

PYROXENE GEOTHERMOMETRY OF THE ADIRONDACK LOWLANDS

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A thesis submitted to
The Graduate School
of
Rutgers, The State University of New Jersey
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
Graduate Program in Geology

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New Brunswick, New Jersey

October, 1981

ABSTRACT OF THE THESIS

Pyroxene Geothermometry of the Adirondack Lowlands

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Amphibolites within the major paragneiss of the Adirondack Lowlands, at granulite facies grade, were densely sampled in this study. Electron microprobe analyses, applied to several pyroxene geothermometers, indicate coexisting orthopyroxene-augite formed at 595°C-710°C (Ross and Huebner geothermometer), 713°C-832°C (Wood and Banno geothermometer), or 719°C-868°C (Wells geothermometer). Ross and Huebner temperatures determined here agree with oxide and feldspar studies carried out by Bohlen and others who also found no systematic pyroxene temperature variations within the Adirondack terrane.

In the present study it has been determined that K_D and pyroxene temperatures for the three geothermometers decrease in a statistically significant manner toward the massif (Colton-Parishville) (away from the orthopyroxene isograd of DeWaard) and that aluminum, Al^{VI} , titanium and sodium in augite, and aluminum in orthopyroxene increase. Also, the ratio of titanium to aluminum (atoms per formula unit) is greater than that reported elsewhere for coexisting igneous pyroxenes. These trends suggest more complete reequilibration, possibly due to deeper, more prolonged burial at higher pressure, as the massif is approached. This is evidenced by attainment of textural and chemical equilibrium toward the massif. Also, a proposed model describes the Lowlands as the upper limb of a nappe hinged at Colton-Parishville with the lower limb tightly oppressed against the Highlands.

The lowering of pyroxene temperatures may only be apparent and may be accounted for by increased amounts of Al_2O_3 in solid solution with CaSiO_3 - MgSiO_3 and an increase in pressure below 900°C stabilizing a wider enstatite-diopside solvus. Chemical trends similar to those noted here in which aluminum in pyroxenes and sodium in augite increase with pressure, with no significant temperature difference between localities, have also been observed elsewhere.

High density sampling and consideration of the orthopyroxene isograd as a base line against which distance, pyroxene temperature, pressure effects and composition might be correlated may be useful in other geologically similar areas. Close agreement of Ross and Huebner temperatures with peak Adirondack oxide and feldspar temperatures suggests that even with reequilibration and pressure-composition effects, that geothermometer has proven most effective.

ACKNOWLEDGEMENTS

A number of people were of great assistance in the development and completion of this dissertation. Drs. Michael J. Carr, Randall D. Forsythe and Roger H. Hewins of the Department of Geological Sciences, Rutgers University, and Dr. C. E. Nehru of the Department of Geology, Brooklyn College of the City University of New York served on my doctoral committee. Roger Hewins, my thesis advisor, deserves special thanks for having introduced me to the field problem and pertinent literature. He guided me through several grant proposals, generously supplied me with a suite of rock samples taken from the field area during a reconnaissance survey during the summer of 1977 and also made available a number of polished sections from that suite. In addition, he negotiated for my use of the electron microprobe at the American Museum of Natural History in New York City and funded a portion of probe time.

I am grateful to Dr. Martin Prinz, chairman of the Department of Mineral Sciences at the museum, for use of the microprobe and ancillary facilities. Also, Mr. Robert Klimentides of that department was of great practical assistance in instructing me in the use of the microprobe and in carbon-coating all specimens.

Field work, probe specimens and probe time were, in part, funded by a Grant-in-Aid of Research from Sigma Xi, The Scientific Research Society of North America; Penrose Research Grant 2333-78 from The Geological Society of America; National Science Foundation grant EAR-7824732, Dr. Roger H. Hewins, Principal Investigator, Department of Geological Sciences, Rutgers University.

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INTRODUCTION

The amphibolite-granulite transition zone of the Adirondack Lowlands (St. Lawrence County, New York) has become one of the classic field areas in metamorphic petrology due, in large part, to the unusually detailed petrologic and petrographic investigations of Engel and Engel (1958, 1960, 1962a), Buddington (1963) and DeWaard (1969a). Their isograd maps show a progression of mineral assemblages in amphibolite and pelitic gneisses indicating a change from middle amphibolite to hornblende granulite subfacies conditions. Several alternative explanations which may be offered for this transition are; (1) an increase in temperature toward the massif as the rocks were reconstituted, possibly either when the earth's geotherm was steeper, or, as a local, prolonged heating event at temperatures above the normal geotherm, (2) falling water pressure and consequent dehydration reactions during progressive metamorphism of rocks in a high-temperature amphibolite facies terrane, (3) lower crustal rocks of pyroxene granulite grade which have been uplifted and progressively hydrated to form hornblende granulites transitional to middle amphibolites in a direction away from the massif, (4) uplift of more slowly cooled, more reequilibrated rocks subjected to lower water pressure as the massif is approached.

There have been detailed studies of a similar transition in the Broken Hill district of New South Wales (Binns, 1962, 1964, 1965) and more recent examination of the Adirondack Highlands (Bohlen and Essene, 1977a, 1977b, 1978, 1979a, 1979b, 1980) and areas close to, or within, the Lowlands (Nielsen, 1971; Stoddard, 1976a, 1980; Hoffman

and Essene, 1978; Hoffman, 1979; Bohlen et al., 1980). These, coupled with recent advances in geothermometry (Wood and Banno, 1977; Fleet, 1974; Ross and Huebner, 1975; Bohlen and Essene, 1977a; Wells, 1977) and recent interest in the Precambrian geology of the Adirondacks (Romey, 1980), suggest it would be of great interest to quantitatively define the metamorphic conditions in the Adirondack Lowlands and to attempt to decipher the thermal history of the region. It would also be appropriate to reevaluate some previously reported metamorphic temperatures for the area (Engel and Engel, 1958, 1960, 1962a; Engel et al., 1964; Buddington and Leonard, 1962; Buddington and Lindsley, 1964; DeWaard, 1969a, 1969b; Nielsen, 1971; Bohlen and Essene, 1977a; Bohlen et al., 1980). These temperatures, which will be discussed below, are based on a variety of geothermometers such as magnesite-dolomite, FeS-sphalerite, Na in muscovite, alkali feldspar, Fe-Ti oxides, and oxygen isotopes, and yet appear to be too low when compared to more recently determined pyroxene temperatures for the Lowlands (Hoffman, 1979; Bohlen et al., 1980).

It is the purpose of this study to determine the character of the metamorphic gradient in the Adirondack Lowlands as determined by microprobe analysis of coexisting pyroxenes in the amphibolites contained within the major paragneiss and to assess and compare several of the pyroxene geothermometers. The reliability of the Fe-Ti oxides of the region as a geothermometric tool is also examined. Also, the metamorphic temperatures determined in this study for the Lowlands are compared with the much larger framework developed by Bohlen and Essene (1977a, 1979b) and Bohlen et al. (1980) for the entire Precambrian terrane of northern New York State.

Regional Geology

That portion of the Adirondack Lowlands examined in this study is located within the Lake Bonaparte, Gouverneur, Russell, Canton, and Potsdam 15 minute quadrangles (Fig. 1). Most of the Lowlands lie within the Grenville Lowlands physiographic province touching and, in places, astride the border (and break in slope) with the Fall Zone Belt which rises southeastward to the Childwold Rock Terrace, both essentially comprising the northwest Adirondack Highlands (Buddington and Leonard, 1962). The border closely parallels what is variously known as the northwest margin of the massif (Fig. 2), the Carthage-Colton zone of mylonitization, the Highlands-Lowlands boundary fault, and, most recently, the axial surface of a nappe along which movement has occurred (Romey et al., 1980). Romey proposed a structural model for the region in which much of the Lowlands is interpreted as the upper limb of a nappe extending from Alexandria Bay to its hinge in the Colton-Parishville area where its lower limb, which dips to the southwest, is folded back isoclinally into the Highlands to the southeast. In the upper limb fine-grained leucocratic gneiss bodies forming domes and basins across the Lowlands tend to be elongate parallel to the northeast strike of the 30° to 60° northwest-dipping foliation. These bodies represent the lowermost observable structural unit and are interpreted as exposures of a continuous, thick, nearly horizontal sheet. The lower limb's map pattern in the Highlands suggests it is steeper, possibly as the result of uplift of the massif and, from Colton-Parishville southwestward to Russell, tightly oppressed against the Stark complex to the southeast (Romey et al., 1980).

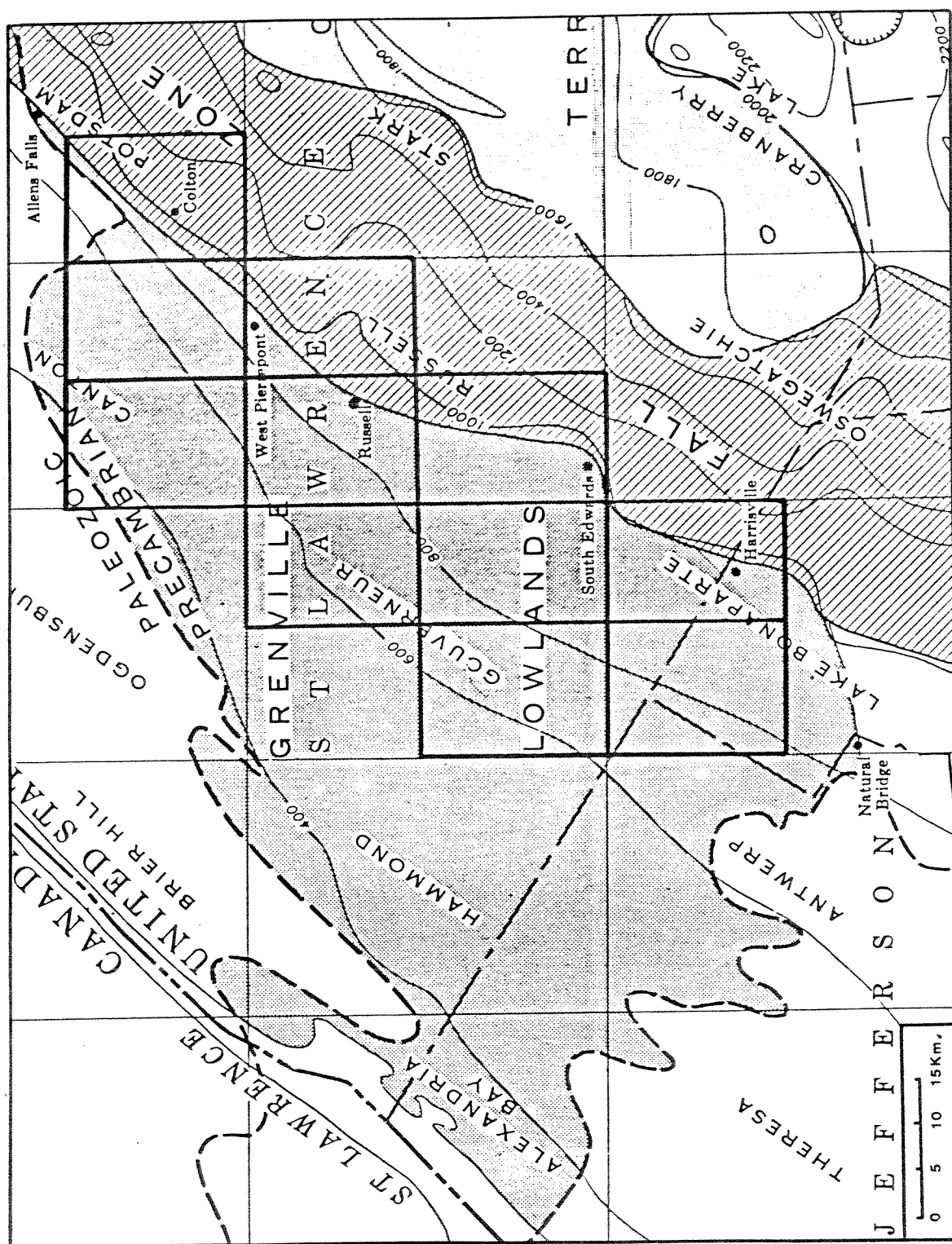


Fig. 1. Location map (after Buddington and Leonard, 1962).

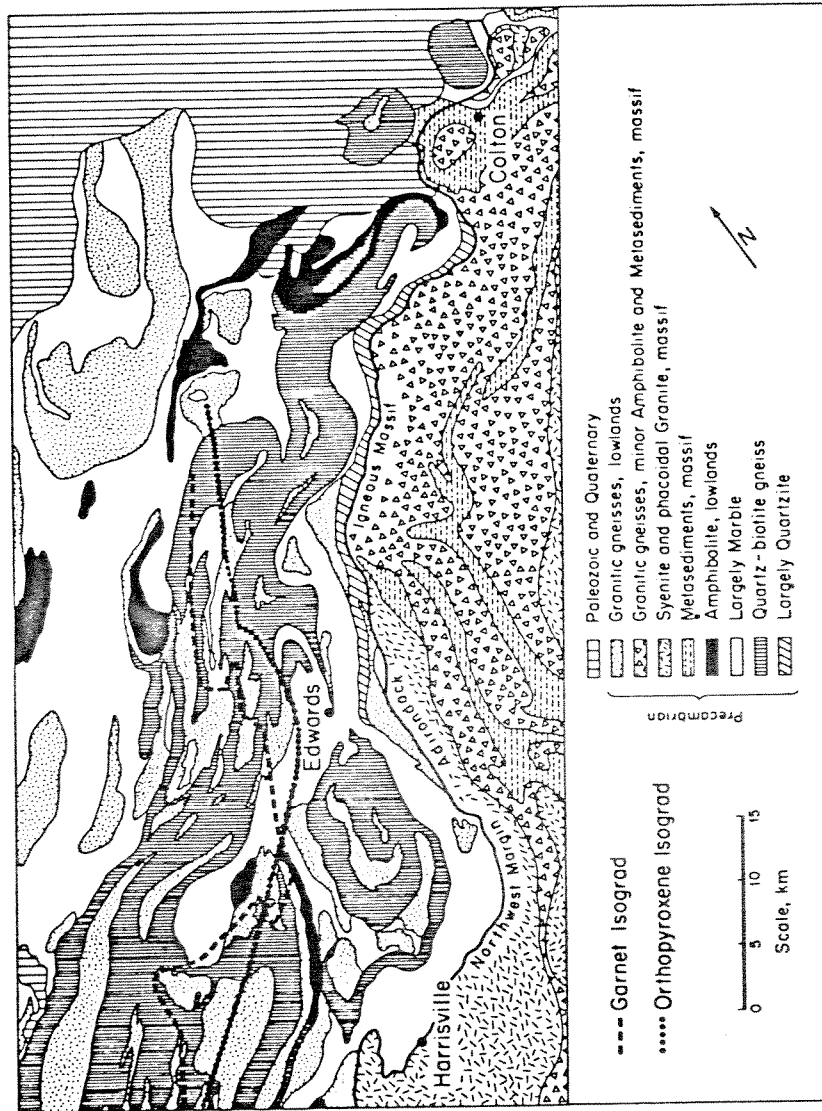


Fig. 2. Geology of the Adirondack Lowlands bordering the northwest portion of the Adirondacks. The areas underlain by quartz-biotite gneiss contain the major paragneiss with interbedded amphibolites (after Engel and Engel, 1960, 1962a). Orthopyroxene isograd after DeWaard (1969a).

The rocks were subjected to Grenville metamorphism which Seyfert (1980) interpreted as having occurred during the riding of Gondwanaland over the Grenville province during collision 1,175 to 1,150 m. y. ago. During this episode nappes were also formed within the Highlands to the southeast. Engel and Engel, in studies of what they call the least altered gneiss (1960) and included least altered amphibolite layers (1962a), in the region ranging along strike from Emeryville to Colton, presented persuasive petrographic evidence for progressive metamorphism, increasing in grade toward the massif. The average modal composition of the presumably isochemical phases of the least altered gneiss is; 40% quartz, 39% plagioclase (An_{25-35}), 1% K-spar, and 17% green-brown biotite, a bulk rock composition which is closest to that of a graywacke (Engel and Engel, 1953). Carl and Van Diver (1971) suggested that the formational environment of such a graywacke is one of minimal weathering and rapid transportation and deposition which is "anathema" to the environment demanded by the thick sections of thin-bedded, persistent marbles and clean quartzites which conformably lie above and below the paragneiss. To account for the unusually high $Na_2O : K_2O$ ratio (1:3), as opposed to 0.4 for normal shales, Engel and Engel (1953) suggested that diagenetic reaction of the shale with Precambrian sea water was responsible. Buddington and Leonard (1962) presented chemical data which suggest the gneiss probably originated as interbedded graywackes and shales.

The origin of the amphibolites within the gneiss complex is also difficult to determine because of the lack of relict textures, minerals, or field relations clearly indicative of the parent rock. The generally conformable nature of the amphibolites to the oldest foliation

(bedding?) in the paragneiss strongly suggests either 1) a simple reconstitution of basaltic sills or flows, 2) metamorphic differentiation of the gneiss with selective amphibolitization of favorable layers or sheared zones (Engel and Engel, 1962a). Closer to the massif the paragneiss exhibits complex flowage folds resulting in cataclastic textures in the enclosed, less ductile, amphibolite.

Previous Geologic Studies

Various workers have described the petrology and changes in metamorphic facies across the Adirondack Lowlands and into the Highlands. Their consideration of isograd mapping in the respective field areas has contributed to an understanding of metamorphic conditions.

Nielsen (1971), working in the 20 mile wide region between the orthopyroxene isograd and the Paleozoic cover on the west, sampled pelitic and amphibolitic rocks of the amphibolite facies because they contain critical phase assemblages used in defining subfacies. Sillimanite was the only alumino-silicate observed and Nielsen recognized rocks ranging from the muscovite-sillimanite-almandine subfacies to the sillimanite-K feldspar-almandine subfacies. Examining mineral assemblages as a function of bulk chemical composition, Nielsen found that T and P_{load} increased from west to east but that he could not map linear isograds within the amphibolite facies because the observed mineral assemblages do not show a consistent increase toward the east. Nielsen concluded that the partial pressure of water varied from one locality to another.

Further east, Engel and Engel's garnet (1960) and orthopyroxene (1962a) isograds were considered by Engel and Engel to subdivide the

Adirondack Lowlands into three zones based on;

- A. The disappearance of muscovite in the gneiss and sphene in the interbedded amphibolite, and the appearance of abundant clinopyroxene in the amphibolite.
- B. The appearance of garnet in the gneiss.
- C. The appearance of orthopyroxene in the amphibolite.

The orthopyroxene isograd separates the amphibolite facies from the hornblende granulite subfacies, and both isograds tend to parallel the edge of the massif (Fig. 2). Engel and Engel presented generalized curves for the variation in mineral and major element content across the Adirondack Lowlands for the least altered gneiss and least altered amphibolite interbeds. They contended that the transition to the granulite facies within the amphibolite layers was accompanied by a whole rock loss of K_2O , H_2O , Si, and a decrease in Fe_2O_3/FeO with residual enrichment in Ca, Mg, and probably Al, causing the bulk composition, initially that of a typical saturated basalt, to change to that of an olivine basalt as metamorphic grade increases. Engel and Engel (1962a) maintained that as the amphibolites are traced from Emeryville toward Colton-Parishville (near the massif), they increase in average thickness, the ratio of their total volume increases when compared to that of the enclosing paragneiss, and mortar and flaser texture increases. Their detailed field studies indicated that the accompanying gneiss and marble decrease in total thickness by about 15% and 30% respectively, but that there is no well-defined change in the volume of the amphibolite. Their suggestion that boudinage and brecciation in the amphibolites also indicated that partial melting was not an important mechanism in the mobilization of elements in the

amphibolites does not everywhere apply because of the presence of migmatized amphibolites throughout the Lowlands.

In the least altered gneiss, on the other hand, Al, Fe^{2+} , total Fe, Mg, Ca, Cr, Ni, and V increase, and K, Si, Fe^{3+} , H_2O , and Ba decrease in a degranitization or basification process producing Si, K, and H_2O as venitic migmatite in the surrounding rocks. Often, this granitic or felsic material occurs as pegmatite at the contact between the gneiss and amphibolite or as fracture fillings, pegmatite, or gneissic banding within the amphibolite. Engel and Engel showed an increase in the amount of this "igneous-looking" venitic migmatite associated with the gneiss complex as the massif is approached. This, coupled with the systematic changes in mineral assemblages and major element content as the massif is approached, and a general increase in grain size and the decarbonation of the marble, could account for the decrease in thickness of the marble and gneiss with increase in metamorphic grade toward the massif.

Some retrograde metamorphism in the gneiss and amphibolite layers is seen as chloritization of biotite, sericitization of plagioclase, and the replacement of amphibole and pyroxene by chlorite or biotite (Engel and Engel, 1962a). This alteration predominates in the amphibolites of the Emeryville area but decreases rather abruptly to the east and becomes uncommon in the vicinity of Colton, suggesting deep burial and low $P_{\text{H}_2\text{O}}$. Retrograde reactions very locally reverse the changes imposed on the rocks by progressive metamorphism, especially along shear zones in the Colton area where pyroxene-rich amphibolites have been inverted to hornblende-andesine (Engel and Engel, 1962a) probably as the result of increased $P_{\text{H}_2\text{O}}$.

