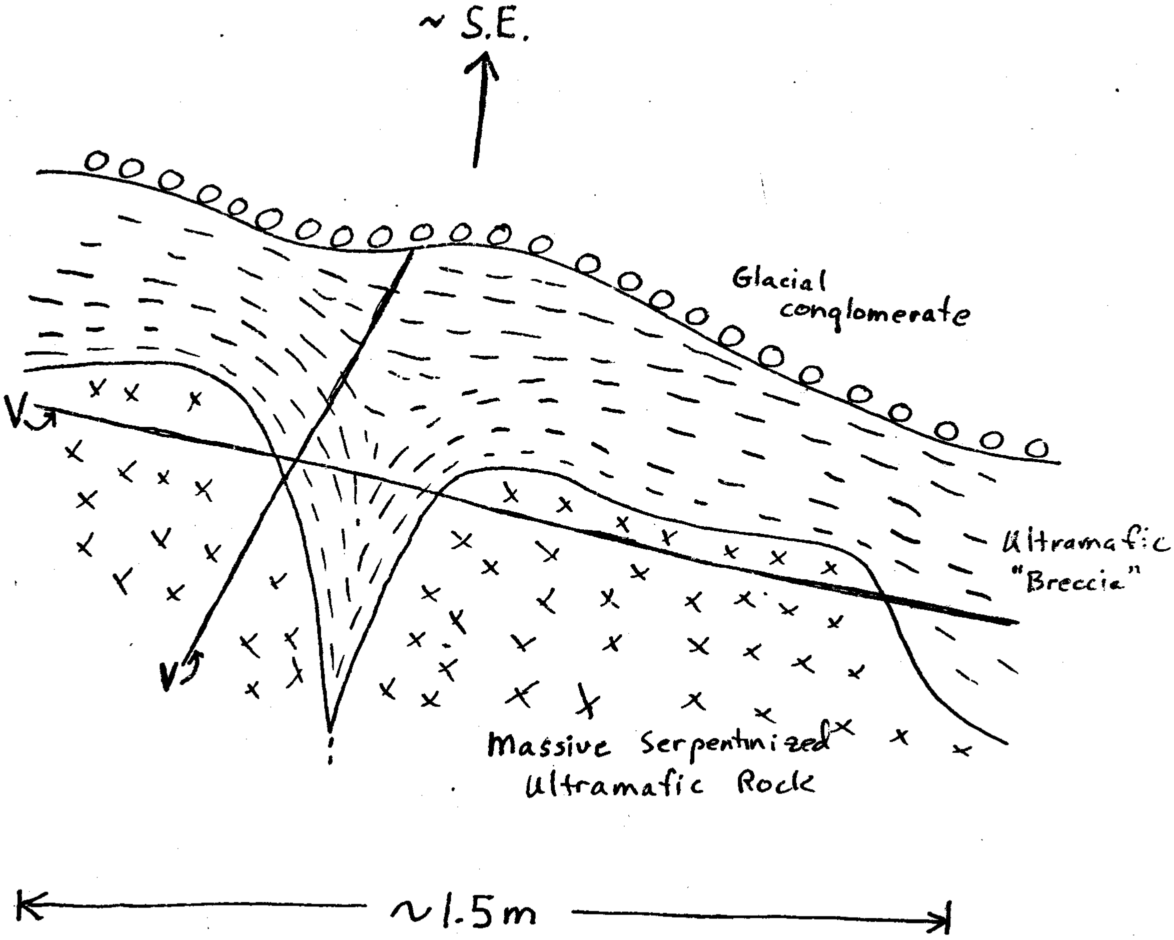


Fig. 29: outcrop of ultramafic "breccia" and glacial conglomerate in Rock River about 250m from the eastern contact with the country rocks.
V- serpentine veins cutting the breccia and the massive ultramafic rock.
Sketch of breccia shows direction of elongation of flattened, elliptical-shaped pieces of ultramafic rock which, together with the matrix material, make up the breccia.

3. secondary alteration products and metasomatic mineralogy (not considered for this thesis).

The map presented in figure 28 represents all assemblages (with the exception of metasomatic zones) and does not imply stable parageneses.

<u>Primary assemblages</u> - it is suggested that the following are "primary" or non-recrystallized minerals:

A. Olivine of Type 1 (Fo_{88}).

B. Chrome spinel of Type 1.

C. Layered (cumulus ?) magnetite.

D. Ghost grains (?).

Type 1 olivines and chrome spinels are found in the core areas of the two largest ultramafic bodies. These core areas are generally 40-60 percent serpentinized, but the magnetite content is rather low for rocks which have suffered such a degree of alteration.

It should be noted that what could be called "ghost" grains are visible in a number of thin sections. These grains have two typical aspects: 1) large (1-2 mm) grains with closely spaced relict cleavage defined by magnetite. The spaces between "cleavage" traces are usually occupied by small recrystallized, randomly oriented olivine grains, while the central cores of a few relict grains are occupied by diopside with its most prominent cleavage at a distinct angle to what is interpreted as relict cleavage in the "ghost" grains; and 2) large (approximately 1 mm) completely serpentinized grains with closely spaced relict cleavage defined by magnetite. These grains are identical to the first type except for the lack of diopside or olivine.

Too few observations of these relict grains were made to make any sense of their geographic distribution, but their association with metamorphic diopside and the implication of former well developed cleavage suggests that they were a pyroxene (orthopyroxene ?).