Buddington (1963) worked in the Adirondack Lowlands and Highlands and defined three isograds in the orthogneisses within the massif; orthopyroxene in amphibolitic orthogneiss, garnet in metagabbro, and garnet in syenite-quartz syenite gneiss, to produce five zones of metamorphism which indicate an increase in metamorphic grade toward the massif (Buddington, 1965). He also determined, however, that there are also both small scale and large scale intermingling of the pyroxene granulite and hornblende granulite subfacies, occasionally within the same outcrop in the orthogneisses. He felt that there was no evidence of retrogression involved in this phenomenon and that it is best interpreted as variation in amount and pressure of H_2O within these higher temperature zones of metamorphism, similar to Nielsen's (1971) observation within the amphibolite facies of the Adirondack Lowlands further to the west. Buddington (1963) considered the various orthogneisses of the Adirondack Highlands to be essentially isochemically reconstituted without degranitization or basification, and extends this concept into the Lowlands. That is, he suggested an hypothesis reverse to that presented by Engel and Engel (1962a); the amphibolites of the Colton area are less altered from their original state, and the more hydrous ones near Emeryville, while formed at a lower P_{load} and T , were subjected to a higher P_{H_2O} .

DeWaard (1967) also observed that there was no regional extent to the pyroxene granulite facies within the Adirondack region but that it was locally developed in some rock units and layers on a limited scale and was the result of a reciprocity developed between H_2O released by dehydration reactions and P_{H_2O} in water-deficient rocks of low permeability. In addition to extending the orthopyroxene and garnet iso-

grads in the Adirondack Lowlands, DeWaard (1969a) defined the cordierite isograd which coincides with the southern extension of his orthopyroxene isograd. An isograd further to the southeast delineating the disappearance of cordierite was also mapped by DeWaard to outline the lower P_{load} (or higher T) biotite-cordierite-almandine subfacies, the lower zone of the hornblende granulite subfacies.

Stoddard (1976a, 1976b, 1976c, 1979, 1980), in an exhaustive petrographic and chemical study of a small area, the West Parishville Syncline at Colton, examined a variety of lithologies which he felt were recrystallized over a relatively narrow range of P and T. These materials included diverse calcareous and quartzitic lithologies plus a pelitic gneiss, semipelite, garnet amphibolite, and garnet-free amphibolite. The pelitic gneiss is the least altered gneiss of Engel and Engel (1962a). It exhibits a variety of phases, including cordierite dependent, in part, on variation in bulk chemistry (cordierite is found in Ca-poor, Al and/or Mg-rich rocks). The semipelites are gradational to the amphibolites and are orthopyroxene-bearing with abundant quartz and feldspar. The amphibolites contain abundant plagioclase and green-brown hornblende, lack quartz, and invariably contain augite, usually orthopyroxene, and may or may not contain garnet. Stoddard (1976a) agreed with Engel and Engel (1962a), maintaining that the nongarnetiferous amphibolites most likely represent layers of reconstituted intercalated basaltic volcanic rocks, and agreed with Buddington and Leonard (1962) that their chemical composition suggests the pelitic gneiss probably originated as interbedded graywackes and shales. Stoddard, however, disagreed with Buddington (1963) and Engel and Engel (1962a) who considered the garnetiferous amphibolites to be

metasomatic in origin. He presented field evidence and chemical data which suggest that the garnet amphibolites may have originated as sills and dikes intrusive into the pelitic sediments and basaltic volcanic rocks. Stoddard (1976b) also determined that orthopyroxene appears in the semipelites where lowered P_{H_2O} restricts biotite stability and that they and the orthopyroxene-free pelites reflect variation in bulk chemistry and cannot be related by any chemical reaction.

Stoddard (1976a), discussing the constrained experimental data of Day (1973) for the system; $\text{mus} + \text{qtz} = \text{Al}_2\text{O}_5 + \text{K-spar} + \text{H}_2\text{O}$, found it and the reaction; $\text{mus} + \text{bio} + 3\text{qtz} = \text{gar} + 2\text{K-spar} + 2\text{H}_2\text{O}$, to provide a convenient marker in the gneiss for the lower boundary for the granulite facies. He lent importance to Day's studies by suggesting that the only unequivocal "isograd" for the beginning of the granulite facies is the breakdown (elimination?) of muscovite since orthoclase coexisting with sillimanite/kyanite and/or garnet, but never muscovite, are the phases found in rocks of appropriate (pelitic) composition in the granulite facies. Apropos of this, Engel and Engel (1960) have stated that the "appearance of garnet (and disappearance of muscovite) at Edwards constitutes the single classical "isograd" in a belt of paragneiss almost 75 miles long (Philadelphia, New York, to Colton, New York)." A comparison of Engel and Engel's generalized curves indicating changes in mineral and major element composition of least altered gneiss (1960; Fig. 1) and least altered amphibolite (1962a; Fig. 4), as traced from Emeryville to Colton, reveals that muscovite only begins to break down as garnet begins to form in the gneiss. Furthermore, the disappearance of muscovite in the gneiss only coincides with the first appearance of orthopyroxene in the amphibolite.

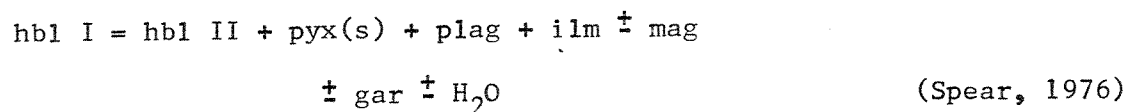
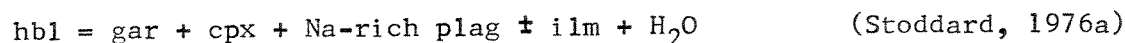
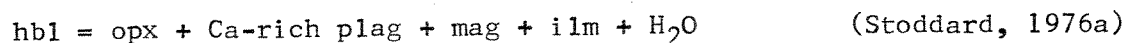
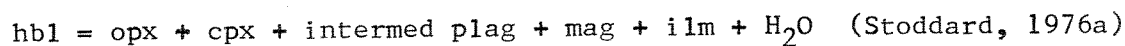
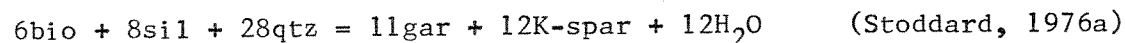
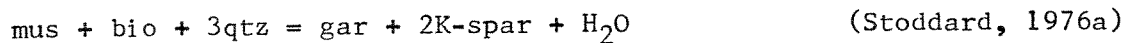
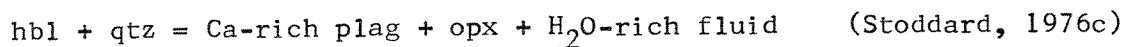
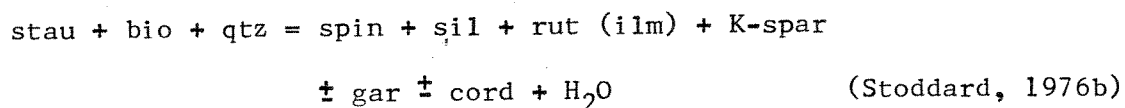
It might be considered, therefore, that the inception of the granulite facies in pelites be marked at the elimination of muscovite.

Stoddard's (1976a) recognition of unaltered cordierite in a few specimens taken from the Colton area is significant in that it requires reinterpretation of DeWaard's (1969a) cordierite isograd.

Hoffman and Essene (1978) found that orthopyroxene in mafic rocks of approximately constant bulk composition makes its first appearance in a northeast trending zone approximately 25 kilometers wide, bounded by the towns of Hermon, Balmot, Fine, and Stark (Fig. 3). This phenomenon is reminiscent of the intermingling of the pyroxene granulite and hornblende granulite subfacies in the Lowlands and massif as observed by Buddington (1963) and DeWaard (1967), Nielsen's (1971) inability to map isograds within the amphibolite facies west of Engel and Engel's (1962a) orthopyroxene isograd, and is in agreement with Stoddard's (1976a) concept of the breakdown (elimination?) of muscovite as the only unequivocal "isograd" for the beginning of the granulite facies. Hoffman and Essene (1978) presented data which suggest that orthopyroxene formed by the reaction; Na-rich plag + pargasitic hbl + qtz = opx + cpx + Na-poorer plag + ilm + H₂O, but that in rocks of different bulk composition, other reactions involving amph, bio, opx, cpx, plag, K-spar + Fe oxides, may also occur. They suggested that there are local variations in T, H₂O, and slight changes in bulk chemistry and that orthopyroxene formed in amphibolites in response to increased metamorphic grade toward the massif (based on oxide and feldspar thermometry in the Lowlands and massif (Bohlen and Essene, 1977a)) and is not necessarily a function of declining fH₂O toward the massif. Engel and Engel (1962a) maintained that the variation noted

in the composition of hornblendes in amphibolites across the Lowlands also is the result of critical changes in the bulk composition of the total rock and is not due to regional gradients in T, P, or changes in kind or composition of coexisting minerals.

In support of the various observations concerning water pressure, it should be noted that within the Adirondack Lowlands there are a number of possible reactions which can release water;



AIMS OF THE PRESENT STUDY

It is the purpose of this study to examine a high density sampling of the amphibolites at granulite facies grade within the major paragneiss of the Lowlands, apply the Ross and Huebner (1975), Wood and Banno (1977), and Wells (1977) orthopyroxene-augite geothermometers, compare their temperature determinations and relate them to pyroxene compositions and the various estimates of metamorphic conditions as determined by previous workers. A strong argument against a study of this nature would come from the work of Bohlen and Essene (1979a, 1979b, 1980) who have concluded that orthopyroxene-clinopyroxene as well as garnet-clinopyroxene, garnet-biotite, and garnet-cordierite Mg-Fe exchange thermometers seem inadequate for quantitative use. In particular, they found no systematic pyroxene temperature variations within the Adirondack terrane (Bohlen et al., 1979). They argued that since the partitioning of cations is generally a function of bulk composition as well as temperature (with only small pressure effects), the temperature determinations from isothermal assemblages could vary dramatically because of bulk compositional effects. They found that empirically and experimentally calibrated K_D thermometry for the various mineral pairs yielded internally inconsistent and highly variable results caused, in part, from long extrapolations from reversed experiments, differential ordering of Jd and/or Ts in experimental vs. natural pyroxenes, improperly assumed T in calibrating systems, and difficulties in evaluating Fe^{2+}/Fe^{3+} .

Stoddard (1980), however, defending his geographically restricted study of the Colton-Parishville area in which he attempted to deter-

mine a well-defined temperature-pressure estimate from a variety of intermingled lithologies, criticized Bohlen and Essene's (1977a), Essene et al. (1977, 1978), and Valley and Bohlen's (1979) regional approach to delineation of Adirondack metamorphic conditions. A review of Bohlen and Essene's (1977a) isotherm map for the Adirondacks (Bohlen and Essene, 1979b, 1980; Bohlen et al., 1980), reveals very few and widely spaced data points for the Lowlands. Since the lithologies of the Lowlands' rocks are quite different from those of the Highlands, it would seem a reasonable approach to try to relate a metamorphic gradient, based on pyroxene temperatures, to the orthopyroxene isograd within the Lowlands, rather than to isotherms centered on a high well within the massif. A similar approach has been successful in the granulites of Broken Hill, New South Wales (Binns, 1962) which have been subdivided into three zones upgrate from the orthopyroxene isograd. Regardless of the method employed (Wood-Banno, 1977; Ross-Huebner, 1975), pyroxene pairs record statistically significant increases in temperature away from the isograd, particularly between the lowest and intermediate subzones (Hewins, 1975). The following are Wood-Banno temperatures;

Zone	Temperature °C
1	843
2	838 $\pm$ 8
3	808 $\pm$ 14

- Orthopyroxene Isograd -

One would expect, therefore, that temperature, based on pyroxene pairs, would demonstrably increase (at least qualitatively) toward the Adirondack Highlands and away from the orthopyroxene isograd. Also, the effect of pressure on minor elements, particularly aluminum, could

be determined (Wilson, 1976) as the massif is approached.

In order to examine the character of the metamorphic gradient in the Adirondack Lowlands utilizing probe data from coexisting pyroxenes, it is first necessary to determine the map position of the orthopyroxene isograd in the area (Fig. 2). It is interesting to note that the isograd maps of Engel and Engel, Buddington, and DeWaard do not entirely agree. The garnet isograd presented by Buddington (1963) (taken from Engel and Engel (1960)), in the Edwards quadrangle, lies from two to three kilometers to the east of Engel and Engel's isograd and, in the Lake Bonaparte quadrangle, from two to three kilometers to the west. DeWaard's (1969a) garnet isograd in these two quadrangles is consistently to the west of that presented by Engel and Engel which suggests that DeWaard, at the later date, was able to more precisely define the isograd in the quartz-biotite gneiss.

Engel and Engel's (1962a) orthopyroxene isograd was mapped only for a distance of approximately ten kilometers but is essentially parallel to, and approximately two kilometers east of, their garnet isograd. Buddington's (1963) orthopyroxene isograd for orthopyroxenes in amphibolite layers in the quartz-biotite gneiss lies about two kilometers to the east of Engel and Engel's orthopyroxene isograd and was extended by Buddington a distance of 30 kilometers north and progressively eastward toward the northwest corner of the Colton quadrangle. It must, however, be assumed that the position of the northern 25 kilometers of this isograd was approximated since the isograd does not cross any areas underlain by the quartz-biotite gneiss (compare with the Geologic Map of New York State, Adirondack Sheet, Isachsen and Fisher, 1970).

DeWaard's (1969a) orthopyroxene isograd parallels his garnet isograd, includes Engel and Engel's orthopyroxene isograd and extends it 30 kilometers to the southwest and 10 kilometers to the north only to the northern edge of the Hermon quadrangle where it terminates 5.7 kilometers to the west of Buddington's orthopyroxene isograd. In the Emeryville area, DeWaard's orthopyroxene isograd overlies a small portion of Engel and Engel's garnet isograd (see Fig. 2) which may be due to the mode of occurrence of garnet in the area. According to Engel and Engel (1958), the disappearance of muscovite in the quartz-biotite gneiss is relatively undeflected at contacts of more or less granitic and pegmatitic gneiss. Garnet, on the other hand, in the Emeryville area, is confined largely to contacts of pegmatite and gneiss and is rare or absent in many parts of the least altered gneiss. Consequently, the isograd (isoblast) drawn at the first appearance of garnet is extremely irregular. Engel and Engel (1958) suggested that garnet formation was facilitated by increased mobility of the reaction due to granitizing and pegmatite-forming fluids acting on mafic constituents in the grains. Consequently, the smooth orthopyroxene isograd (Fig. 2) of DeWaard (1969a) which parallels his K feldspar-almandine isograd delineating the disappearance of muscovite in quartz-bearing rocks may be a more reliable and realistic expression of T and P (in amphibolites) than the more composition-dependent garnet isograd (in the gneiss) of Engel and Engel (1962a).

DeWaard's orthopyroxene isograd was also considered the most reliable and useful in this study because; 1) it extends well to the southwest where it transects large areas underlain by the quartz-

biotite gneiss, 2) it does not extend to the north much beyond the gneiss exposures near Hermon, 3) Hoffman (1979) has determined a temperature for coexisting pyroxenes on DeWaard's orthopyroxene isograd at the northern edge of the Hermon quadrangle, 4) coexisting pyroxenes were observed in this study in a specimen (No. 154) 0.2 kilometers to the west of Buddington's (1963) orthopyroxene isograd, 5) DeWaard's isograds have been used on the Generalized Tectonic-Metamorphic Map of New York by Fisher et al., (1971). Unfortunately, DeWaard's orthopyroxene isograd could not be extended, in this study, into the massive amphibolites which lie in the southern portion of the Canton quadrangle. However, the map by Fisher et al., (1971) does extend the isograd so that most of the massive amphibolites lie within the orthopyroxene field. Buddington's orthopyroxene isograd, therefore, in its northern extension particularly, does appear to be located too far to the east.

Specimens from the amphibolites interbedded with the quartz-biotite gneiss and the more massive amphibolites of the Adirondack Lowlands were collected from both sides of DeWaard's orthopyroxene isograd (Fig. 2) to make two-pyroxene bearing rocks (see Table 1) available for petrographic and probe study and to more precisely determine the location of the isograd. There is some variation in the petrography of the specimens studied, and this will be discussed below (see Appendix A for individual descriptions and Appendix B for photographic plates).

Quantitative chemical analyses of major and minor elements in coexisting pyroxenes in amphibolites from the Lowlands were obtained with an ARL-SEMQ electron microprobe analyser. The microprobe has

Distance from Orthopyroxene Isograd (Km.)	Specimen No.	Outcrop Map No.	T (Wood & Banno)	T (Wells)	T (Ross & Huebner)
1.45	10	156C	788	823	700
1.45	11	159E	789	831	695
2.00	18	159A	795	830	670
2.15	3	519	824	860	700
2.15	2	520	824	863	675
2.45	7	524	789	836	700
2.45	9	525	803	825	675
3.00	5	505	773	787	650
4.70	1	512	784	811	670
5.20	12	201B	782	808	660
5.90	13	515	830	864	675
5.90	14	514	832	868	710
7.30	15	88B	800	837	650
9.00	17	76B	817	819	630
10.40	20	222C	790	832	650
16.05	22	232A	713	719	595
16.20	6	534	800	835	640
16.30	23	234	761	787	610
16.50	25	236B	765	783	625
16.50	16	236C	794	820	650
16.50	24	236A	770	786	630
24.00	28	260B	772	801	620
24.00	27	260A	769	793	620
25.50	26	259F	774	802	620

Table 1. List of coexisting pyroxene specimens from the Adirondack Lowlands, their right-angle distance from DeWaard's (1969a) orthopyroxene isograd, and their centigrade temperatures as determined by several geothermometers.

six fixed (Si, Ti, Al, Fe, Mg, and Ca), and three variable wavelength dispersive (LIF, LIF, and TAP) crystal spectrometers (see Appendix C; Materials and Methods). Natural augite, hypersthene, hedenbergite, corundum, and quartz were used as element and background probe standards. Using transmitted light optics, pyroxenes were easily distinguished in the microprobe because of their high relief and texture. Clinopyroxene was distinguished from orthopyroxene by use of the calcium audio ratemeter which was maximized to establish the most Ca-rich compositions of clinopyroxene grains. Approximately ten compositional determinations for clinopyroxenes and five to ten determinations for orthopyroxenes (because of their usually tight clustering of plots on the pyroxene quadrilateral) were made for each polished section with percent oxide maintained at $100 \pm 2\%$.

Oxides

In a classic paper by Buddington and Lindsley (1964), the temperature - fO_2 dependence of coexisting ulvospinel-magnetite and ilmenite-hematite solid solution was calibrated. Because coexisting titaniferous magnetite and ferrian ilmenite react extensively as metamorphic temperatures wane, the reaction; $Fe_2O_3 + Fe_2TiO_4 = Fe_3O_4 + FeTiO_3$, results in the formation of ilmenite and magnetite as the ulvospinel component in titaniferous magnetite becomes oxidized and the hematite component in ferrian ilmenite is reduced. This subsolidus oxidation-reduction reaction results in the formation of exsolution textures, two of which are common in the Adirondack Highlands (Bohlen and Essene, 1977a). The first is granule "exsolution" which appears as small grains of ilmenite surrounding or nearly surrounding

the magnetite, and the second is a sandwich or trellis-type in which ilmenite lamellae exsolve within magnetite. Associated with these exsolution intergrowths are larger ilmenite grains which are compositionally different on the basis of minor elements and which bear no textural relationship to magnetite grains and are assumed to not have reequilibrated with magnetite after ulvospinel exsolution. Bohlen and Essene (1977a) have devised an analytical technique which permits reintegration of ilmenite lamellae to form a theoretical original homogeneous titaniferous magnetite but which requires homogeneous magnetites with homogeneous ilmenite lamellae to be present in the section. Unfortunately, the ilmenites and magnetites in the amphibolites of the Adirondack Lowlands examined in this study show no exsolution features due to extensive reequilibration. This has resulted in an increase in the ilmenite and magnetite components of the rhombohedral and spinel series phases, respectively, causing a reduction in slope of their tie-lines on the TiO_2 - FeO - Fe_2O_3 diagram (Ashwal, 1978). This causes their compositions to plot outside the usable range of the $f\text{O}_2$ - T diagram of Buddington and Lindsley (1964). Significantly, Bohlen and Essene (1977a) and Bohlen et al. (1980) avoid oxide thermometry in the Lowland portions of their isotherm maps and prefer to present only a few temperature determinations based on coexisting feldspars. Additionally, Stoddard (1976a, 1980), working in the Colton-Parishville area of the Lowlands found that the application of the Fe-Ti oxide geothermometer was precluded by high vanadium contents in the magnetite.

Valley and Bohlen (1979) have shown that the oxide and feldspar temperatures presented by Bohlen and Essene (1977a) are consistent

with the stabilities of various silicate, silicate carbonate and silicate sulfide assemblages studied throughout the Adirondack region. The Ross and Huebner pyroxene temperatures determined in the present study nicely fit the revised isotherm map of Bohlen et al. (1980) which they indicated represents peak or near peak metamorphic temperatures since they are derived, in any given area, from anorthosites and amphibolites (no partial melting) and charnockite-mangerite and kinzigite (probably partially melted).

Pyroxene Petrography

As previously mentioned, petrographic descriptions of individual specimens are offered in Appendix A. Appendix B contains photographic plates of selected features. Since there is some variation in the petrography of specimens studied, a composite picture is presented here for the various features observed in the sections probed to determine the compositions of their coexisting pyroxenes. In most slides the pyroxenes are equant and of a uniform size. Orthopyroxene generally is pink-green pleochroic although, in a few slides, it is colorless. Clinopyroxene is almost always greenish. In many specimens the pyroxenes are poikiloblastic, appearing as optically continuous, detached grains of more or less uniform size, themselves occasionally poikiloblastic, containing hornblende, plagioclase, oxides, and biotite (Plate 1, Figs. 1-3). In several sections there are a few non-poikiloblastic pyroxene grains which are many times larger than neighboring pyroxenes, but which are identical in composition to these more numerous, smaller pyroxenes. These larger pyroxenes are also always intimately associated with granitic or felsic material which appears

either as filled fractures, pegmatitic veinlets, or migmatitic amphibolite, and these regions are also commonly surrounded by an aureole, or make up a band, notably free of hornblende (Plate 1, Figs. 4-5). This feature in the amphibolites may be due to one or several of the hornblende dehydration reactions previously discussed, with loss of water to fractures or to local melting.