The description of unaltered chrome spinel grains from Alpine-type peridotites (Irvine and Findley, 1970; Loney et al., 1971) is in good agreement with the description of Type 1 chrome spinels found in Zone 1 of the largest ultramafic bodies.

Metamorphic assemblages - textural and other evidence (see above) suggests that the following minerals are metamorphic in origin:

A. Olivine of Type 2 (Fo_{88}).
B. Chrome spinels of Types 2 and 3.
C. Diopside.
D. Serpentine.
E. Tremolite (uralite).
F. Clinozoisite.
G. Magnetite (not layered).

The following sequence could explain many of the observed mineralogical and textural relationships:

Stage 1 - low temperature alteration and deformation of the original peridotite: uralitization of pyroxenes; serpentinization, formation of metasomatic zones. Simplified expressions for this stage may be represented by the following reactions:

1a. olivine (T_1) + H_2O + SiO_2 = serpentine + magnetite

1b. pyroxene + H_2O = tremolite + SiO_2

Stage 2 - regional metamorphism/deformation: removal of metasomatic zones through "rotation" of the bodies; generation of olivine, diopside, clinozoisite; alteration of chrome spinels.

2a. serpentine = olivine (T_2) + H_2O + SiO_2

2b. tremolite + calcite + quartz = diopside + CO_2 + H_2O

Stage 3 - limited serpentinization and deformation.

3a. olivine (T_2) + H_2O = serpentine ($\pm$ magnetite)

Petrographic observation has revealed no pyroxene in the East Dover rocks which could be called "original." Jahns (1967) reports finding no evidence of original pyroxene from ultramafic rocks further north in Vermont. There is also no petrographic evidence for reactions 2a or 2b.

The observation of the same degree of serpentinization in parts of both Zone 1 and Zone 3, contrasted with the observed differences in magnetite content for these two zones (fig. 26) creates some confusion. If two initially similar areas underwent an equal amount of serpentinization under similar circumstances, then they should have the same magnetite content. Clearly, serpentinization alone could not account for the observed magnetite distribution.

If, on the other hand, recrystallization of olivine proceeded without the intermediate formation of serpentine, an essentially solid-state reaction such as:

4. olivine (Fo_{88}) + O_2 = olivine (Fo_{88}) + magnetite could explain all the observed mineralogical features, including: 1) the distribution of magnetite; and 2) the increase in the thickness of magnetite rims on spinels as the margins of the bodies are approached.

There is some evidence for reaction number 4 in the "exsolved" aspect of some magnetite associated with large T_2 olivine grains. The increase in intensity of recrystallization of the ultramafic bodies as the margins are approached could be represented by equation number 4 proceeding to a greater extent near the margins, and a much lesser extent in the core areas.

It is interesting to speculate that differing partial pressures of oxygen may have played a role in the observed magnetite distribution. A lower relative P_{O_2} for the core areas would result in less magnetite forming in the core with respect to the margins, even though both areas suffered the same amount of serpentinization. In units with the dimensions of the largest ultramafic bodies at East Dover, it is not unreasonable to expect some differences in P_{O_2}, perhaps induced by hydrogen loss during metamorphism or alteration.

The location of tremolite-bearing assemblages (non-metasomatic) presents another problem (fig. 28). Evans and Trommsdorff (1970, 1974) have shown that the assemblage, olivine + tremolite + antigorite represents a higher metamorphic grade than the assemblage, olivine + diopside + antigorite. Clearly the location of tremolite-bearing assemblages and the evidence provided by olivine and chrome spinel textural variations suggest that this tremolite cannot represent a higher metamorphic grade than the surrounding diopside-bearing rocks. Indeed, this tremolite is decidedly uralitic in aspect, implying low temperature alteration of some pre-existing pyroxene. It is suggested here that the formation of tremolite (uralite) was not contemporaneous with the regeneration of olivine or the formation of diopside. The occurrence of clinozoisite in the tremolite-bearing rocks is not well understood.

Concluding Remarks:

In summary, the following can be said about the petrology of the East Dover ultramafic rocks:

1. The distribution of olivine textural and chemical variations, and chrome spinel textural variations can be attributed to differing intensities of recrystallization.

2. Serpentinization is uniform over large areas of the ultramafic bodies but must be described as randomly developed with respect to the margins.

3. The only pyroxene now observed is metamorphic in origin (but may be pseudomorphic).

4. The distribution of magnetite is not simply related to the development of serpentine, as a simple serpentinization process would imply. It may, rather, be a function of removal of the iron component from olivine during recrystallization, or differing partial pressures of oxygen during serpentinization.

5. A stage of tremolite development (uralitization) occurred at a different time than the development of T_2 olivine and diopside.

RELATIONSHIP OF MAGNETIC ANOMALIES TO PETROLOGY

It has been suggested that the high positive magnetic anomalies observed over some parts of the serpentinized ultramafic rocks at East Dover (Murphy, 1964) correlate with relatively "unaltered" areas (Stuckless, 1972; DeFilippo, written communication, 1974).

Using the available magnetic data (Murphy, 1964) and the information available in this thesis, it can be seen that high positive magnetic anomalies correlate with:

1. olivine and chrome spinel textural zones III (the margins of the bodies, fig. 30);
2. relatively high modal magnetite content (fig. 26).

These correlations are easy to understand if we accept that Zone III in both the olivine and chrome spinel distributions reflects a high degree of recrystallization of the host rocks. Contrary to previous ideas, then, high positive magnetic anomalies are shown to be present over the most altered areas.

Local variations in the magnitude of anomalies reflect local differences in magnetite content due to variations in the degree of recrystallization of the ultramafic rocks.

Fig. 30A: magnetometer traverses after Murphy (1966) with the interpretation of the shape of the bodies as presented in this thesis. Roads are also sketched.

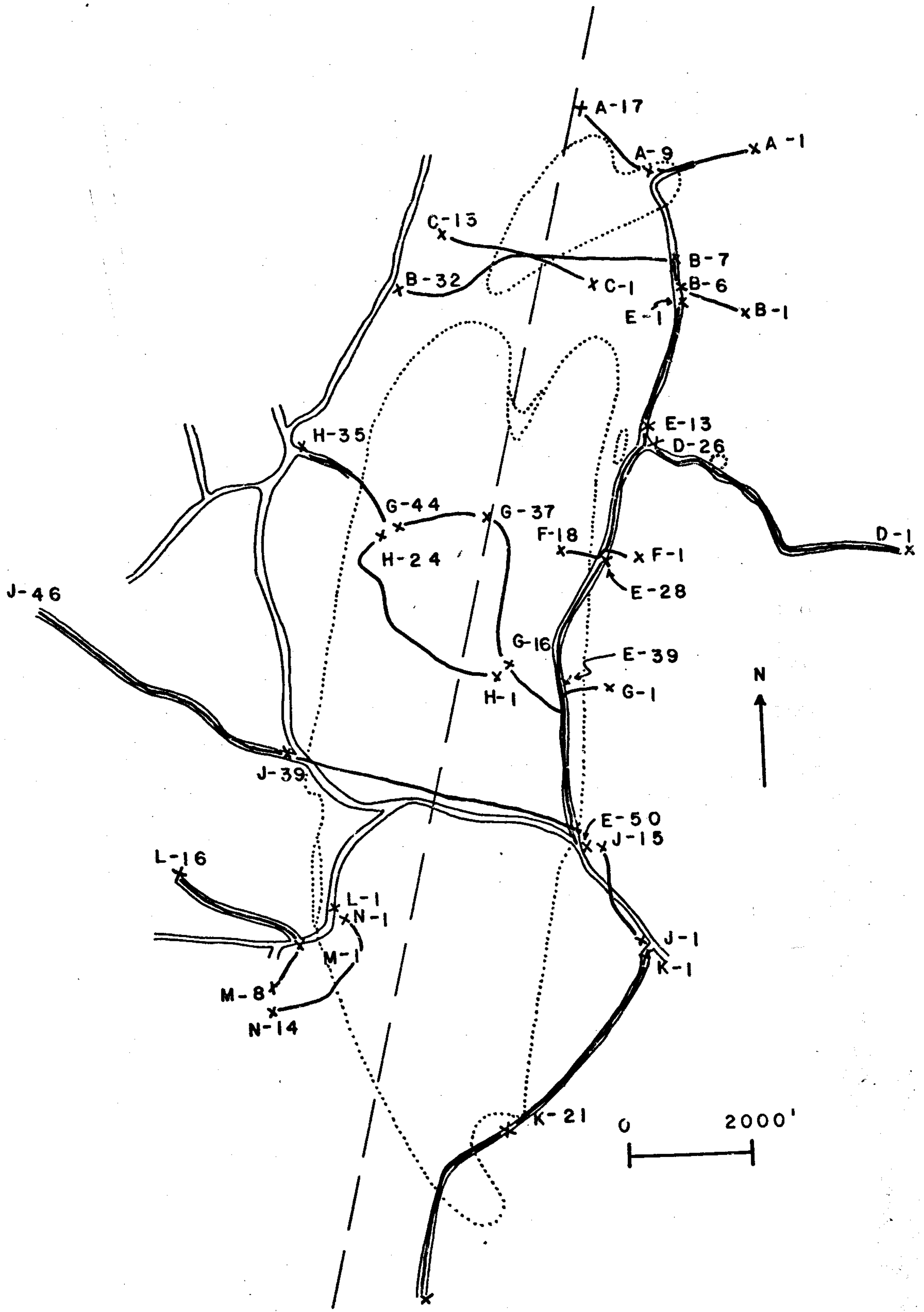
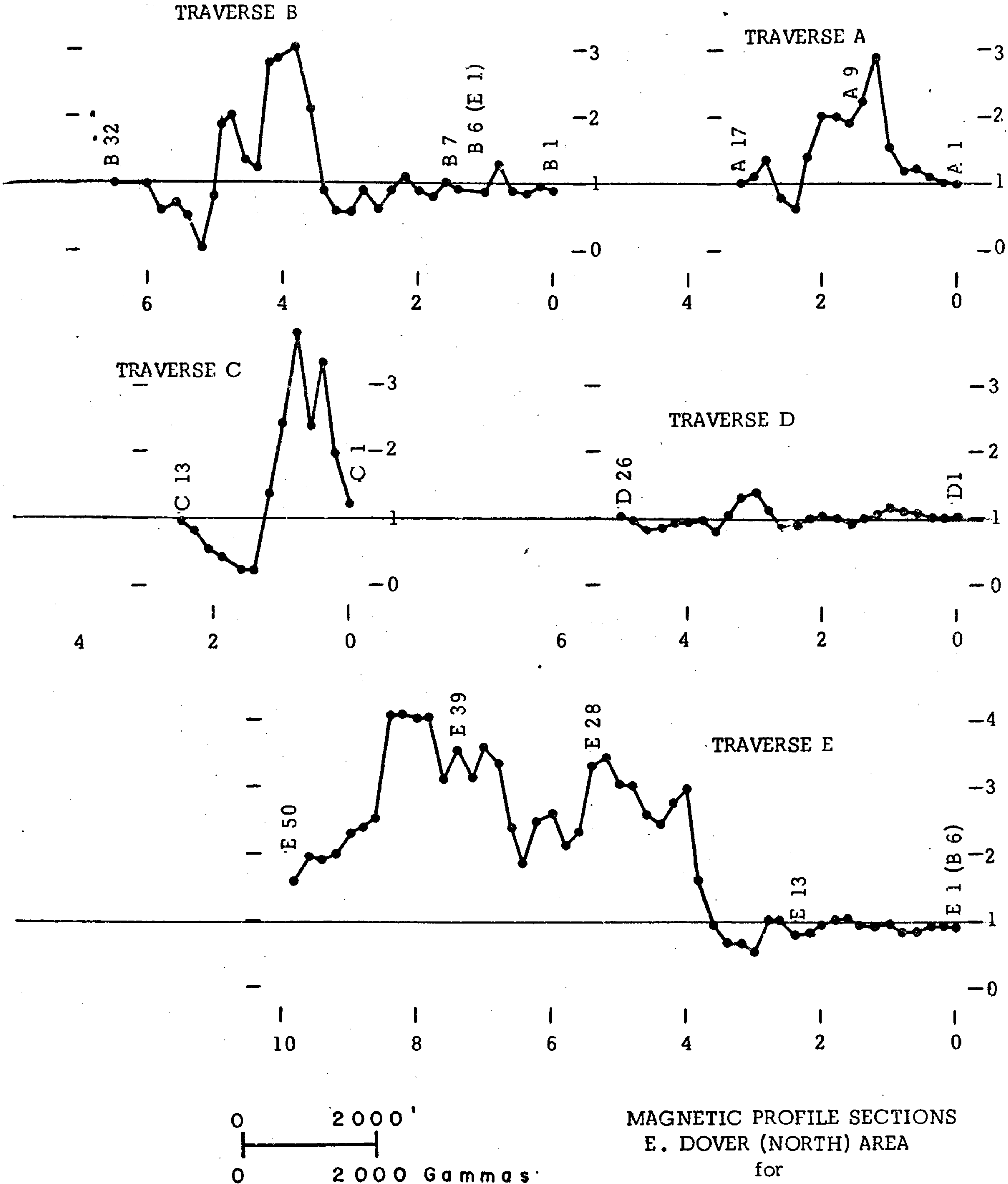
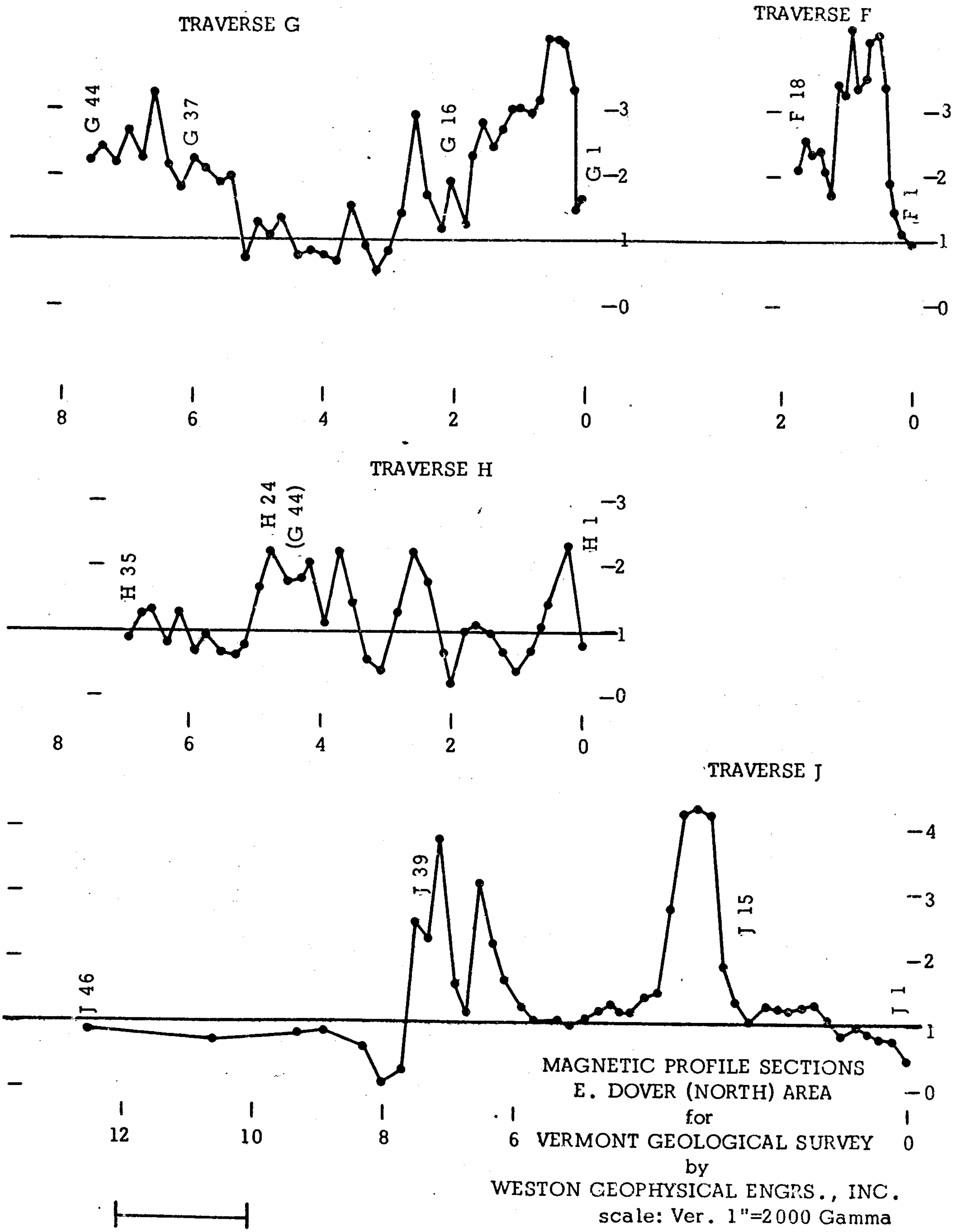