Additionally, in three slides, emplaced felsic material is also associated with large garnet porphyroblasts. These garnets may have formed due to increased mobility of reactant phases as Engel and Engel (1958) noted with regard to garnet in pegmatitic seams within the quartz-biotite gneiss. It is likely that the larger pyroxenes associated with felsic material in the amphibolites interbedded with the gneiss may have had similar origins.

The larger orthopyroxenes often are slightly altered to fine-grained serpentine (antigorite?) and the larger clinopyroxenes to hornblende. Both pyroxenes occasionally contain more or less equally-spaced deformation lamellae which appear as slightly undulatory, birefringent bands which extinguish a few degrees from the rest of the grain. These lamellae are similar in appearance to those reported for olivine and quartz (Fairbairn, 1949) in that they are closely spaced and taper at the ends, generally terminating within the grain boundaries. In most grains recrystallization has removed all traces of the birefringent lamellae but has left relict planes of inclusions (Fairbairn, 1949) which are delineated by extremely fine needle-like oxide grains of various lengths and orientations depending on the plane of section, but which indicate the relict planes are extremely thin. Relict planes are also very common in the smaller, more numer-

ous pyroxene grains (Plate 2, Figs. 1-6; Plate 3, Figs. 1-3).

All specimens contain a great deal of clear and/or slightly sericitized plagioclase which is commonly polysynthetically and, more rarely, pericline twinned. Some clear potassium feldspar is also often present. There is usually a large amount of generally elongate, green-brown, pleochroic hornblende which is almost always larger in size than the other minerals. A small amount of light to dark-brown, clear, pleochroic, aligned and elongate biotite is present in many slides. A few slides contain small amounts of quartz associated with the feldspar and there are traces of zircon, sillimanite, apatite and a few percent of ilmenite and magnetite, commonly touching in many specimens. Traces of pyrite are also common.

Some slides contain little or no hornblende and many slides contain little or no biotite which suggests they may be from the pyroxene granulite subfacies (Buddington, 1963). A few slides from the vicinity of Colton contain a greenish hornblende similar in color to those which Engel and Engel (1962a) found in the vicinity of Emeryville. Engel and Engel suggest that the Colton hornblende in the more pyroxenic "amphibolites" formed either in conjunction with local pockets of water-rich, alkali silicate fluid or as a retrograde mineral formed after the peak stage of regional metamorphism.

In many slides incipient to extensive fine to coarse-grained symplectite composed of plagioclase, hornblende, biotite, pyroxenes, and oxide grains is present at many or all grain boundaries (Plate 3, Figs. 5-6). Stoddard (1976a) interpreted these symplectites to be the reaction product of hornblende dehydration but also points out, however, that in general, rocks in the Colton area possess textures which

are consistent with textural equilibrium. These include mutual contacts of grains of various phases and lack of symplectic intergrowths. Three sections from the Colton area examined in the present study also suggest textural equilibrium because they exhibit no evidence of symplectic intergrowth even though two contain abundant hornblende. In all other green-brown hornblende-bearing amphibolites examined in this study, abundant symplectite was present.

Aside from being symplectite-free, the sections from the vicinity of Colton (Plate 1, Figs. 2-3) exhibit extremely well developed pyroxene poikiloblasts, are not obviously migmatitic and lack larger, non-poikiloblastic pyroxene porphyroblasts.

Pyroxene Analyses

Coexisting pyroxenes in twenty-four specimens were analyzed. Plots of their compositions on the pyroxene quadrilateral may be found in Appendix D and are numbered D-1 to D-28. These analysis numbers are located on a map of the Adirondack Lowlands (Fig. 3). Figure 4 is the same map showing field numbers of analyzed specimens. Figures 5-7 are maps of these same localities showing pyroxene temperatures as determined by the Ross and Huebner (1975), Wells (1977), and Wood and Banno (1977) geothermometers respectively (see Table 1), and are discussed below. Sample locations are described and listed in Appendix E, and averaged pyroxene compositions (Table 2), as determined by microprobe analysis, are presented in Appendix F. Some specimens exhibit fairly tight clusters of orthopyroxene and/or clinopyroxene points, whereas others have clusters which are more scattered (Figs. D-1 - D-28). Some of these exhibit slightly elongate cluster-

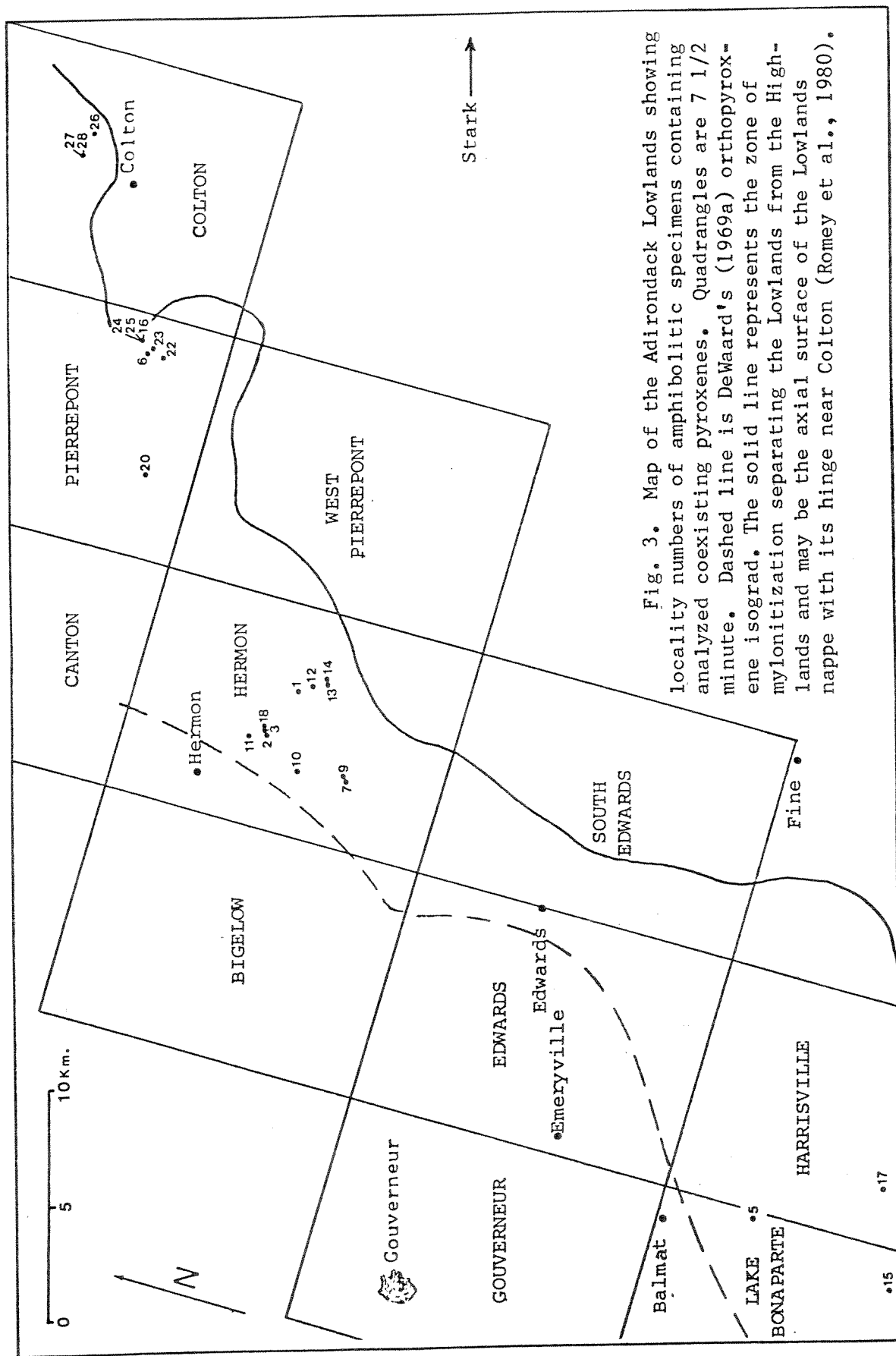


Fig. 3. Map of the Adirondack Lowlands showing locality numbers of amphibolitic specimens containing analyzed coexisting pyroxenes. Quadrangles are 7 1/2 minute. Dashed line is DeWaard's (1969a) orthopyroxene isograd. The solid line represents the zone of mylonitization separating the Lowlands from the Highlands and may be the axial surface of the Lowlands nappe with its hinge near Colton (Romey et al., 1980).

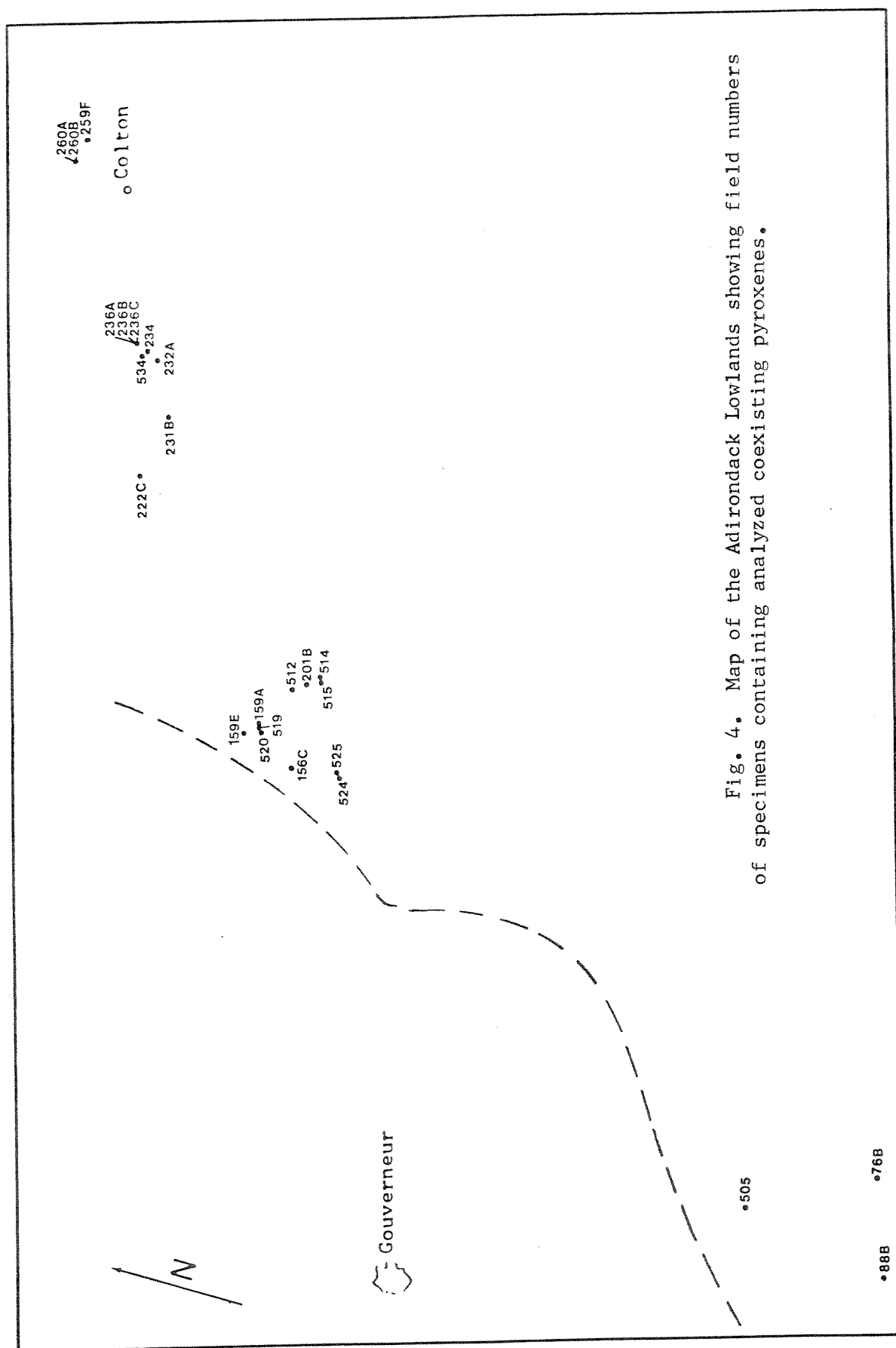


Fig. 4. Map of the Adirondack Lowlands showing field numbers of specimens containing analyzed coexisting pyroxenes.

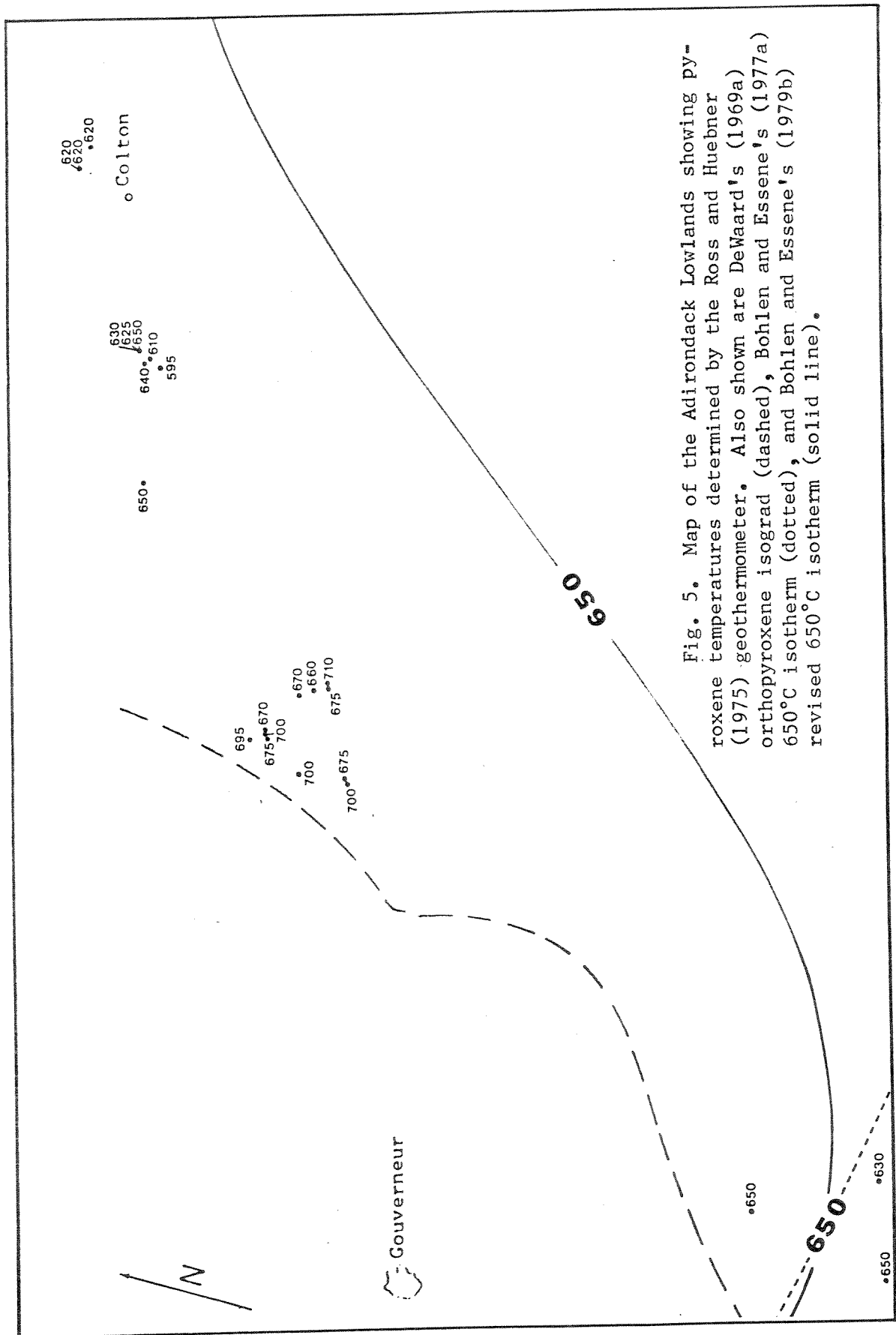


Fig. 5. Map of the Adirondack Lowlands showing pyroxene temperatures determined by the Ross and Huebner (1975) geothermometer. Also shown are DeWaard's (1969a) orthopyroxene isograd (dashed), Bohlen and Essene's (1977a) 650°C isotherm (dotted), and Bohlen and Essene's (1979b) revised 650°C isotherm (solid line).

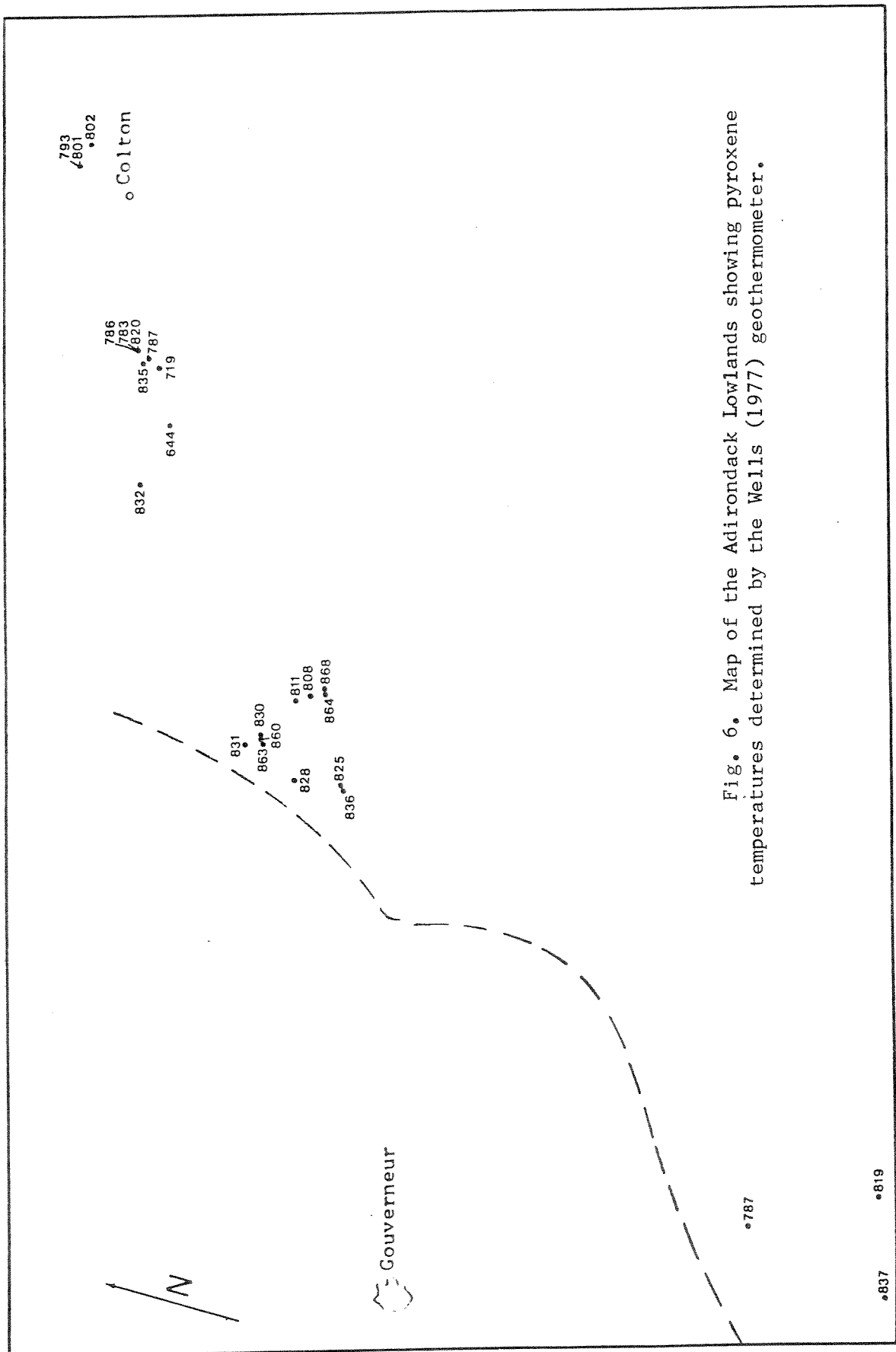


Fig. 6. Map of the Adirondack Lowlands showing pyroxene temperatures determined by the Wells (1977) geothermometer.

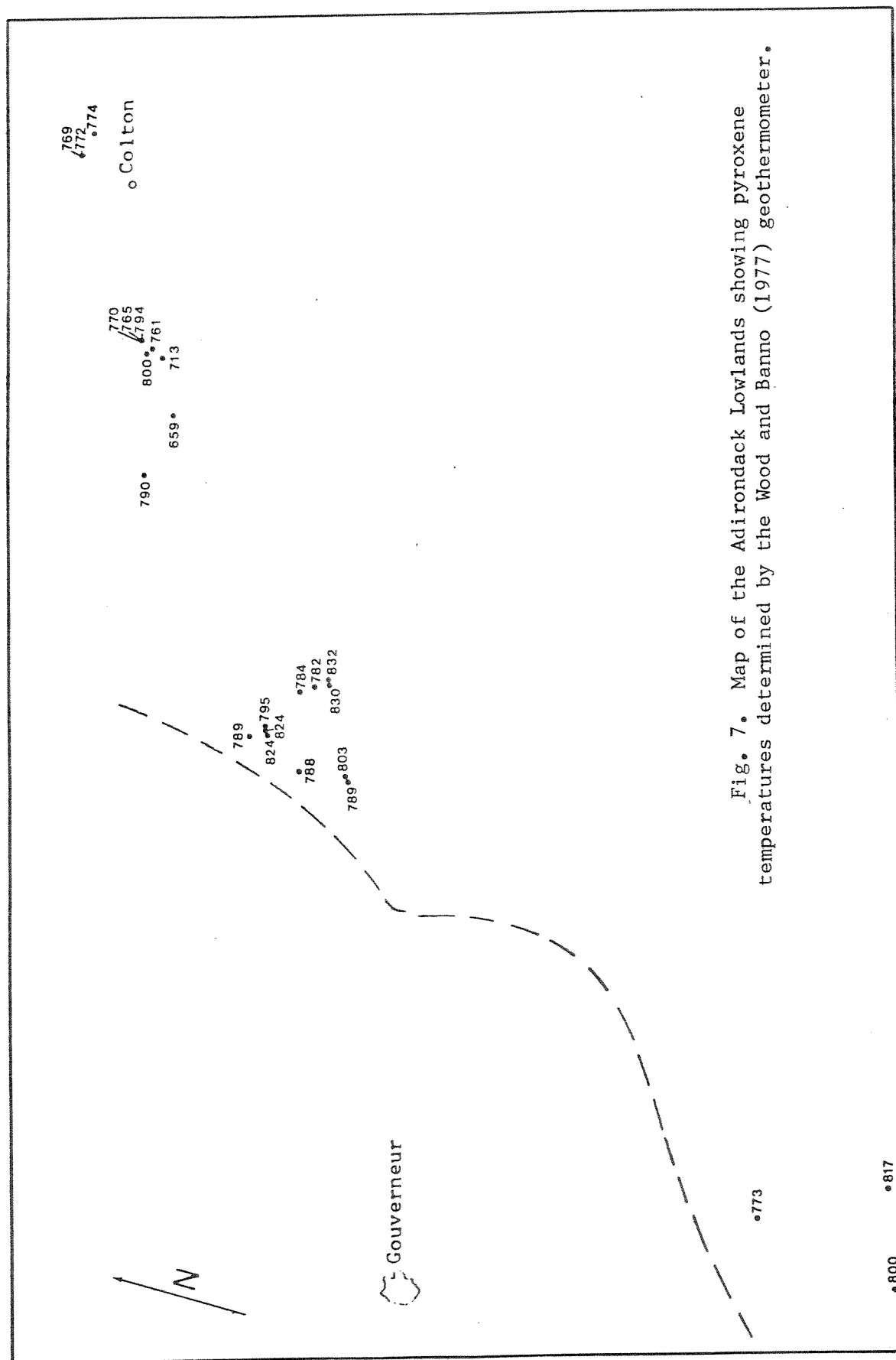


Fig. 7. Map of the Adirondack Lowlands showing pyroxene temperatures determined by the Wood and Banno (1977) geothermometer.

ing of clinopyroxene compositions either along the orthopyroxene-clinopyroxene tie-line, or at angles to the isotherms determined by Ross and Huebner (1975) for the pyroxene quadrilateral. Most clinopyroxenes plot in the salite field (Poldervaart and Hess, 1951) but some plots, or portions of plots of material examined in this study, also fall in the augite and subcalcic augite fields, commonly stretched out on or close to their respective tie-lines. One specimen (D-7) plots in the ferrosalite and ferroaugite fields. All orthopyroxenes plot as hypersthene with a few points falling in the intermediate pigeonite field. The more scattered clusters, particularly clinopyroxenes, are from amphibolites which have been migmatized (D-2, D-6, D-11, D-23, D-25) or associated with felsic veinlets (D-20) or chloritized shear zones (D-24), suggesting allochemical reactions.

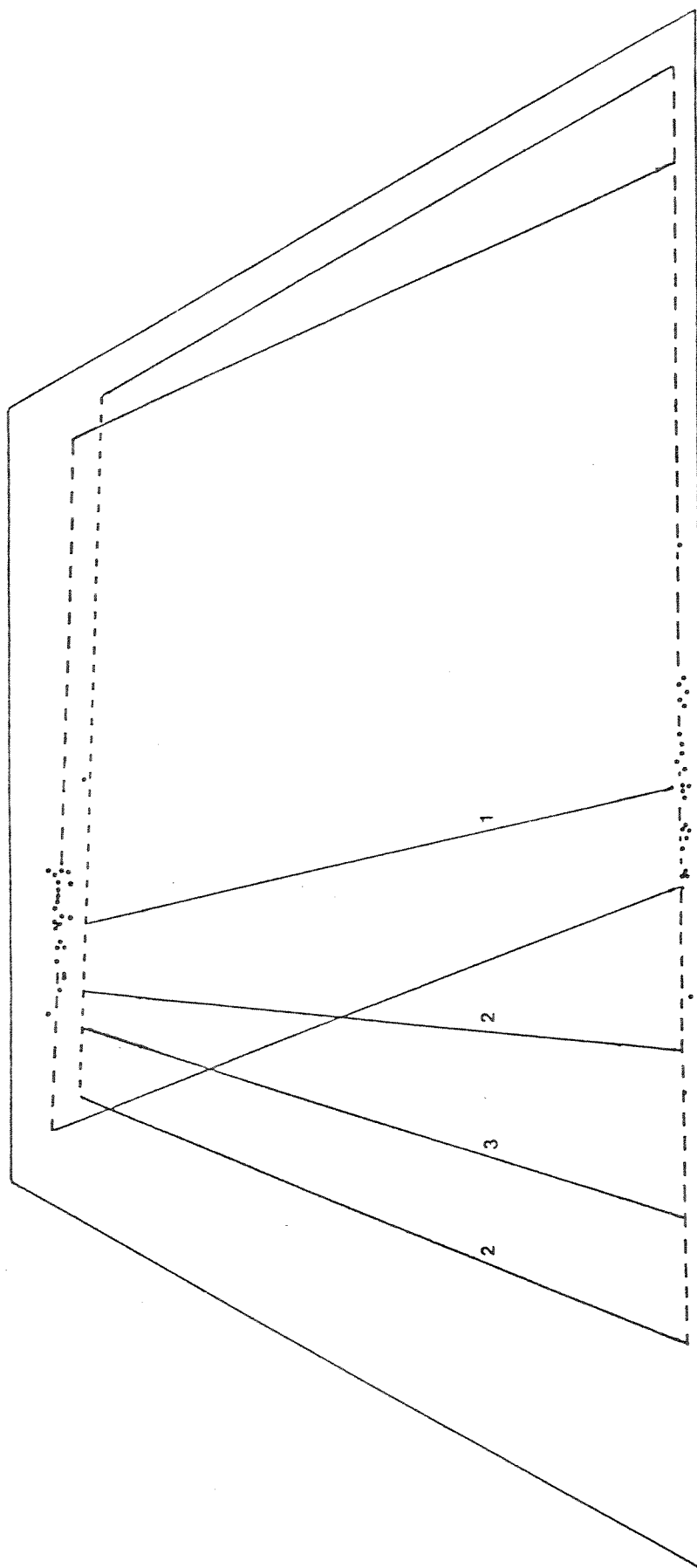
There are essentially no compositional differences between large non-poikiloblastic, poikiloblastic, or the smaller, numerous randomly oriented clinopyroxenes or orthopyroxenes within any of the specimens examined. Some of the Ca-poor clinopyroxene points or pigeonitic points from orthopyroxene grains are from pyroxenes which exhibit alteration along relict deformation lamellae. One specimen (D-11) contained augite grains with lamellar cores which were Ca-poor (W_{38}) as compared to their lamella-free edges (W_{47}). This may have been caused by overlap of fine exsolution lamellae and host grain which were unresolved by the narrow beam of the probe. It should be noted that Engel et al. (1964) did not observe exsolution lamellae in the pyroxenes from the amphibolites of the Lowlands, whereas Bohlen and Essene (1979b) frequently saw very small homogeneously distributed exsolution lamellae. Bohlen and Essene compared wide beam reintegration

ted analyses with narrow beam analyses from the same pyroxenes containing thin, minor exsolution lamellae and found that the wollastonite content of pyroxenes differed by less than 0.5 mole percent, indicating precise and accurate narrow beam compositional determinations. In the present study other cored clinopyroxenes (D-16, D-24) or orthopyroxenes (D-20, D-26), however, did not exhibit compositional differences between the edges and core (see Plate 3, Fig. 3). All data points which did not fall within the main clusters on any of the pyroxene quadrilateral plots were excluded from the tabulations seen in Appendix F and were not utilized in pyroxene temperature determinations according to the methods of Ross and Huebner (1975), Wells (1977), and Wood and Banno (1977) (see Table 1). There appears to be no systematic relation regarding distance of the specimen locality from the orthopyroxene isograd, cluster tightness or shape, presence of hornblende, biotite, or extent of migmatization of the specimen.

Hornblendes associated with the pyroxenes generally gave satisfactory percent oxide totals (if the probe was standardized for pyroxenes) and almost always fell at W_{30} , often a few percent to the Fe-rich side of the pyroxene tie-line. Hornblende compositions will be discussed below.

The pyroxenes from the amphibolites of the Adirondack Lowlands exhibit a moderately broad range of compositions (En_{34-63} for orthopyroxenes, and En_{26-40} for clinopyroxenes). The average compositions for each specimen (D-1 to D-28) are shown as data points in Fig. 8. The rhomboid also plotted in Fig. 8 outlines compositions from the more Fe-rich metamorphosed anorthosites, mangerites and charnockites from the Adirondack Highlands utilized by Bohlen and Essene (1978) in

Fig. 8. Pyroxene quadrilateral plot of average compositions of coexisting pyroxenes (dots) from the Adirondack Lowlands as determined in this study. The rhomboid outlines compositions of coexisting pyroxenes from more Fe-rich metamorphosed anorthosites, mangerites and charnockites from the Adirondack Highlands (Bohlen and Essene, 1978). The trapezoid outlines compositions of coexisting pyroxenes from the Hudson Highlands (Monroe quadrangle, tie-line 1), Belchertown complex (Massachusetts, tie-lines 2), the Cortlandt complex (Peekskill, New York, tie-line 3), and the Adirondack Highlands (Mt. Marcy quadrangle, remainder of the trapezoid) (Jaffe et al., 1975). Note that the igneous and metamorphic tie-lines cross, consistent with different temperature conditions.



their geothermometric study. Pyroxene data from other regions in the northeastern United States are also shown (Jaffe et al., 1975).

Pyroxene Geothermometry

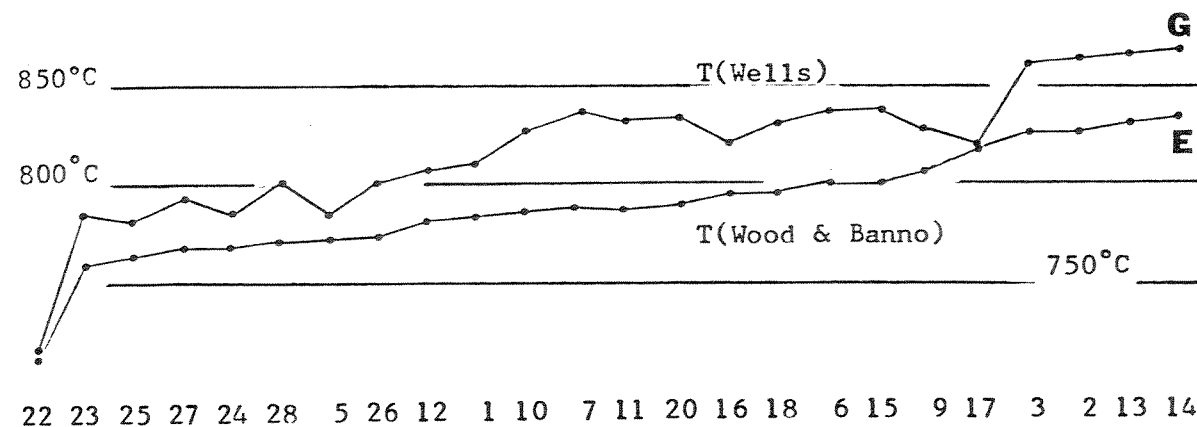
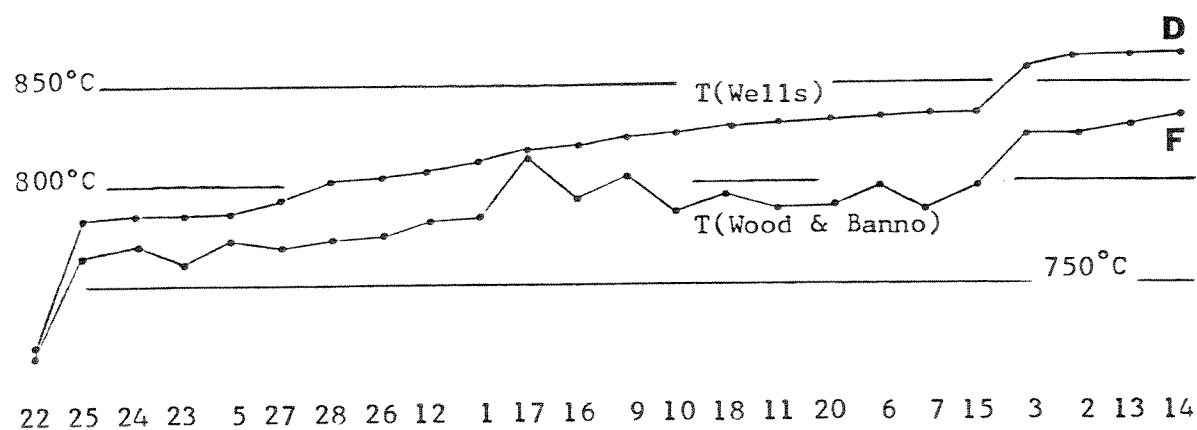
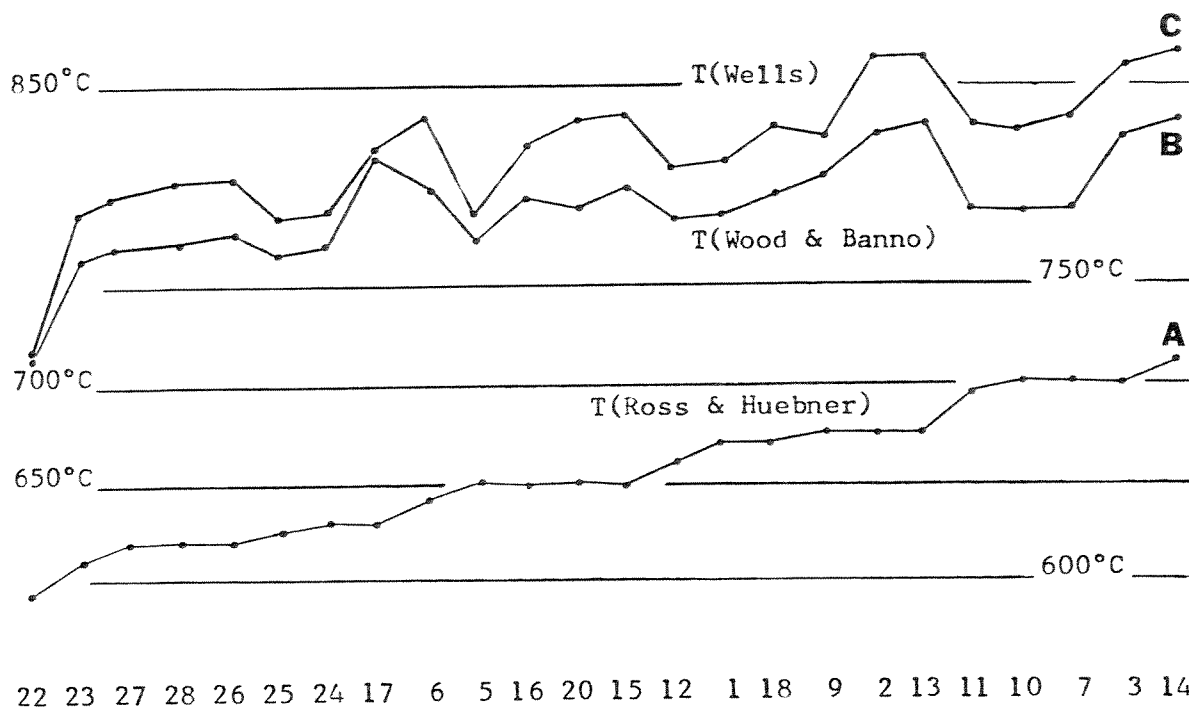
Most pyroxene experimental studies have been carried out for pure end member systems. A number of workers such as Nehru and Wyllie, 1974; Nehru, 1976; Holland et al., 1979; Lindsley and Dixon, 1976; Saxena and Nehru, 1975; Mori and Green, 1975, 1976, have studied synthetic, iron-free pyroxene systems and these have provided valuable information on conditions of pyroxene formation. Unfortunately, these systems are strongly affected by the presence of iron and will not be considered here. Also, it has been shown that significant effects on the equilibrium coexistence of natural pyroxenes may be exerted by minor components such as Mn, Na, Ti, Fe^{3+} , Cr and Al (Herzberg and Chapman, 1976; Boyd and Nixon, 1973). Consequently, pyroxene temperature determinations in this study were made with geothermometers which consider these components. Ross and Huebner's (1975) graphic pyroxene geothermometer is based on older experimental data, on new heating experiments involving lunar as well as terrestrial orthopyroxenes (which contain minor elements and exhibit augite lamellae) and on an isotherm for metamorphic pyroxenes. The temperature at which pigeonite first appeared in the orthopyroxene host was determined after rapid quenching. The pyroxene quadrilateral could thus be used to show isotherms and three-phase triangles. Wood and Banno's (1977) geothermometer is an empirical relation of activities, compositions and temperatures and assumes that the M_1 site is occupied by Al, Cr, Ti and Fe^{3+} , M_2 by Ca, Na and Mg and that $(\text{Fe}/(\text{Fe} + \text{Mg}))\text{M}_1 =$

$(\text{Fe}/\text{Fe} + \text{Mg})_{\text{M2}}$. Based on Wood and Banno's thermometer, Wells (1977) has also fit experimental data to an empirical linear relation which, according to Wells, compensates for inaccuracies in the Wood and Banno thermometer due to disequilibrium in Mg-rich compositions.

Tightly clustered clinopyroxene probe determinations plotted on the pyroxene quadrilateral (see Appendix D) were averaged and Ross and Huebner (1975) pyroxene temperatures graphically determined. If the points did not cluster well, the low temperature portion was averaged and used for the point plot. Wells (1977) and Wood and Banno (1977) temperatures were determined with the computer program PXTEMP, written by R. H. Hewins. All data from Table 2 (Appendix F) were used in these two geothermometric calculations.

Inspection of temperatures ($T_{\text{Ross and Huebner}}$, T_{Wells} , and $T_{\text{Wood and Banno}}$) (Figs. 5-7) based on average compositions suggests no obvious metamorphic gradient across the Adirondack Lowlands except for low Ross and Huebner temperatures in the vicinity of Colton. Some field localities exhibit disparate temperatures because two or more specimens were studied from each of those places. A comparison of sequentially increasing $T_{\text{(Ross and Huebner)}}$ with $T_{\text{(Wood and Banno)}}$ and $T_{\text{(Wells)}}$ (Fig. 9A, 9B, 9C) shows the Ross and Huebner temperatures (mean = 655.00°C) approximately 135°C and 165°C lower than those of Wood and Banno (mean = 789.08°C) and Wells (mean = 817.71°C) respectively, with $T_{\text{(Wood and Banno)}}$ closely mimicing $T_{\text{(Wells)}}$, but not $T_{\text{(Ross and Huebner)}}$. What is suggested here is that a relationship apparently exists between $T_{\text{(Ross and Huebner)}}$, $T_{\text{(Wood and Banno)}}$ and $T_{\text{(Wells)}}$. $T_{\text{(Wells)}}$ is always greater than $T_{\text{(Wood and Banno)}}$, yet both are significantly greater than $T_{\text{(Ross and Huebner)}}$. A change in

Fig. 9. A. Graph of $T(\text{Ross and Huebner})$ as determined for pyroxenes from the Adirondack Lowlands. Specimen numbers (see Fig. 3) form the abscissa and are arranged so as to produce sequentially increasing temperatures. B and C. $T(\text{Wood and Banno})$ and $T(\text{Wells})$ plots, respectively, with the same arrangements of specimen numbers. Note the coherent aspect of these plots. D and E. Plots of sequential increments of $T(\text{Wells})$ and $T(\text{Wood and Banno})$, respectively, produced by rearrangement of specimen number sequence. Accompanying plots (F and G) appear to be less coherent than B and C.



the numerical sequence of specimen numbers in the abscissa causes $T_{\text{(Wells)}}$ (Fig. 9D) to increase more uniformly than the Ross and Huebner temperatures, and another change causes the Wood and Banno temperatures to increase even more smoothly (Fig. 9E), but the parallel nature of the accompanying temperature curves (Fig. 9F, 9G), as seen in Fig. 9B, 9C, is lost.

Figures 10, 11, and 12 are plots of temperature versus temperature for the three pyroxene geothermometers. The last, that between $T_{\text{(Wells)}}$ and $T_{\text{(Wood and Banno)}}$, exhibits the best linear relationship because of the similar theoretical approach.

As previously mentioned, Hewins (1975) discussed a sequential increase of pyroxene temperatures in the granulite facies, away from the orthopyroxene isograd, in the Broken Hill granulites of New South Wales. A plot of temperature for the three pyroxene geothermometers versus distance from DeWaard's (1969a) orthopyroxene isograd (Fig. 13) shows a decrease in temperature as the distance increases. This is in direct contradiction to Engel and Engel's (1958, 1962a) estimate of the temperature gradient, from Emeryville to Colton, as determined by the geothermometers which they employed, although at Colton they proposed a temperature of 625°C which matches those presented here (620°C , T_{Ross} and Huebner). Engel and Engel's (1962a) proposed thermal sequence for the least altered amphibolite layers as they are traced across the Lowlands is as follows;

- 525°C Least altered amphibolite at Emeryville. Volume percent is; qtz 10%, andesine 20%, hbl 68%, ilm + pyt 2%.
- 540°C First appearance of green clinopyroxene near Emeryville.
- 575°C First appearance of pink orthopyroxene near East Edwards.