A-17
A-9
A-1
C-13
B-7
B-32
C-1
B-6
E-1
B-1
E-13
D-26
H-35
G-44
G-37
F-18
F-1
D-1
H-24
E-28
J-46
G-16
E-39
N
H-1
G-1
J-39
E-50
J-15
L-16
L-1
N-1
J-1
M-1
K-1
M-8
N-14
K-21
0
2000'

Fig. 30B: actual magnetic profiles from Murphy (1966). Horizontal lines through each profile represent the magnetic signature (background level) of enclosing Moretown Formation (~1000 gammas).



MAGNETIC PROFILE SECTIONS
E. DOVER (NORTH) AREA
for
VERMONT GEOLOGICAL SURVEY
by
WESTON GEOPHYSICAL ENGRS., INC.
scale: Ver. 1"=2000 Gamma
Hor. 1"=2000 Feet



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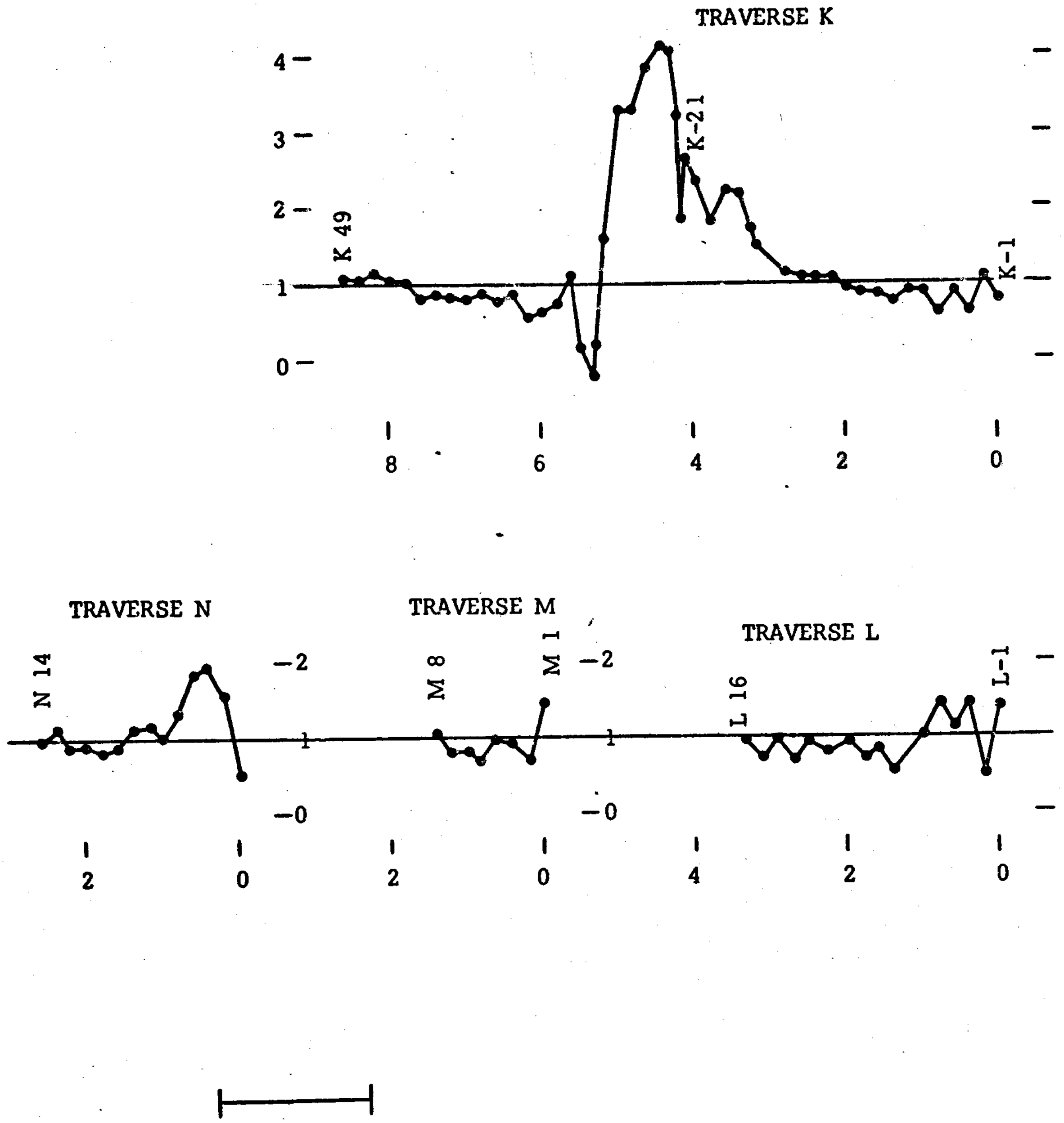

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Hor. 1"=2000 Feet

APPENDIX I

X-ray Diffraction Methods Used To Determine Fo Content of Olivines

Hotz and Jackson (1963) presented an X-ray determinative curve for determining the Fo content of olivines in the range Fo_{80}-Fo_{95} (± ½ %). The method is based on measuring the 20 differences in position of the (062) peak of olivine and the (220) peak of LiF (an added internal standard). This difference is linearly related to the Fo content of high Mg olivine with an error of about ± ½ Fo unit.

Analyses in this study attempted to duplicate the methods of preparation of samples and the operating conditions of the above authors as closely as possible (Jackson, 1960). Multiple scans were made on all samples and the average value of the 20 differences determined. It was found necessary to extrapolate the curve of Hotz and Jackson (1963) to approximately $Fo_{98}/20_{(062)}$ olivine - $20_{(220)}$ LiF = 2.71° (fig. A-I-1). The linearity of Hotz and Jackson's (1963) curve suggests that this extrapolation is valid. However, the error limits near Fo_{98} may be no better than ± 1 mole percent Fo.

The conclusion that some samples contained olivine of two distinct compositions was arrived at by the observation of "split" peaks for (062) olivine (fig. A-I-2). Where this split peak was observed the (130) peak of olivine (also a sensitive indicator of composition; see Yoder and Sahama (1957)) was also scanned. Where this peak was also seen to be "split" (fig. A-I-2), the bimodal distribution of olivine compositions was considered valid.

The results of all scans are presented in table A-1.

Table A-1
Results of X-ray diffraction analyses of olivines

Semple	Approx. olivine mode	Olivine textural zone	No. scans	2θ LiF$_{(130)}$ - 2θ Olivine$_{(062)}$	%Fo	Comments
6-14-6	50-60	I	2 (A) (B)	(A) 2.76 and 2.890 (B) 2.74 and 2.885	95.2, 87.9 96.3, 88.1	Split peaks. Olivine$_{(130)}$ also split with comp. difference of 10 mole% implied by diff. in 2θ$_{(130)}$
7-7-14(Y_1)	50-60	I	2 (A) (B)	(A) 2.795 (B) 2.845	93.2 90.3	Average comp. 91.8
6-19-14	60-70	II	2 (A) (B)	(A) 2.775 (B) 2.81	94.2 92.2	Average comp. 93.2
8-23-2	65-75	II	2 (A) (B)	(A) 2.795 (B) 2.83	93.2 91.2	Average comp. 92.2
7-7-5	70-80	II	1	2.775	94.2	
6-7-8	75-85	II	2 (A) (B)	(A) 2.71 and 2.81 (B) 2.74 and 2.79	97.9, 92.2 96.2, 93.5	Split peaks. Olivine$_{(130)}$ also split with comp. difference of 5-6 mole % implied by diff. in 2θ$_{(130)}$
6-5-5	85-95	II	2 (A) (B)	(A) 2.760 (B) 2.795	95.2 93.2	Average comp. 94.2
7-7-7	40-50	III	2 (A) (B)	(A) 2.76 (B) 2.71	95.2 97.9	Average comp. 96.6
9-13-3	40-50	III	4 (A) (B) (C) (D)	(A) 2.70 (B) 2.745 (C) 2.78 (D) 2.765	98.5 96.0 94.0 94.75	$d_{\text{Olivine (130)}}$ measured to be 2.7673Å. Average comp. 95.81