Figs. 10, 11, 12. Graphs of T versus T for the Ross and Huebner, Wood and Banno, and Wells geothermometers as applied to pyroxenes from the Adirondack Lowlands. The following statistical data have been derived for the following comparisons;

10. T(Ross and Huebner) versus T(Wood and Banno).
11. T(Ross and Huebner) versus T(Wells).
12. T (Wood and Banno) versus T(Wells).

	Regression equation	Standard deviation
10.	$Y = 419 + 0.565 X$	19.43 with 22 degrees of freedom
11.	$Y = 294 + 0.800 X$	21.19 with 22 degrees of freedom
12.	$Y = -127 + 1.200 X$	10.44 with 22 degrees of freedom

	Coefficient of determination = r^2	Correlation coefficient = r
10.	$r^2 = 45.8\%$ adjusted for 22 d. f.	$r = 0.677$
11.	$r^2 = 59.2\%$ adjusted for 22 d. f.	$r = 0.769$
12.	$r^2 = 90.1\%$ adjusted for 22 d. f.	$r = 0.949$

	Variance ratio = F	t-ratio for $\underline{b}$
10.	$F = 20.413$	$t = 4.52$
11.	$F = 34.431$	$t = 5.87$
12.	$F = 201.603$	$t = 14.51$

Since r is greater than $r(22/0.010) = 0.492$ for all comparisons, there is a real correlation between the temperatures determined by the different geothermometers. All determined F values are much greater than $F(1/22 / 0.05) = 4.30$. Thus, there is a highly significant dependence between the temperatures determined by the different geothermometers. That is, the variation due to regression is significantly greater than the variation from regression. Also, the t-ratio for the regression coefficient $\underline{b}$ for the different comparisons is larger than $t(22/0.025) = \pm 2.074$. Again, there is a statistically significant relationship between the temperatures for the compared geothermometers.

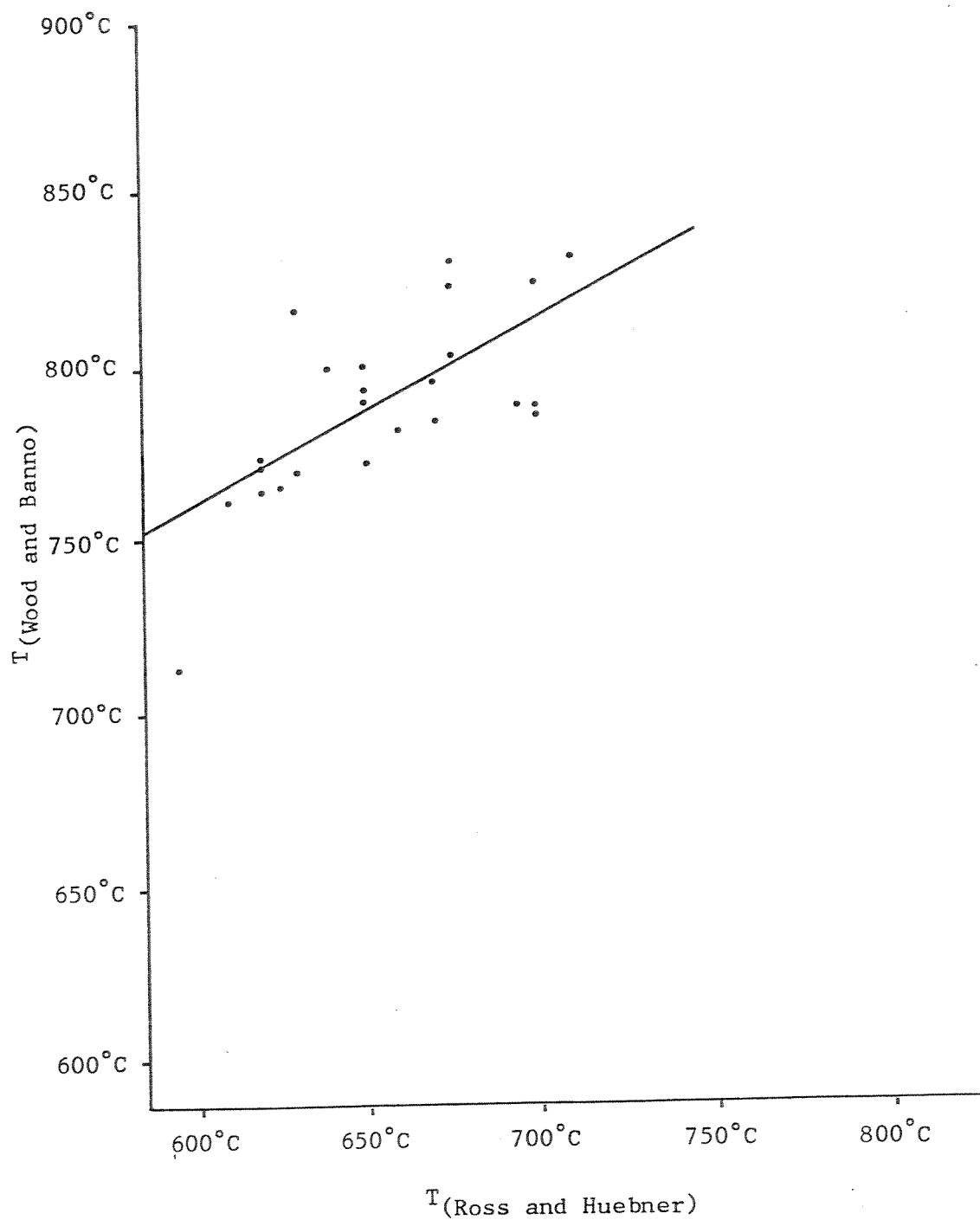


Fig. 10. Plot of $T(\text{Ross and Huebner})$ versus $T(\text{Wood and Banno})$. The solid line represents the least-squares fit of the data points.

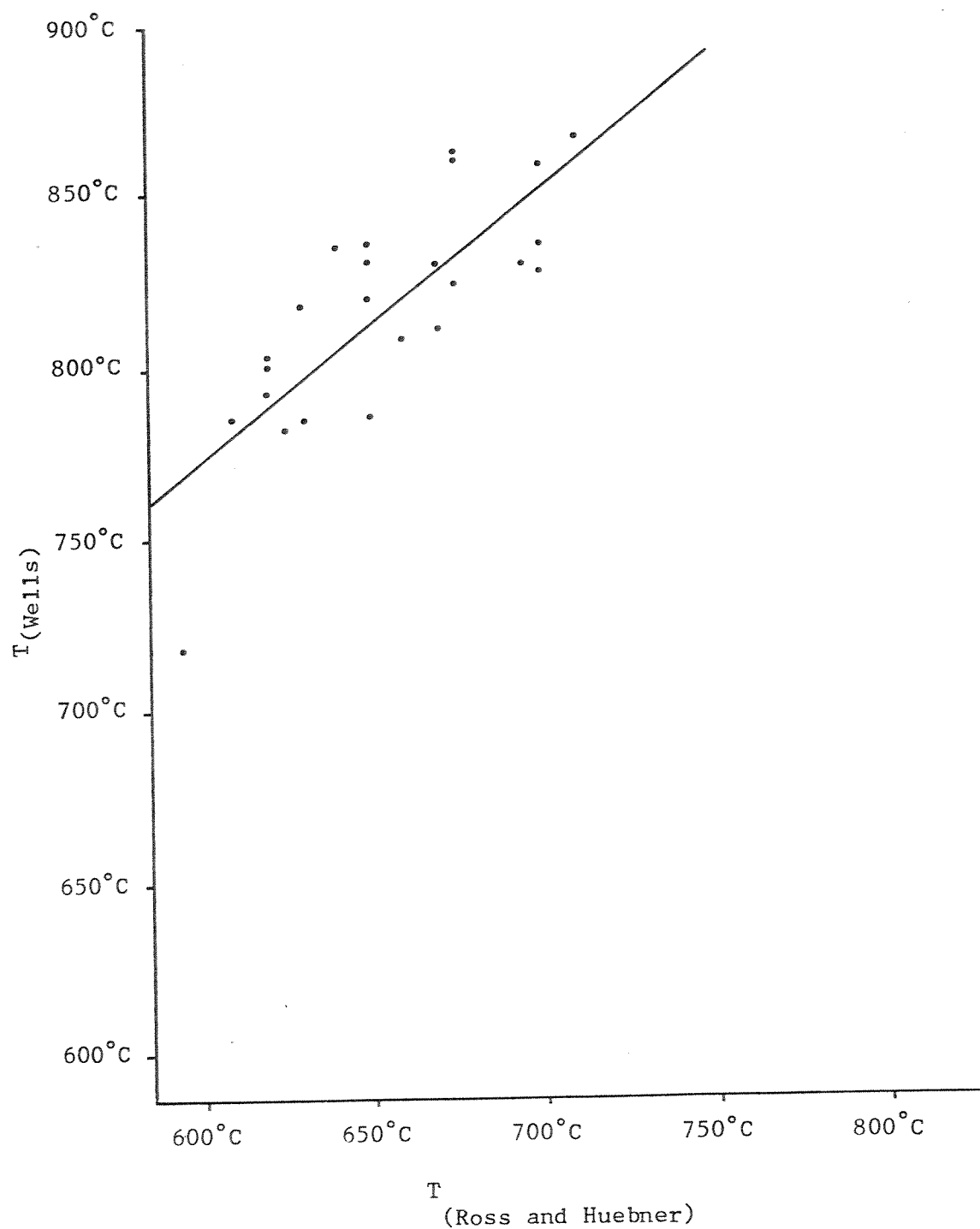


Fig. 11. Plot of $T_{\text{(Ross and Huebner)}}$ versus $T_{\text{(Wells)}}$. The solid line represents the least-squares fit of the data points.

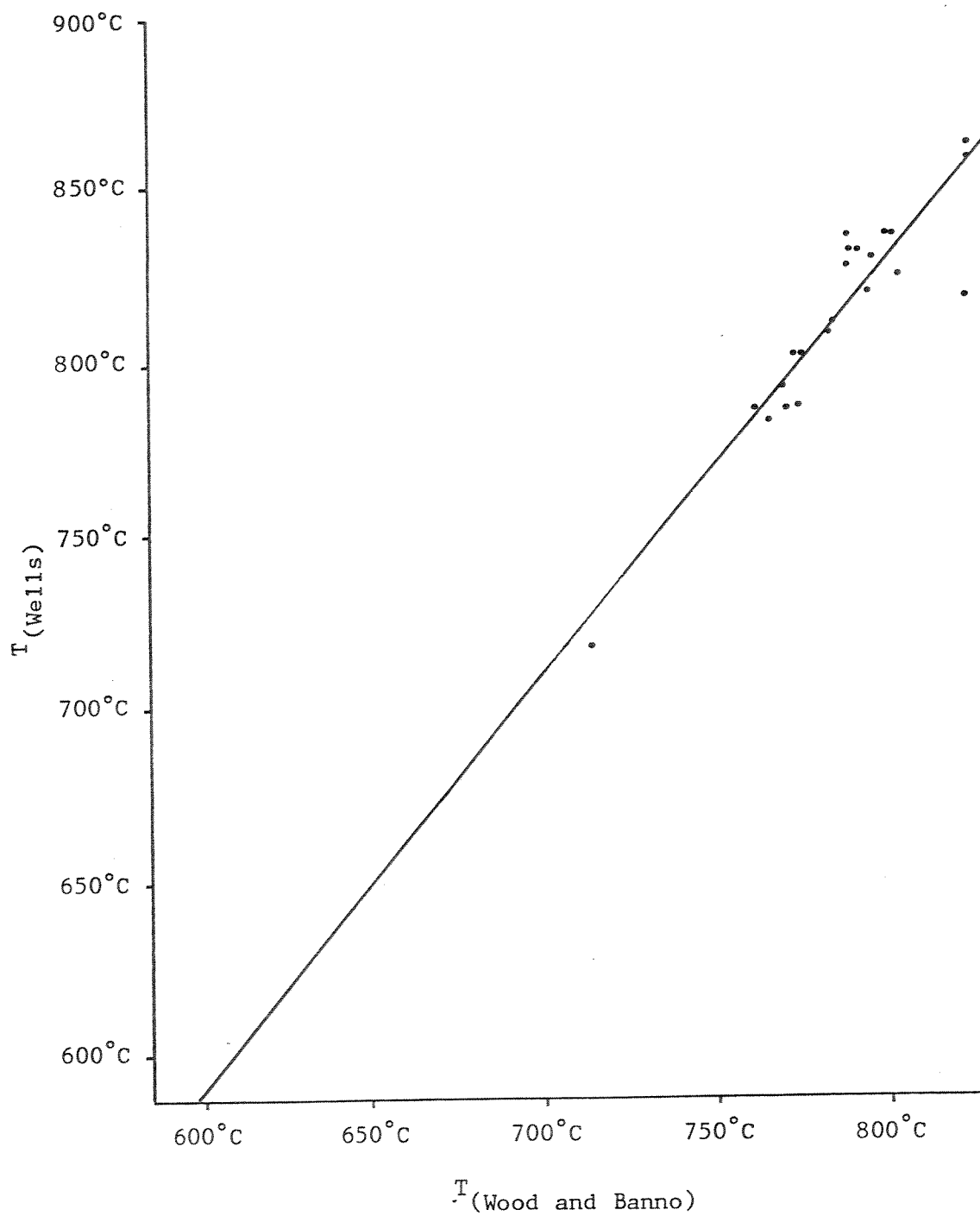
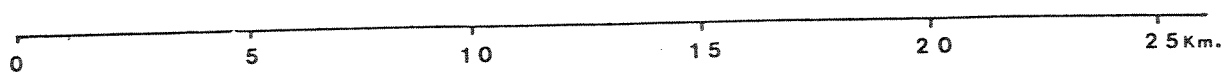
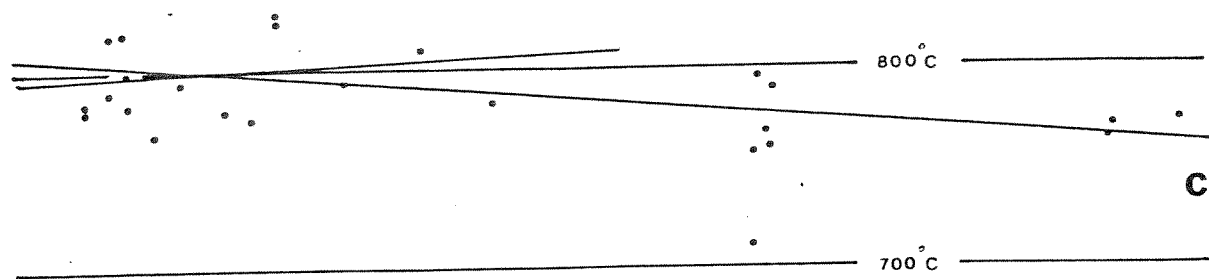
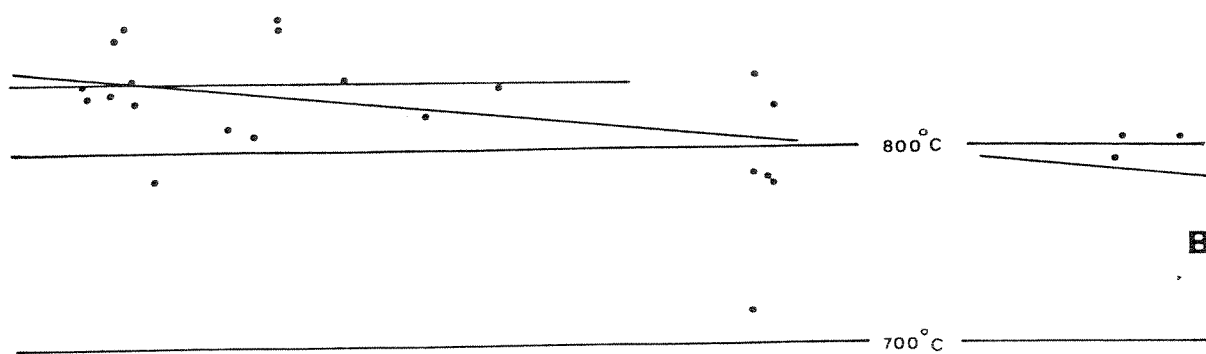
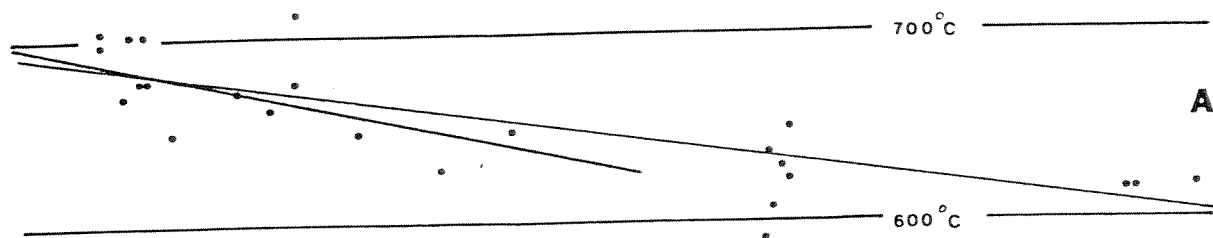


Fig. 12. Plot of $T_{\text{(Wood and Banno)}}$ versus $T_{\text{(Wells)}}$. The solid line represents the least-squares fit of the data points.

Fig. 13. Plot of T(Ross and Huebner), T(Wells), and T(Wood and Banno) (A, B, C, respectively) versus distance in kilometers from DeWaard's (1969a) orthopyroxene isograd. Lines represent the least-squares fit of data points have been entered for all data points and for those between the orthopyroxene isograd to a distance of 11 kilometers. The following statistical analyses have been determined for; 1) all data points, 2) those between the isograd and a distance of 11 kilometers.

1)		2)	
Regression equation			
A.	$Y = 688 - 3.31 X$		$Y = 696 - 5.12 X$
B.	$Y = 840 - 2.22 X$		$Y = 834 - 0.11 X$
C.	$Y = 806 - 1.70 X$		$Y = 797 + 1.04 X$
Standard deviation			
A.	19.24 with 22 d. f.		18.98 with 13 d. f.
B.	28.69 with 22 d. f.		23.80 with 13 d. f.
C.	23.13 with 22 d. f.		19.70 with 13 d. f.
r^2 adj. for 22 d. f.		r^2 adj. for 13 d. f.	
A.	64.7%		34.2%
B.	25.3%		-7.7%
C.	23.1%		-5.1%
r		r	
A.	0.804		0.584
B.	0.503		0.278
C.	0.481		0.226
F t-ratio for $\underline{b}$		F t-ratio for $\underline{b}$	
A.	43.250 -6.58		8.270 -2.88
B.	8.775 -2.96		0.002 -0.05
C.	7.918 -2.81		0.315 0.56

These analyses suggest a strong correlation between T(Ross and Huebner) and the distance from the orthopyroxene isograd both for all data points and those between zero and 11 kilometers. The least-squares lines for the Ross and Huebner temperatures exhibit the steepest slopes as well as the smallest difference in slope.



625°C Least altered amphibolite at Colton. Volume percent is; calcic andesine 39%, hbl 22%, cpx 21%, opx 14%, ilm + pyt 2%.

Similar temperatures across the Lowlands were determined by Engel and Engel (1958) for the enclosing least altered gneiss (see Table 3). These temperatures were based on older geothermometers such as the Ti content of magnetite associated with ilmenite (Buddington et al., 1955), the amount of Mg in solid solution with calcite (Graf and Goldsmith, 1955), solid solution of paragonite in muscovite (Eugster and Yoder, 1955), FeS content of sphalerite (Kellerud, 1953), albite in coexisting K feldspar and plagioclase (Barth, 1956), and the O^{18}/O^{16} ratio in coexisting quartz and magnetite (Clayton and Epstein, 1958).

Nielsen (1971), working to the west of the orthopyroxene isograd, reported that at the isograd metamorphic temperatures may have ranged from 640°C to 720°C, and the partial pressure of water may have ranged from 4.7 to 6.6 kbars, respectively. These conditions were determined by the lowest temperature at which the granite system begins to melt and sillimanite is stable, to the highest temperature at which muscovite reacts with quartz to produce sillimanite (Guidotti, 1970). Since P_{H_2O} was probably much less than the total pressure, Nielsen determined that the pressure-temperature conditions in the granulite facies of the Lowlands, near the orthopyroxene isograd, probably where $680 \pm 30^\circ\text{C}$ and P_{total} was 6.5 ± 0.3 kbars (see Table 3). These temperatures match almost exactly those determined here (660°C to 710°C) using the Ross and Huebner geothermometer for pyroxenes in the Hermon quadrangle which are relatively close to the orthopyroxene iso-

Emeryville Northwest Lowlands	Amphibolite (No linear isograds Nielsen, 1971)	Engel and Engel (1958, 1962a)	Buddington and Lindsley (1964) Buddington et al. (1955) Buddington (1963, 1965)
Colton Adirondack Massif	mus- sil- alm ? sil- K-spar- alm	525-540 $\pm$ 50°C, 2 kbar-5 miles garnet isograd	Zone A — 500-550°C Isograd 1
	Hornblende granulite ↓ (Some inter- mingled pyroxene granulite, Buddington, 1965; DeWaard, 1967)	575°C — orthopyroxene isograd — - muscovite - sphene 3 kbar-7 miles 625 $\pm$ 50°C	Zone B Isograd 2, 2a — 550-625°C paragneiss orthogneiss
Central Highlands			Zone C Isograd 3 Zone D — 600-640°C Isograd 4 Zone E — 635-665°C
			650°C

Table 3. Comparison of previous work in the Adirondack Highlands and Lowlands.

DeWaard (1967, 1969a)	Nielsen (1971)	Stoddard (1976a, 1980)	Hoffman and Essene (1978)
Northwest Lowlands	(Paleozoic cover) 640°C, 4.7 kbar P_{H_2O}		
690°C, 1.7 kbar P_{H_2O} 5.5 kbar P_{load}	garnet isograd		
700°C OPX isograd	720°C, 6.6 kbar P_{H_2O}	muscovite "isograd"	OPX "isograd" 25 km wide 650 ± 50°C, 10 ^{3.2 ± 0.5} fH ₂ O
Adirondack Massif	(Lowlands near Colton) 590-610°C (Highlands near Colton) 660°C	(Lowlands near Colton) 730 ± 30°C 5 ± 1 kbar P_{lith} 1.5 ± 1 kbar P_{H_2O} 10 ⁻¹⁵ - 10 ⁻¹⁸ fO ₂ (725 ± 50°C, 4.5-5.5 kbar, 1980)	
760°C, 10 kbar P_{load}			
Central Highlands 800°C, P_{H_2O} P_{load}			

Table 3 (contd.).

Valley and Essene (1980)	Bohlen and Essene (1977a) Bohlen et al. (1980)	Bohlen and Essene (1979b)	Gorycki (1981) (this paper)
Northwest Lowlands			
650 $\pm$ 30°C (Balmat) 6.5 $\pm$ 1 kbar (various geothermometers)	510°C (feldspars) 620°C (oxides) 650°C near Colton	pyroxenes near Colton 795°C (Wood and Banno) 825°C (Wells)	685°C ↓ 620°C OPX isograd Lowlands pyroxenes (Ross and Huebner) 6.5 kbar (Hoffman and Essene, 1978), P increases toward massif.
Adirondack Massif	760°C (feldspars) 780°C (oxides) 700-750°C (1980)		
Central Highlands (kyanite, ackermanite) Saranac Lake 750°C, 8 $\pm$ 1 kbar	800°C $\pm$ 30°C P < 9 kbars 750-800°C (1980)		

Table 3 (contd.).

grad and far from the axial trace of the Lowlands nappe (see Figs. 3 and 5).

Stoddard's (1976a) early estimates of pyroxene temperatures for the Colton area, as determined by the Ross and Huebner geothermometer, are higher than those presented here, ranging from 700°C to 750°C. However, a plot on the Ross and Huebner geothermometer of Stoddard's clinopyroxene En, Fs, and Wo average compositions, taken from his Tables 19 and 27 (Stoddard, 1976a), produces temperatures which range rather uniformly from 550°C to 760°C, with an average value, for nine specimens, of 655°C. The disparity in temperatures may have been due to a plotting problem because Stoddard (1980) later revised downward the Ross and Huebner temperatures to 650°C to 750°C. Stoddard's (1976a, 1980) Wood and Banno temperatures (725°C to 800°C) bracket those presented here (769°C, 772°C, 774°C) for the Colton area. The same is true for his Wells temperatures (730°C to 850°C) compared to those present here (793°C, 801°C, 802°C) (see Figs. 6 and 7).

Stoddard also utilized element partitioning based on experimental, theoretical, and empirical calibration of exchange equilibria for orthopyroxene-clinopyroxene, garnet-cordierite, garnet-biotite, Fe-Ti oxides, calcite-dolomite, and feldspars to estimate metamorphic conditions in the Colton area. He concluded (Stoddard, 1979) that these conditions were; $T = 730 \pm 30^\circ\text{C}$, $P_{\text{lith}} = 5 \pm 1 \text{ kbar}$, $f_{\text{O}_2} = 10^{-15}$ to 10^{-18} bar , $P_{\text{H}_2\text{O}} = 1.5 \pm 1 \text{ kbar}$ (see Table 3). Stoddard (1976a) combined phase equilibria curves for the various pertinent systems in a single diagram to block in the conditions at Colton, but later admitted (Stoddard, 1980) that his pressure estimate was not very well constrained and was approximately 1.5 kbars lower, and his tempera-

ture estimates about 75°C higher, than various estimates presented by others (Bohlen and Essene, 1977a; Essene et al., 1977, 1978; Valley and Bohlen, 1979; Brown et al., 1978) for the Adirondack Lowlands. He also ascribed to Buddington's (1963) placement of isograds.

Buddington (1963, 1965) estimated temperatures for the five metamorphic zones extending into the Adirondack Highlands based on Fe-Ti oxides (Buddington and Lindsley, 1964) which are in accordance with those presented by Engel and Engel for the Lowlands (see Table 3). Later, DeWaard (1967) indicated that the temperature estimates of Engel and Engel (1958, 1962a) were 150°C too low. In an elegant argument using some of the field evidence presented by Engel and Engel (1962a), DeWaard makes use of the breakdown (dehydration) curve of muscovite in the presence of quartz (Yoder and Eugster, 1955; Segnit and Kennedy, 1961; Evans, 1965) and the melting curve of the granite system (Tuttle and Bowen, 1958; Luth et al., 1964). These curves intersect at about 690°C at a P_{H_2O} of approximately 1.7 kbars, conditions in the field represented at the garnet isograd in the gneiss where muscovite begins to react and in which aplitic, venitic migmatites have developed. This is about three kilometers downgrade from the orthopyroxene isograd and so DeWaard (1967) estimated a minimum of 700°C for the beginning of granulite facies metamorphism in the Lowlands. DeWaard described other experimental curves for granodiorite melting and for the intersection of estimated dehydration curves for natural biotite and hornblende and estimated a minimum of approximately 800°C at 1.5 kbar P_{H_2O} for granulite facies granodioritic migmatites within the Highlands.

The second set of experimental data utilized by DeWaard relates

the intersection of the extrapolated alkali feldspar solvus crest with the curve for the reaction; $\text{opx} + \text{plag} = \text{gar} + \text{cpx} + \text{qtz}$. His data suggested a temperature of at least 760°C and about 10 kbar $P_{\text{H}_2\text{O}}$ for the garnet-clinopyroxene isograd well within the massif (see Table 3). Additionally, DeWaard pointed out that Buddington and Lindsley's (1964) temperature estimates based on the titaniferous magnetite-ilmenite geothermometer represents the late stage metamorphic condition during which the oxide minerals reequilibrated upon cooling. He cites Vincent and Phillips (1954) whose temperature estimates determined from oxide minerals in gabbros of the Skaergaard complex are about 200°C lower than temperatures determined by other methods.

As mentioned earlier, Bohlen and Essene (1977a) and Bohlen et al. (1980) have presented a thermal structure for the entire Adirondacks (see Fig. 5). It is independently based on reintegrated exsolution lamellae; albite in K feldspar coexisting with plagioclase (510°C to 760°C), and ilmenite in magnetite in coexisting iron-titanium oxides (620°C to 780°C), principally in anorthosite and charnockitic rocks, with the highest temperatures in the center of the massif at Saranac Lake. Because of the close matching of feldspar and oxide temperature determinations from unmelted rocks such as anorthosite and amphibolite and locally closely associated partially melted charnockite-mangerite and kinzigite, Bohlen et al. (1980) suggested that the temperatures inferred from felsic rocks do not represent the solidi of magma but are instead peak or near peak metamorphic temperatures. They also noted that the data of Brown and Fyfe (1970) and Wyllie (1977) indicate that the melting of relatively dry biotite-bearing granitic and dio-

ritic rocks begins at temperatures 30°C to 50°C above nearly all oxide and feldspar temperatures determined by Bohlen and Essene (1977a).

Pressure estimates based on a variety of self-consistent systems such as the ubiquity of sillimanite in the Lowlands, one occurrence of kyanite in Blue Mountain quadrangle near the center of the massif (Boone, 1978), sphalerite barometry at Balmat (Brown et al., 1978) and occurrences of iron-rich orthopyroxene and fayalite + quartz in the Highlands (Jaffe et al., 1978; Bohlen et al., 1979), show a regional increase from $650 \pm 30^{\circ}\text{C}$, 6.5 ± 1 kbar at Balmat to more than 750°C , 8 ± 1 kbar at Saranac Lake (Valley and Essene, 1980) (see Table 3). Valley and Bohlen (1979) estimated the T-P path for Adirondack metamorphism to follow a line very near, and roughly parallel to, the kyanite-sillimanite boundary with a slope of approximately $20 \text{ bar}/^{\circ}\text{C}$.

The Ross and Huebner temperatures presented here also closely match the 650°C isotherms determined by Bohlen and Essene (1977a, 1979b) from oxide and feldspar data. Those temperatures above 650°C on the low temperature side of the 650°C isotherm (see Fig. 5) are numerically closer than Hoffman's (1979) Wood and Banno temperatures for a similar portion of the Lowlands as presented by Bohlen and Essene (1979b). Since the Ross and Huebner geothermometer was calibrated for metamorphic pyroxenes, it is probably the best thermometer for pyroxenes with fairly low concentrations of minor elements, formed at low temperatures and low (to moderate) pressures. It is interesting that the Ross and Huebner pyroxene temperatures show a much clearer decrease away from the orthopyroxene isograd than those based on the other methods. Some possible explanations for the decrease are; 1)

decreasing water pressure towards the massif, 2) slower cooling and more equilibration near the massif, both of which conditions would cause a real decrease in pyroxene temperatures. Apparent decreases in pyroxene temperatures could be caused by; 3) pressure increases away from the orthopyroxene isograd and toward the massif. As shown by Mori and Green (1975), increased pressure causes the enstatite-diopside solvus to be slightly widened at 900°C and below. Wilson (1976) has shown that the Al content of coexisting pyroxenes and the Na in clinopyroxenes increase (with no significant temperature difference) from a low to a high pressure locality in mafic granulites in the Frazer Range of Western Australia. Also, in the high pressure locality, the Al content in the pyroxenes was more nearly independent of the Al content of the host rock. In addition, Boyd (1970) has shown that increased Al_2O_3 in solid solution with $\text{CaSiO}_3 - \text{MgSiO}_3$ stabilizes a wider solvus which also lowers equilibration temperatures. As discussed below, concentrations of aluminum, Al^{VI} , sodium and titanium in augite, and aluminum in orthopyroxene from the Adirondack Lowlands increase away from the orthopyroxene isograd of DeWaard (1969a). These would tend to widen the miscibility gap and result from an increase in pressure away from the isograd. Also, the increase in pressure would in itself tend to widen the gap.

Since the effect of a wider miscibility gap in the solvus has not been calibrated in the Ross and Huebner thermometer, the increase in minor elements away from the orthopyroxene isograd might also account for the decrease in Ross and Huebner pyroxene temperatures. The Wells and Wood and Banno methods, though inaccurate because they have been extrapolated down temperature, do consider the effects of minor ele-

ments by formulating the activities of Mg, Fe, and Ca. Therefore, the flatter gradients seen in Figs. 13B and 13C may have resulted from these thermometers correcting for the Al effect. This decrease in pyroxene temperatures does not match the general increase in temperature toward the Adirondack Highlands as inferred from feldspar and oxide data, reported by Bohlen and Essene (1977a, 1979b). However, Bohlen and Essene took great pains to obtain peak metamorphic temperatures (Bohlen et al., 1980) rather than temperatures of final equilibration (which would be very low). Thus, there need not be any conflict between the two sets of results. Additionally, the pyroxenes in the Adirondack Lowlands may have acted as "speedometers", not faithfully recording the initial, maximum temperature of the Grenvillian thermal event.

All of the evidence presented by Bohlen, Essene, and others strongly suggests metamorphic conditions in the Adirondack Lowlands to have peaked at approximately $650 \pm 50^\circ\text{C}$, with $P_{\text{total}} = 6.5 \pm 1$ kbar (see Table 3). Also, pressure and temperature determinations indicate an increasing gradient toward the center of the massif.

Distribution Coefficient (K_D) and Pyroxene Compositions

As previously mentioned, Bohlen and Essene (1979a, 1979b, 1980) have found a great variation in the distribution coefficient of several coexisting mineral pairs from various lithologies across the Adirondack region. K_D data for orthopyroxene-clinopyroxene yielded temperatures ranging from 400°C to 1000°C using Howie's (1965) empirical calibration. Consequently, Bohlen and Essene considered Fe-Mg partitioning, in general, to be less than useful as a geothermometric

indicator for natural systems. It should be noted, however, that the distribution of Fe^{2+} and Mg between any two coexisting ferromagnesian minerals not only depends on pressure and temperature, but also on mineral composition which may reflect non-ideal solid solution or competition by other cations for the Fe^{2+} and Mg pyroxene structural sites. Kretz (1963), examining a compilation of K_D determinations for coexisting pyroxenes, reported a similar spread for both igneous (1.16 - 1.54) and metamorphic (1.54 - 1.96) pyroxenes, but found that the latter were distinctly higher. Maxey and Vogel (1974) have shown that K_D is not only dependent on the temperature of crystallization and on pyroxene composition, but also on total rock composition. Maxey and Vogel defined K_D as;

$$K_D = \frac{X_{\text{Fe}^{2+}}^{\text{opx}} (1 - X_{\text{Fe}^{2+}}^{\text{cpx}})}{X_{\text{Fe}^{2+}}^{\text{cpx}} (1 - X_{\text{Fe}^{2+}}^{\text{opx}})} = \frac{\left(\frac{\text{Fe}^{2+}}{\text{Mg}}\right)_{\text{opx}}}{\left(\frac{\text{Fe}^{2+}}{\text{Mg}}\right)_{\text{cpx}}} = \frac{\left(\frac{\text{FeO}}{\text{MgO}}\right)_{\text{opx}}}{\left(\frac{\text{FeO}}{\text{MgO}}\right)_{\text{cpx}}} \approx \frac{\left(\frac{\text{FeO}^*}{\text{MgO}}\right)_{\text{opx}}}{\left(\frac{\text{FeO}^*}{\text{MgO}}\right)_{\text{cpx}}}$$

where FeO^* = total iron as FeO. They preferred the last formula because of the lack of FeO data in the literature. Other authors have used inverted formulae which yield reciprocal values of K_D . Bohlen and Essene (1978), in a study of igneous pyroxenes from metamorphosed anorthosites determined K_D as;

$$K_D = \frac{\left(\frac{\text{Fe}^{2+}}{\text{Mg}}\right)_{\text{opx}}}{\left(\frac{\text{Fe}^{2+}}{\text{Mg}}\right)_{\text{cpx}}}$$

However, they found that results were not altered significantly if

total Fe + Mn, or total Fe was used. Consequently, Maxey and Vogel's (1974) formula for K_D has been used here.

In keeping with published data by Kretz (1963), K_D for coexisting pyroxenes from the Adirondack Lowlands (1.59 - 2.26) are similar to those in the literature and also distinctly higher than those reported from igneous rocks. An inspection of K_D versus pyroxene composition (Fig. 14) reveals that as K_D increases, there is a statistically significant increase in clinopyroxene MgO and a decrease in clinopyroxene FeO, TiO_2 , Na_2O , and Al_2O_3 and orthopyroxene Al_2O_3 . In a study of compositions of coexisting pyroxenes from a 20 X 35 mile area in the New Jersey Precambrian highlands, Maxey and Vogel (1974) found that as K_D for the pyroxenes increased, weight percent Al_2O_3 and MgO decreased and FeO increased, trends which are opposite to those in the Adirondack Lowlands for iron and magnesium. Orthopyroxene MgO and FeO trends for granulites from Broken Hill, New South Wales (Binns, 1962; Davidson, 1968) are steeper and opposite to those in New Jersey. Maxey and Vogel (1974) suggested that the New Jersey trends did not exhibit a systematic areal variation and are characteristic of Fe-poor pyroxenes as compared to the Australian trends which are characteristic of Fe-rich pyroxenes. Inspection of K_D versus pyroxene weight percent FeO and MgO in Fig. 14 partially confirms Maxey and Vogel's observations. That is, the pyroxenes from the Adirondack Lowlands are more Fe-rich and more Mg-poor than those from New Jersey.

Regression analysis of K_D versus distance in kilometers from DeWaard's (1969a) orthopyroxene isograd suggests a statistically significant correlation indicating that K_D decreases with distance

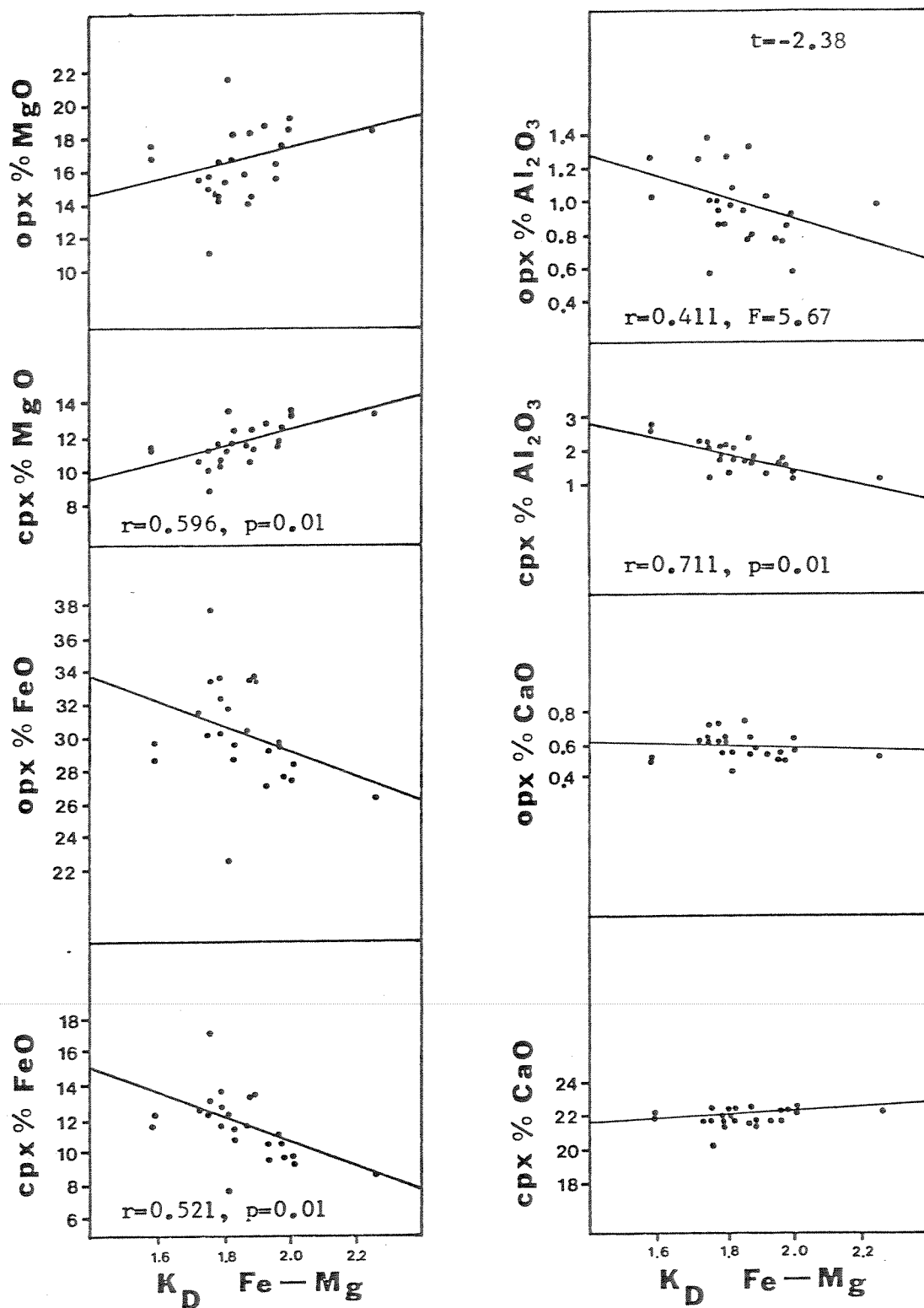


Fig. 14. Plot of pyroxene compositions versus K_D for amphibolites from the Adirondack Lowlands. The solid lines represent the least-squares fit of the data points. Regression analysis indicates a correlation between K_D and some oxide weight percents.