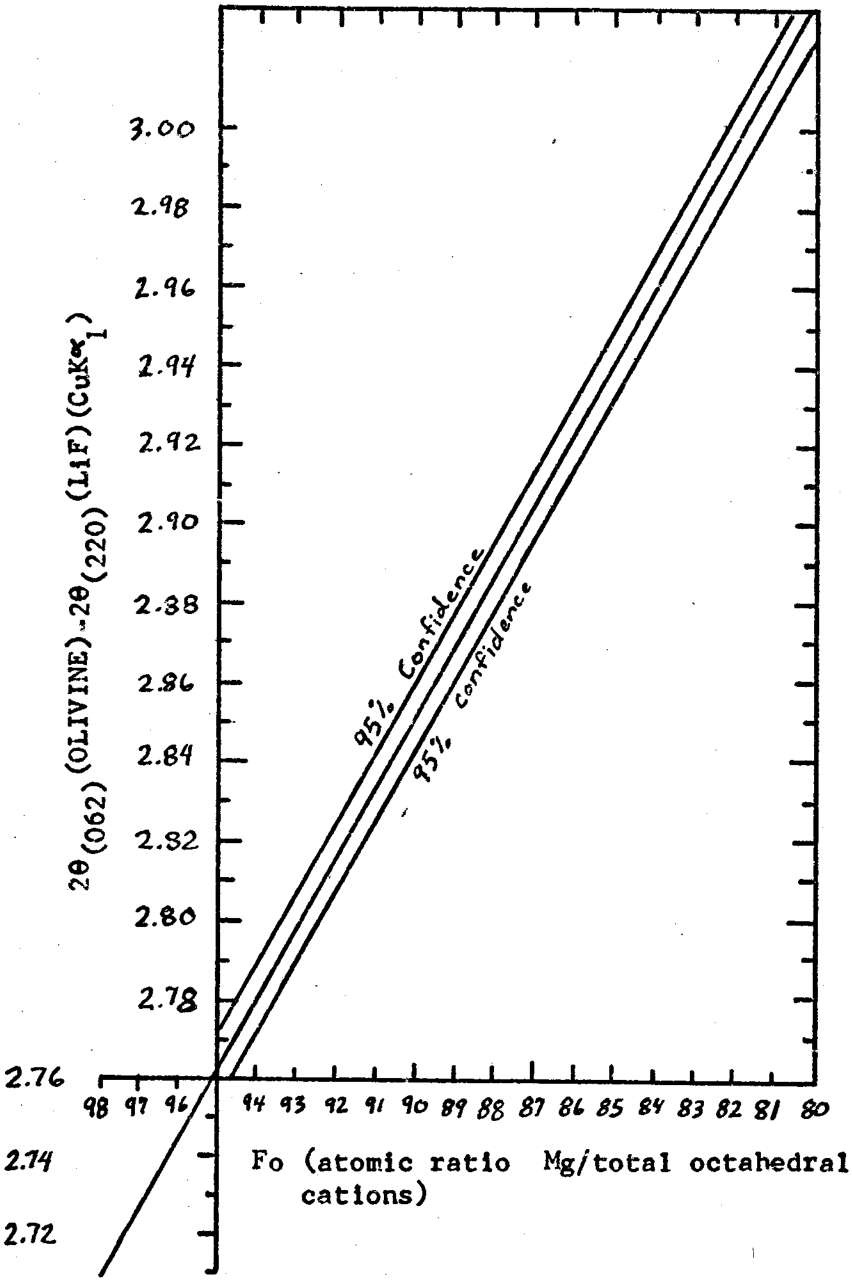
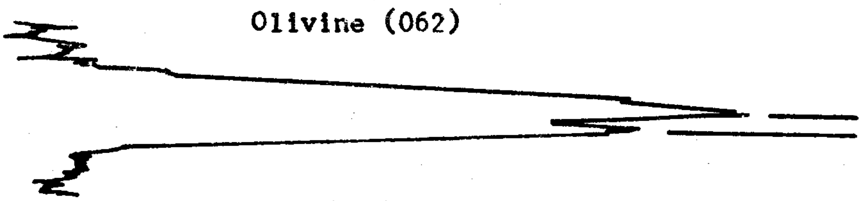
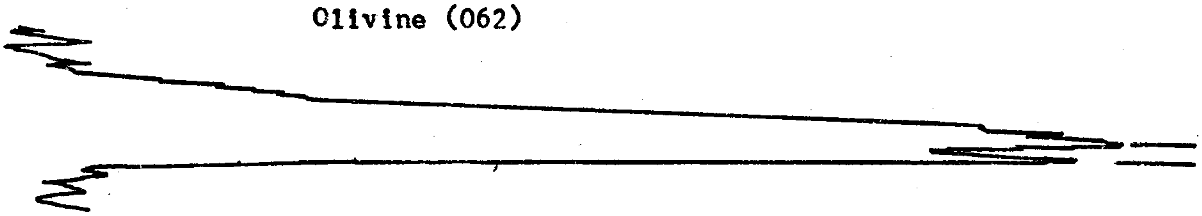


Fig. A-I-1 : Extrapolation of X-Ray curve (after Hotz and Jackson, 1963) used to determine Fo content of olivines.





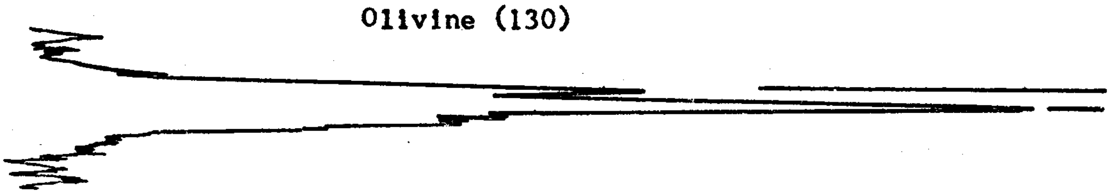


Fig. A-I-2: "Split" peaks for olivine. All examples are from sample 6-14-6. Split nature of peaks shown by parallel lines to the right of each peak.

APPENDIX II

A Note On The Optical Determination Of 2V In High Mg Olivines (Fosterites)

The relationship of 2V and % Fo in olivines is a straight line with a small negative slope (Deer, et al., 1972). Accurate measurement of 2V should allow an accurate determination of % Fo.

Method: General Universal Stage Method

All 2V measurements were made on a 4-axis universal stage with polychromatic light. The 4-axis stage requires that 2V be determined (for minerals with large 2V) on a stereographic (Wulff) net. R.I. estimates for each mineral were used to apply the corrections for differences in R.I. between the hemispheres and minerals (Emmons, 1943).