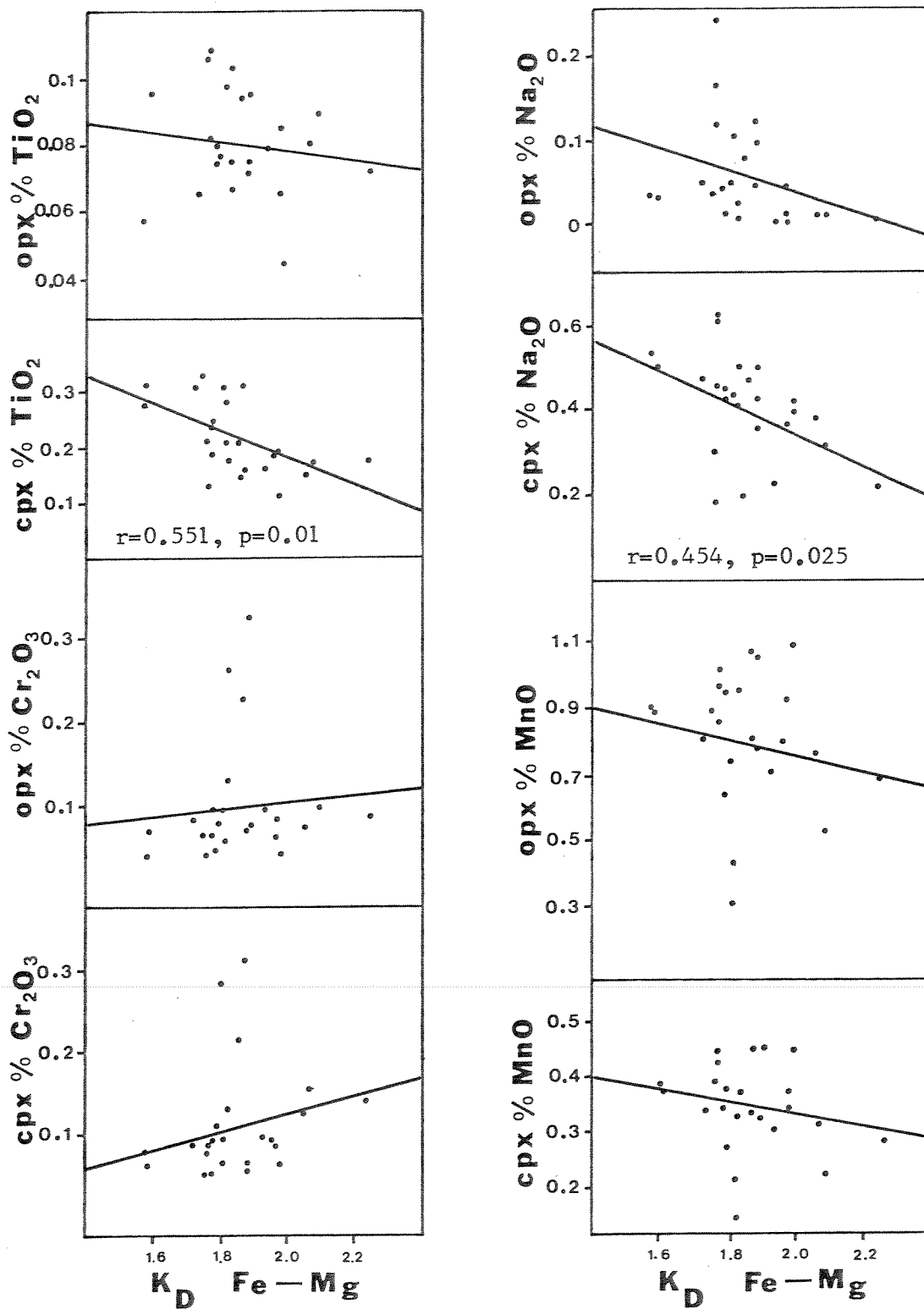


Fig. 14 (contd.).

(Fig. 15) and that element partitioning occurs even with no statistically significant variation in iron or magnesium with distance from the isograd. Based on this observation, weight percent TiO_2 , Al_2O_3 , Na_2O , Cr_2O_3 , FeO , CaO , MnO , and MgO from coexisting pyroxenes were plotted versus distance from the same isograd and subjected to regression analysis (Fig. 16). Statistically significant increases in clinopyroxene TiO_2 , Na_2O , Al_2O_3 and orthopyroxene Al_2O_3 with increasing distance from the orthopyroxene isograd apparently exist. This is similar to Wilson's (1976) observation that Al in coexisting pyroxenes and Na in clinopyroxene increase with increasing pressure and could, in part, explain (as previously discussed) the lower pyroxene temperatures away from the isograd. Assuming that $\text{Al}^{\text{IV}} = 2.00 - \text{Si}$, and $\text{Al}^{\text{VI}} = \xi \text{Al} - \text{Al}^{\text{IV}}$, there is also a statistically significant increase in the number of ions per formula unit of Al^{VI} (based on six oxygens) in the clinopyroxenes away from the orthopyroxene isograd (Fig. 17). Al^{VI} , which can substitute for the larger Mg or Fe^{2+} ions in octahedrally coordinated sites in the pyroxenes, implies a volume reduction. Since there is also an increase in weight percent clinopyroxene Na ("jadeite") (Fig. 16B), which is strongly pressure dependent, an increase in pressure away from the isograd is strongly suggested.

A comparison of Ross and Huebner pyroxene temperatures from the Adirondack Lowlands (Fig. 9A) with the plot of Al versus Ti as total atoms per formula unit for the same pyroxenes (Fig. 18) reveals that the high Ti, high Al clinopyroxenes tend also to be those from the low temperature end of the graph. Also, plots of Ti:Al for coexisting pyroxenes fall between 1:8 and 1:32 indicating considerable amounts of

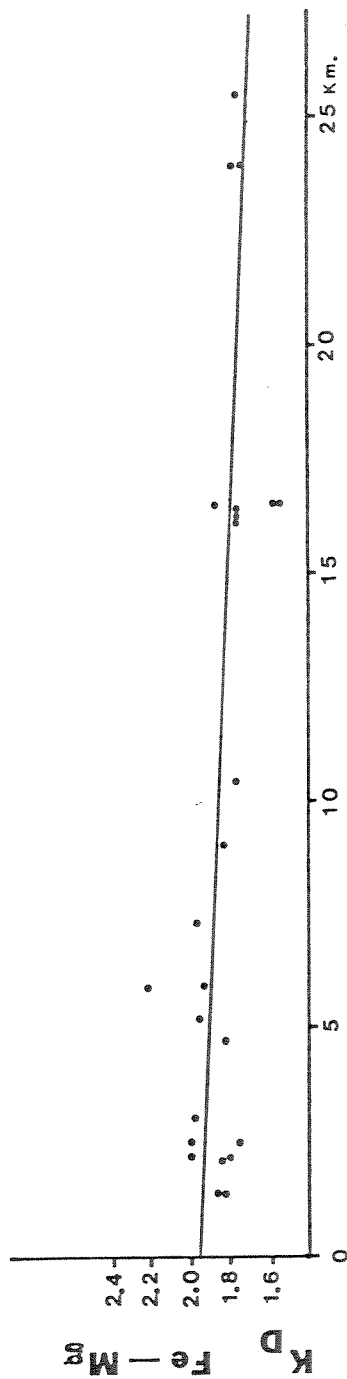


Fig. 15. Plot of K_D for coexisting pyroxenes from amphibolites from the Adirondack Lowlands versus distance in kilometers from DeWaard's (1969a) orthopyroxene isograd. The solid line represents the least-squares fit of the data points.

Regression equation; $Y = 1.96 - 0.014 X$ $r^2 = 27.6\%$ adjusted for 22 d. f. $F = -15.009$
 Standard deviation; 0.1275 with 22 d. f. $r = 0.525$ $t = -3.12$

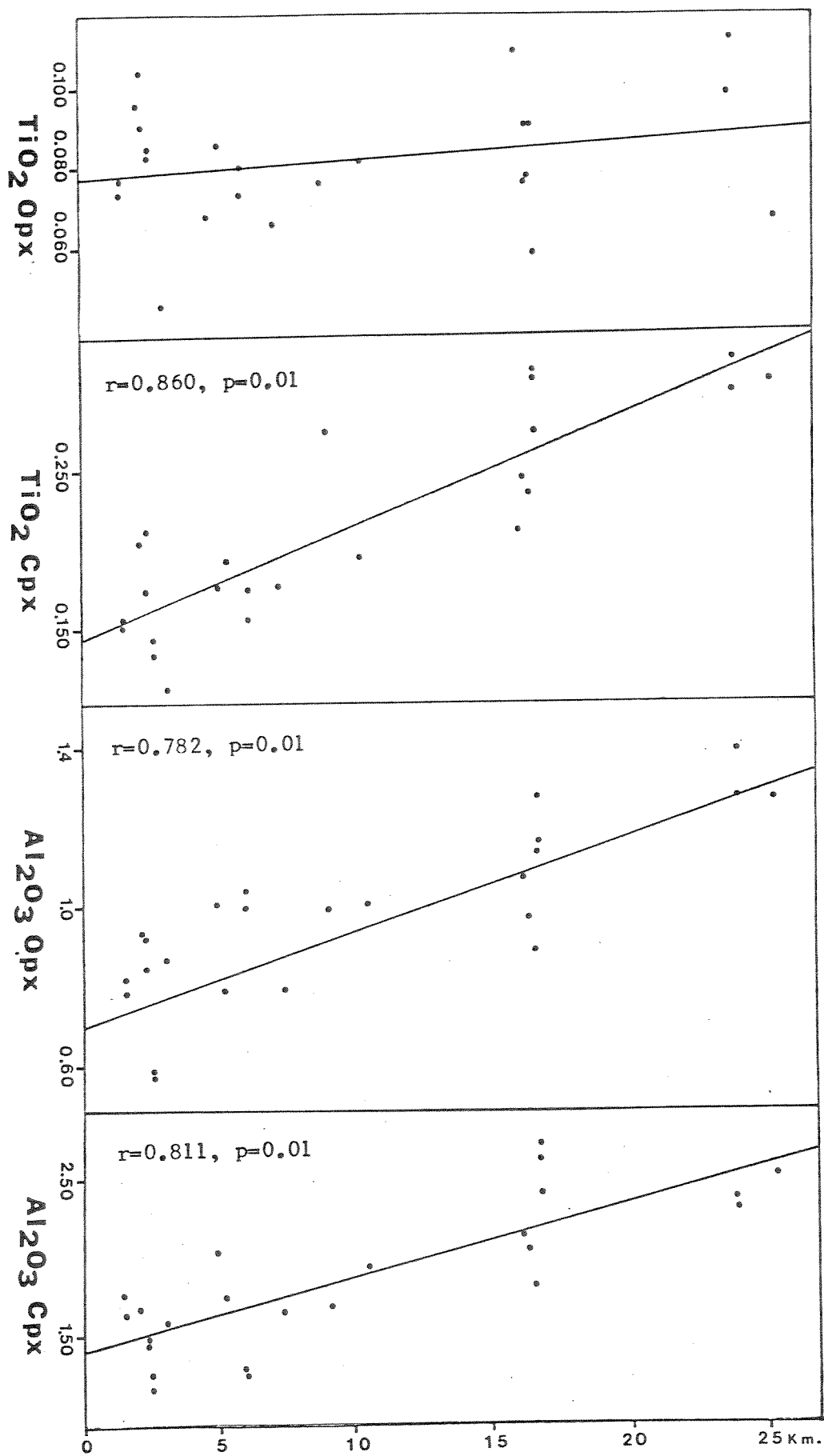
Since $r(22/0.010) = 0.492$, $F(1/22 / 0.05) = 4.30$, and $t(22/0.025) = +2.074$, there appears to be a strong, statistically significant correlation between K_D and distance from the orthopyroxene isograd.

Fig. 16. Plots of weight percent oxides for orthopyroxenes and clinopyroxenes coexisting in amphibolites from the Adirondack Lowlands versus distance in kilometers from DeWaard's (1969a) orthopyroxene isograd.

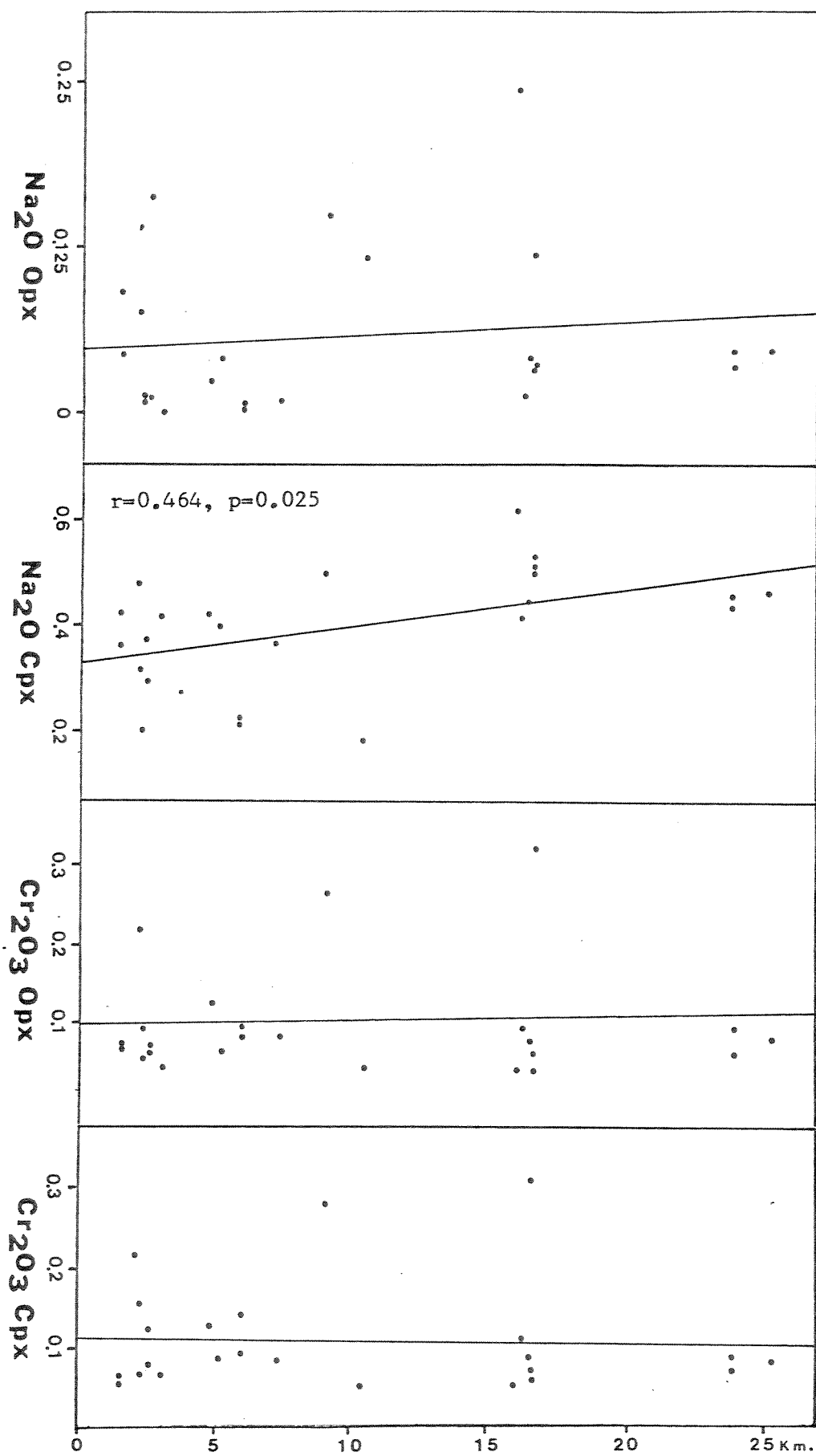
- A. TiO_2 and Al_2O_3
- B. Na_2O and Cr_2O_3
- C. FeO and CaO
- D. MnO and MgO

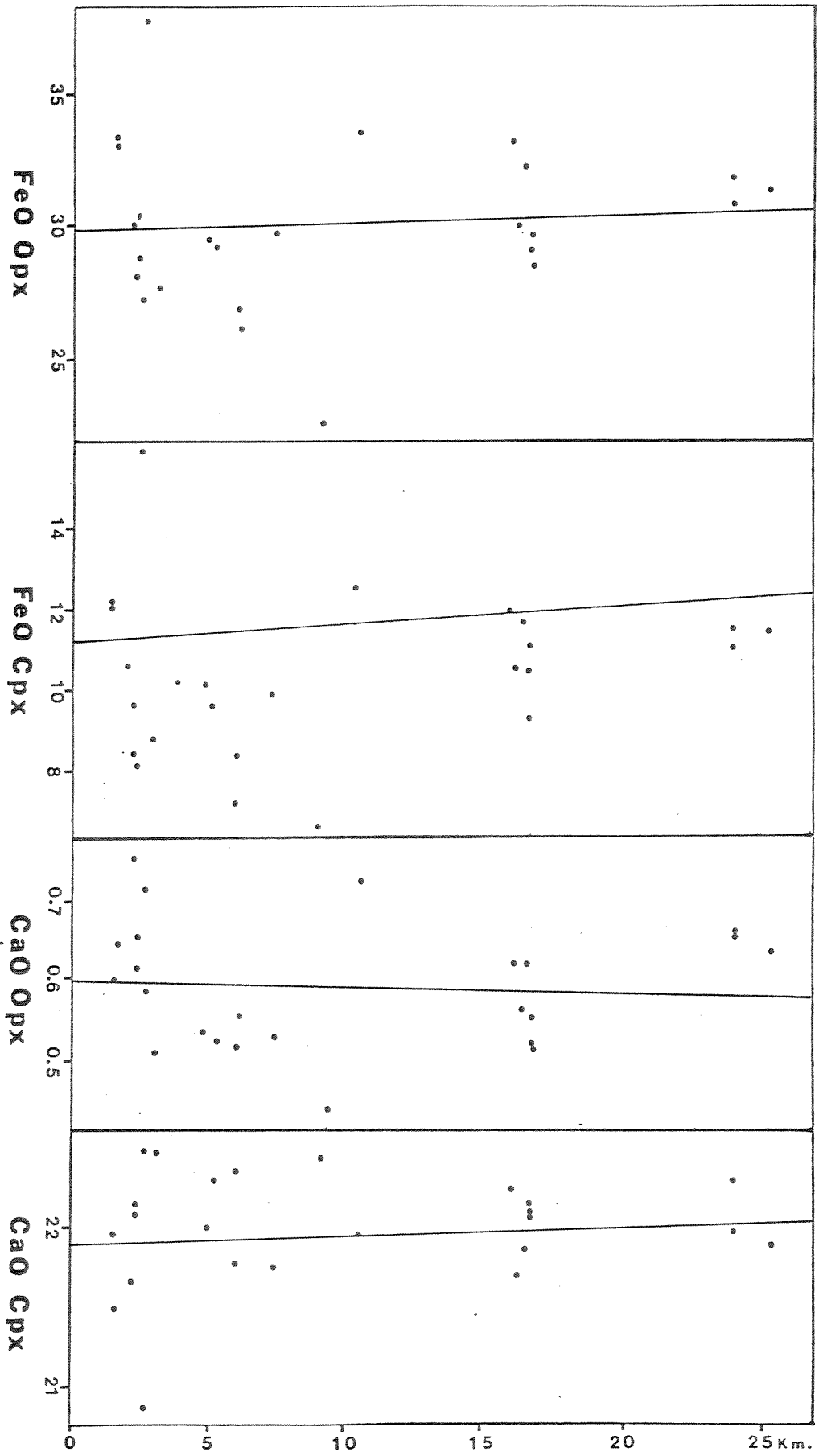
The solid lines represent the least-squares fit of the data points. Regression analysis indicates a statistically significant correlation between distance and clinopyroxene TiO_2 , Na_2O , Al_2O_3 , and orthopyroxene Al_2O_3 .