Olivine Determinations:

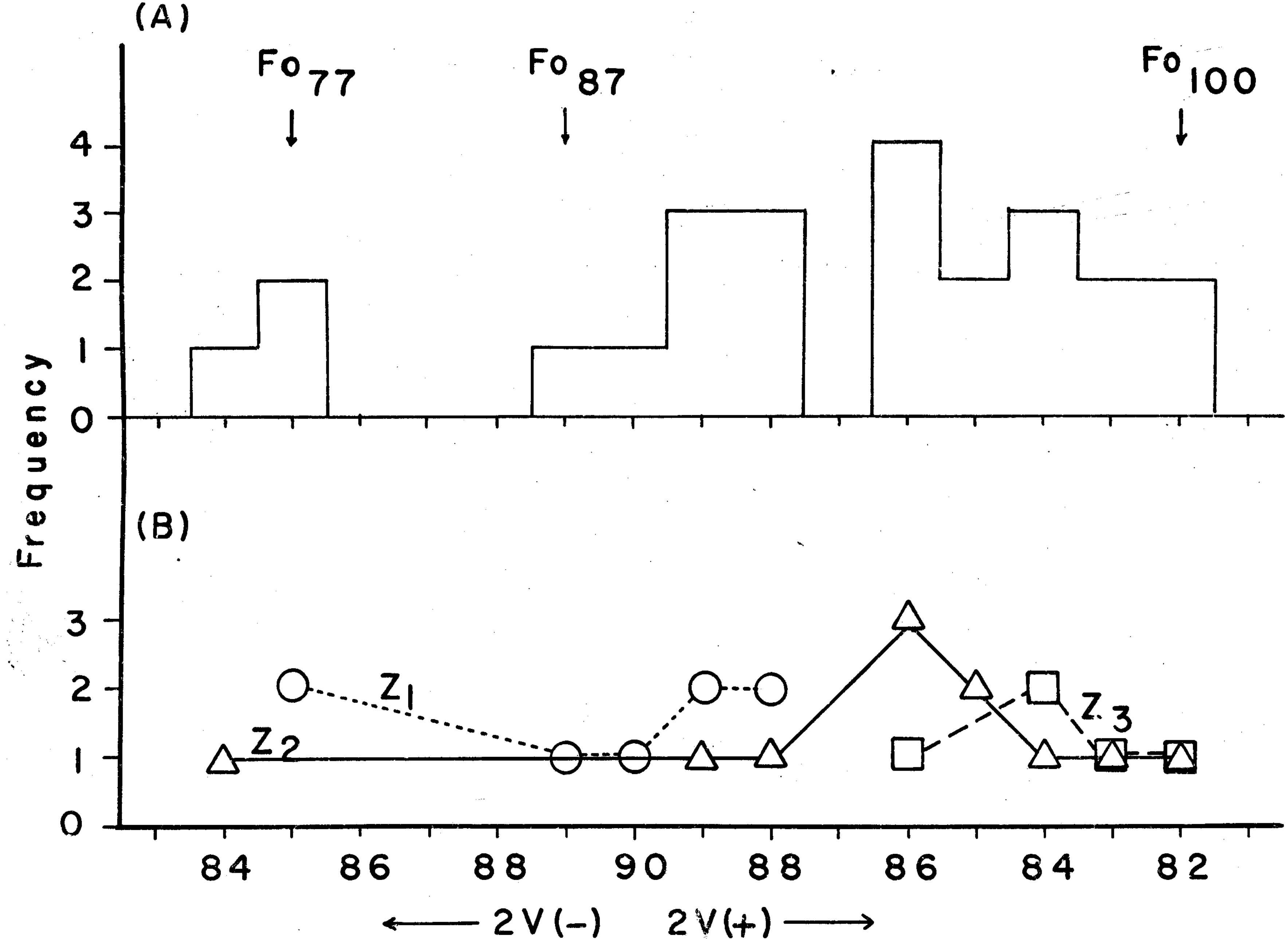
Figure A-II-1 presents the results of 2V measurements for olivine grains. As can be observed both 2V(+) and 2V(-) values were recorded: the positive values evenly distribute about a 2V(+) = 86° maximum, while the negative values are 2V(=) = 84-85°, and 88-89°. This implies olivine compositions of Fo_{100-87} and Fo_{77} (fig. A-II-1).

Looking at the distribution of 2V values for each olivine zone (fig. A-II-1b) it is apparent that 2V values for Zone 1 indicate lower Fo contents than 2V values for Zone 3. Also, 2V values for Zone 2 cover the entire range of values in both Zone 1 and Zone 3. This information is consistent with the data from the X-ray diffraction study of olivines.

Discussion:

Duplicate measurements showed that the precision of V measurements on olivine (generally only V for large 2V minerals can be determined with a 4-axis U-stage) was no better than ± 2 degrees. Applying all

Fig. A-II-1: A) frequency vs. 2V for all olivines measured. B) frequency vs. 2V for olivines from each olivine textural zone (labeled Z_1, Z_2, Z_3).


(A)
Fo77
Fo87
Fo100
Frequency
4
3
2
1
0
(B)
3
2
1
0
Z1
Z2
Z3
84
86
88
90
88
86
84
82
← 2V(−)
2V(+) →

the corrections as per Emmons (1943), accuracy is probably not better than ± 1 degree for V. The total error then is given by:

$$E = \sqrt{(1)^2 + (2)^2} = \sqrt{5} \quad \pm 2.24^{\circ}$$

Error in 2V is therefore ± 4.5°, this corresponding to a potential error of ± 8 mole percent Fo (equivalent to the entire range of Fo values determined by X-ray!).

This being the situation, sign determination for $2V_{(+ \text{ or } -)}$ close to 90° must be suspect

Does figure A-II-1, then, have any significance? Taken in conjunction with the X-ray data, figure A-II-1b presents an attractive argument for 2V detection of a bimodal distribution of olivine composition, however, absolute values of both olivine composition ranges and specific compositions determined by 2V measurements probably have no significance here other than to indicate very high Fo contents.

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