A



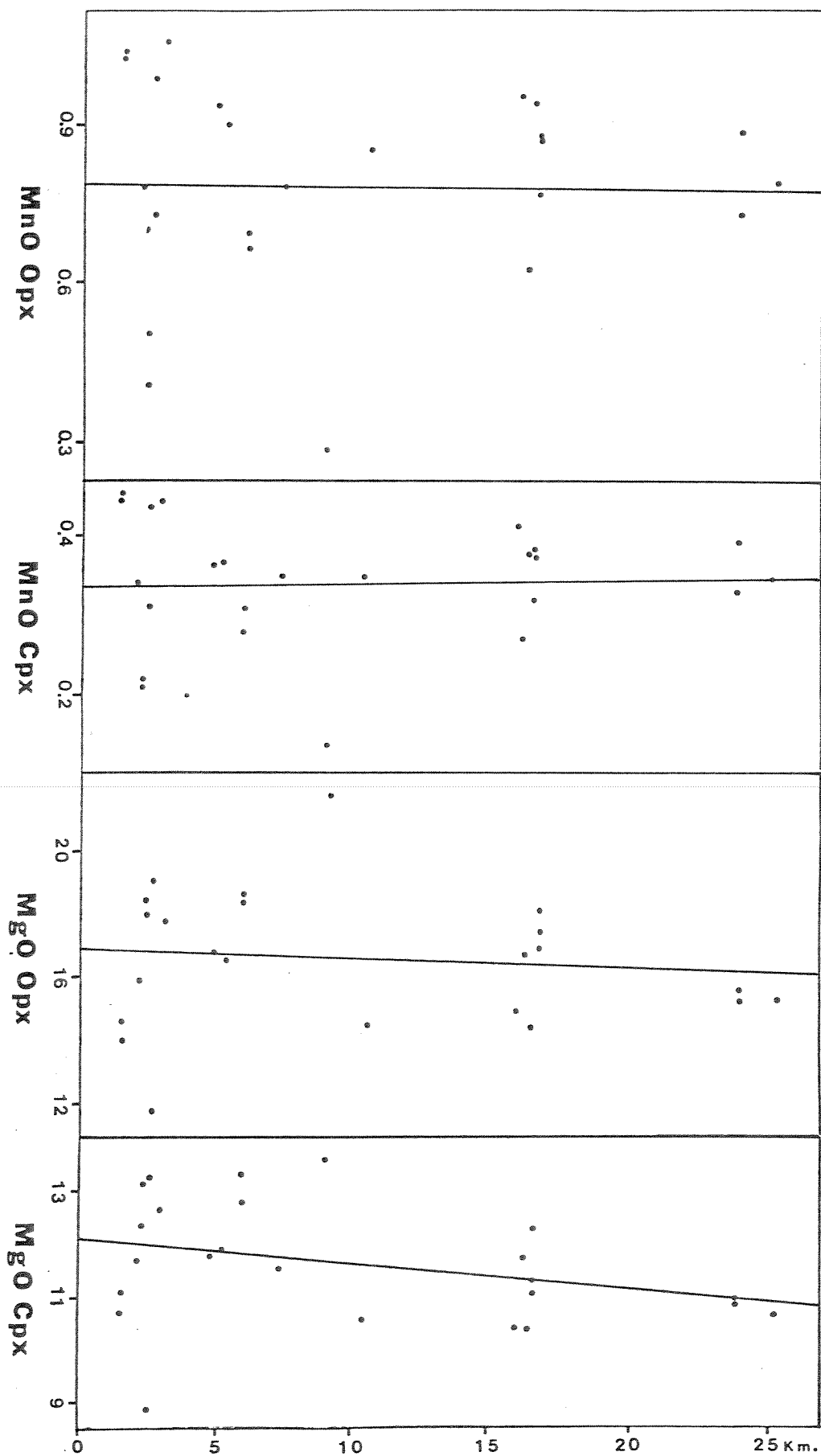
B





C

D



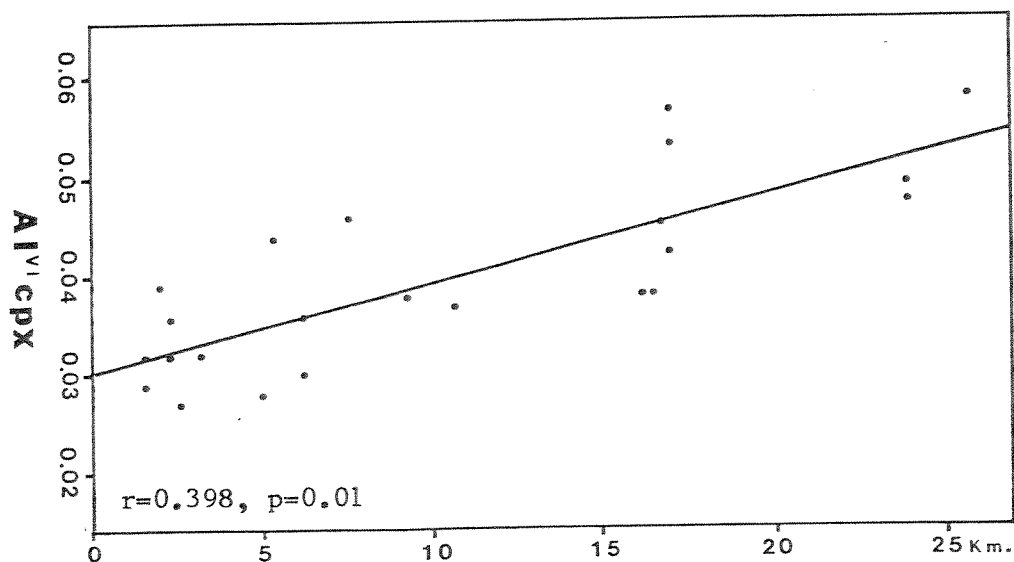
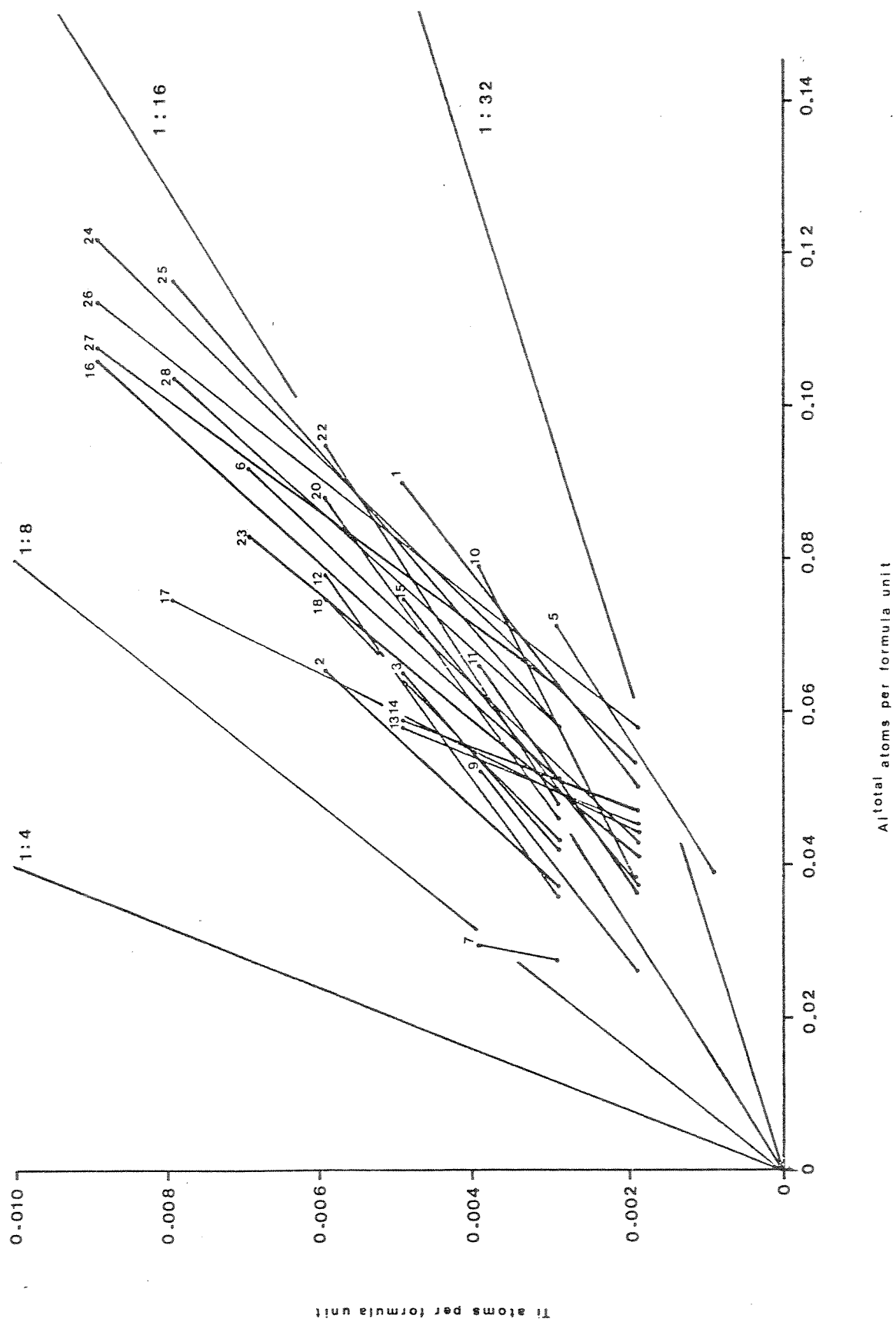


Fig. 17. Plot of the number of ions of clinopyroxene Al^{VI} per formula unit on the basis of six oxygens, versus distance from DeWaard's (1969a) orthopyroxene isograd. The solid line represents the least-squares fit of the data points. Regression analysis indicates a statistically significant correlation between Al^{VI} and distance.

Fig. 18. Plot of Al versus Ti as total atoms per formula unit in coexisting pyroxenes from amphibolites from the Adirondack Lowlands. Clinopyroxenes contain the higher percentages of Ti and Al. Lines from the origin indicate ratios of Ti:Al. Numeration refers to locality numbers as mapped in Fig. 3.



octahedrally coordinated aluminum (Rietmeijer, 1979). This trend could not be detected with Bohlen and Essene's (1978) pyroxene data obtained from integrated coarse (igneous) and small, equant (metamorphic) coexisting pyroxenes from the Adirondack anorthosites. However, this trend is consistent with data presented by Rietmeijer (1979) for Ti versus Al (atoms per formula unit) for coexisting pyroxenes. His data, from the (quartz-) monzonitic phase of the Bjerkreim-Sokndal lopolith (ca 1050°C) and the Botnavatnet igneous complex (ca 950°C) in southwest Norway, plots between the lines $Ti:Al = 1:16$ and $1:4$ which is similar to Philpotts' (1966) observations for pyroxenes from the Morin anorthosite in Canada, from which pyroxene temperatures are notably higher than those from the Adirondack Lowlands. Rietmeijer also noted that pyroxenes with $Ti:Al$ ratios less than 1:4 generally are from lunar basalts which crystallized at temperatures higher than those for the terrestrial, igneous pyroxenes. $Ti:Al$ ratios equal to 1:2 represent the maximum amount of Ti^{4+} in pyroxenes (Hodges and Kushiro, 1974) since it is generally accepted that Ti^{4+} cannot enter into tetrahedrally coordinated sites (Hartman, 1969). Ratios larger than 1:2 are considered to indicate the presence of Ti^{3+} (Rietmeijer, 1979).

It is not implied here that Ti/Al is temperature dependent. Textural evidence in lunar basalts suggest that an increase in the $Ti:Al$ ratio for zoned pyroxenes coincides with the onset of plagioclase crystallization (Virgo, 1973). As will be described below, it is suggested here that the volumetric decrease in hornblende during dehydration reactions caused Ti, Al (and Na) to be made increasingly available to the pyroxenes in the Adirondack Lowlands with increasing

distance from the orthopyroxene isograd. A coincidental increase in pressure in the same direction would permit pyroxenes to incorporate increasing amounts of Al, Na (and Ti). As previously discussed, there is textural evidence for equilibrium having been attained, possibly due to deeper burial at higher pressure. Additionally, Romey et al. (1980) presented structural evidence indicating the Adirondack Lowlands are underlain by the upper limb of a large nappe with its hinge in the vicinity of Colton-Parishville. From there, its lower limb, tightly oppressed against the massif, extends to the southeast.

Hornblende Compositional Changes

Engel and Engel (1962b) determined that hornblende volumetrically decreases in the least altered amphibolite as the massif is approached, and that at Colton orthopyroxene and clinopyroxene formed at the expense of about half the hornblende. A comparison of average chemical composition of hornblendes from the Emeryville area and those from Colton (Engel and Engel, 1962b; Engel et al., 1964) shows that Ti, Na, K, F, Cr, V, Sc, Co, and Ni increase; and Mn, Zn, OH, $\text{Fe}_2\text{O}_3/\text{FeO}$, and Fe/Mg decrease. Si, Ca, and Al remain unchanged in the hornblendes. Only Ti and Na increase toward the massif (and away from the orthopyroxene isograd) in both hornblende and clinopyroxene. The whole rock chemical composition of the least altered amphibolite also varies between Emeryville and Colton (Engel and Engel, 1962a). That is, as the massif is approached, Si, K, H_2O , F, Cl, and Fe^{3+} decrease, and Ca, Mg, and probably Al increase. Since some pyroxene-bearing amphibolites in the Colton area contain relatively large amounts of hornblende and there are changes in the amounts and compositions of

pyroxenes, hornblendes, and plagioclase (and, possibly whole rock allochemical exchanges), it is difficult to explain trends in pyroxene composition on the basis of compositional variation in the whole rock and in hornblende, and volumetric variations in hornblende and pyroxenes. However, pyroxene K_D does decrease and there is a corresponding increase in Fe/Mg in hornblende as distance from the orthopyroxene isograd increases. If the hornblende Si, Al, and Na content remain unchanged, and even though hornblende Ti and Na content increase, the volumetric decrease in hornblende in the amphibolites caused Ti, Al, and Na to be made more available for the pyroxenes with increasing distance from the isograd. Plagioclase similarly increased in volume and became more Ca-rich because of the availability of Si, Ca, and Al. Stoddard (1976a) determined that the plagioclase of two-pyroxene, garnet-free amphibolites in the Colton area consistently exhibited reverse (Ca-rich rims) chemical zonation which he interpreted as being the result of reactions involving the dehydration of hornblende. Fe is also consistently enriched, but not saturated, in the plagioclase rims.

CONCLUSIONS

Pyroxene temperatures determined with the Ross and Huebner (1975) geothermometer compare quite favorably with integrated oxide and feldspar determinations made by Bohlen and Essene (1977a) for the Adirondack Highlands and Lowlands, and also with Stoddard's (1976a) pyroxene data and, later, pyroxene temperatures determined with the Ross and Huebner geothermometer (Stoddard, 1980). The Wells (1977) and Wood and Banno (1977) pyroxene geothermometers give results which are too high by approximately 100°C but show a statistically significant correlation with each other and with the Ross and Huebner thermometer. The pyroxenes in the Adirondack Lowlands record the temperatures of the last metamorphic event (reequilibration) rather than peak temperatures. Various independent geothermometric and geobarometric investigations, principally by Bohlen, Essene, and others, strongly suggest metamorphic conditions in the Adirondack Lowlands to have peaked at approximately $650 \pm 50^{\circ}\text{C}$, with $P_{\text{total}} = 6.5 \pm 1$ kbar; pressure and temperature increasing toward the center of the massif.

There is a statistically significant decrease in pyroxene temperatures for all three geothermometers, decreases in pyroxene K_D , and increases in clinopyroxene Na_2O , TiO_2 , Al_2O_3 , Al^{VI} , and orthopyroxene Al_2O_3 , versus distance from DeWaard's (1969a) orthopyroxene isograd. The decrease in pyroxene temperature away from the isograd strongly suggests a more complete reequilibration had occurred in that direction, possibly due to deeper, more prolonged burial and/or decreasing water pressure. This is suggested by the diminution of retrograde alteration and sericitization of feldspar, reduction in

water content, and volumetric decrease in hornblende in the amphibolites as the massif is approached (Engel and Engel, 1962a; Engel et al., 1964). The lack of ilmenite lamellae in magnetite and textural evidence such as lack of symplectite, mutual contact of various phases, and poikiloblastic pyroxenes in the vicinity of Colton (near the massif) also suggest more complete reequilibration away from the orthopyroxene isograd.

The decrease in pyroxene temperatures away from the isograd may be due to the increase in minor elements, particularly Al and Na, which suggest, also, an increase in pressure. These conditions would serve to stabilize a wider solvus which, not calibrated in the Ross and Huebner thermometer, result in its indicating a steeper decrease in temperature when compared to the Wells or Wood and Banno geothermometer. Structural evidence for a large nappe with its hinge in the vicinity of Colton and its lower limb tightly oppressed against the massif also supports the concept of an increase in pressure away from the orthopyroxene isograd. Since the Ross and Huebner pyroxene temperatures in the vicinity of Colton have been lowered compared to the rest of the Lowlands, and Bohlen and Essene (1979b) presented Lowland data only from the Colton area, their Ross and Huebner pyroxene temperatures were too low and not representative of the Lowlands as a whole even though they were consistent with their oxide and feldspar determinations. Possibly, pressure effects within the Highlands may have been responsible for the anomalously low Ross and Huebner temperatures ($< 600^{\circ}\text{C} - 750^{\circ}\text{C}$, Tupper Lake; $600^{\circ}\text{C} - 800^{\circ}\text{C}$, Mt. Marcy) reported by Bohlen and Essene (1979b).

Results of this study suggest that a consideration of temperature

versus composition and use of the orthopyroxene isograd as a base line against which temperature, K_D , and pyroxene composition can be correlated with high density sampling could be employed in other geologically similar areas.

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APPENDIX A

Petrographic Descriptions

1 (512) This medium-grained (< 1 mm), banded specimen consists of 40% green-brown hornblende, subequal amounts of greenish augite (15%), and pink-green pleochroic orthopyroxene (15%), both of which exhibit optical continuity (poikiloblastic), and 30% fresh-looking, commonly twinned plagioclase. There is also a trace of ilmenite.

2 (520) Several large (1 cm diameter) orthopyroxene porphyroblasts make up about 45% of this coarse-grained slide. They are pink-green pleochroic and slightly serpentized. The rest of the slide is a confused mixture of 5% brown biotite, quartz mosaics with sub-aligned optic axes (15%), and a coarse intergrowth of colorless garnet, magnetite, sillimanite, clear augite, sericitized plagioclase, chlorite, and ilmenite. The complicated petrography is due to a pegmatitic intrusion into amphibolitic country rock. The growth of the garnet and large pyroxenes apparently was facilitated by an increased mobility of constituents involved in the reactions.

3 (519) This medium-grained slide is unusual in that it contains subequal amounts of nearly colorless, non-pleochroic orthopyroxene and augite. The augite is poikiloblastic and optically continuous for distances greater than 1 cm. Hornblende and biotite are incipient (replacing the pyroxenes) and, in some places, there is a well-displayed symplectite composed of biotite, hornblende, pyroxenes, oxides, and plagioclase. There are a few percent of quartz and biotite, the plagioclase and symplectite making up approximately equal amounts. In one corner, a few slightly larger than average pyroxene grains are associated with a small amount of granitic material. There are also traces of magnetite, ilmenite, and sillimanite in the slide.

5 (505) Forty-five percent of this medium-grained amphibolite is light-to-dark-green hornblende with 10% brown biotite. Plagioclase, which is commonly twinned, and clear quartz, make up about 35% and 5%, respectively. A few large (3 mm) greenish augite grains are slightly hornblendized (3%) and 2% of the slide is composed of small grains of augite and orthopyroxene with magnetite, hornblende, and plagioclase forming a surrounding symplectite. All grains other than the large augites are smaller than 1 mm in diameter. There is also a trace of apatite. The unusual green color of the hornblende, absence of symplectite associated with it, and the remnant appearance of the smaller pyroxenes suggest nearly complete retrograde metamorphism.

6 (534) The central portion of this slide is composed of medium-grained pyroxenes; non-pleochroic orthopyroxene and greenish augite, each amounting to 30%. Twinned plagioclase (35%) and 5% ilmenite/magnetite are present, the oxides commonly as adjacent grains. There is an area at one end of the slide which is composed of subequal amounts of coarse perthitic plagioclase and quartz. The orthopyroxene

at the contact between these two areas is serpentized and slightly larger than those in the remainder of the slide. At the other end of the section there is a trace of hornblende with traces of a fine-grained symplectite composed of hornblende, plagioclase, pyroxenes and oxides.

7 (524) This is a medium-grained (< 1 mm) section composed of 30% green-brown hornblende, 20% occasionally twinned plagioclase, 10% quartz, pink-green pleochroic orthopyroxene (15%), greenish augite (15%), and about 10% magnetite and ilmenite. Large areas contain poikilitic orthopyroxene grains which are optically continuous. Some larger pyroxenes are clustered in hornblende-free, quartz-rich areas. Most grain edges are symplectic.

9 (525) This medium-coarse-grained (< 2 mm) section contains 10% brown biotite, an unusual yellow-green hornblende (5%), colorless, non-pleochroic orthopyroxene (10%), colorless augite (20%), slightly sericitized twinned and untwinned plagioclase (40%), 20% quartz, and a trace of magnetite.

10 (156C) Three-fourths of this slide is composed of a medium-grained amphibolite containing elongate (up to 4 mm) green-brown pleochroic hornblende (45%), pink-green pleochroic orthopyroxene (5%), and greenish augite (10%). Nearly equigranular fine-to-medium-grained (1 mm) plagioclase, often untwinned but with many grains exhibiting polysynthetic or pericline twinning, accounts for 40%. Traces of ilmenite, magnetite, and pyrite are also present. A fine-grained thin zone of symplectite composed of hornblende, plagioclase, pyroxenes, oxides, and biotite is at most grain boundaries between pyroxenes, hornblende, and plagioclase. The rest of the slide is a granitic band composed of plagioclase, quartz, pyroxenes, and a trace of biotite. Some of the augite (associated with a few larger than average orthopyroxene grains and the granitic material) is in the form of very large (1 cm) porphyroblasts (in places replaced by chlorite) which exhibit deformation lamellae and undulatory extinction, both of which appear under crossed polars. In places, the lamellae contain extremely fine parallel needle-like oxide inclusions which appear in various lengths and orientations depending on the plane of sectioning, but which indicate the lamellae are extremely thin planes of inclusions, relict after deformation lamellae.

11 (159E) More or less equal amounts of hornblende, plagioclase with quartz, orthopyroxene, and augite make up this medium-grained section, although hornblende and plagioclase, plagioclase and quartz, and orthopyroxene and augite tend to be segregated into separate bands. The hornblende is elongate (2 mm), green-brown pleochroic, is slightly larger than the other minerals and is associated with plagioclase. Pink-green pleochroic orthopyroxene and greenish augite, associated with plagioclase and quartz, are slightly altered to serpentine and hornblende, respectively. Most grains show a symplectic border composed of pyroxenes, plagioclase, hornblende, and oxides. The pyroxenes commonly exhibit deformation lamellae, and augite is commonly larger than orthopyroxene. The plagioclase is usually poly-

synthetically twinned.

12 (201B) Green-brown hornblende makes up 40% of this medium-grained, lineated section. The grains are elongate (up to 3 mm), often with elongate, oriented oxide inclusions. Pink-green pleochroic orthopyroxene (15%), 15% green augite, commonly with deformation lamellae, 5% brown biotite, some fine grains of ilmenite, 5% quartz and 20% plagioclase, commonly twinned, make up the rest of the slide. Most grain edges and areas between grains exhibit symplectite composed of fine grains of plagioclase, pyroxenes, oxides, biotite, and hornblende.

13 (515) This fine-grained (< 0.5 mm) section consists of 30% very light brown biotite with a few zircon inclusions. Colorless orthopyroxene and augite, in places, are optically continuous and each make up about 20%. Well-twinned plagioclase makes up the remainder of the slide (20%) along with less than 1% ilmenite and magnetite.

14 (514) This medium-grained specimen (< 1 mm) contains very large (1.5 cm) poikiloblastic and optically continuous, colorless orthopyroxene and augite, each containing plagioclase and hornblende, and each making up about 25% of the slide. There are also green-brown hornblende (10%) and brown biotite (1%). The remainder of the slide is composed of well-twinned plagioclase and a trace of magnetite.

15 (88B) This is a medium-grained slide with most grains less than 1 mm in diameter. Green-brown hornblende comprises 40% and is more or less equant. Pink-green pleochroic orthopyroxene and greenish augite each make up about 15% and grade into coarse-grained symplectite composed of plagioclase, magnetite, pyroxene, hornblende, and biotite. Some equant quartz grains form veinlets which are surrounded by larger augite grains slightly altered to hornblende where in contact with the quartz. The region around the augite and quartz is free of hornblende and suggests the reaction; $hbl + qtz = cpx$. About 15% of the slide is plagioclase which is usually twinned.

16 (236C) This medium-grained amphibolite (1 mm maximum grain diameter) is composed of 30% green hornblende with symplectic edges. Equal amounts (20%) of pink-green pleochroic orthopyroxene and greenish, optically continuous augite, 30% plagioclase (mostly twinned) and traces of biotite, ilmenite, magnetite, and pyrite make up the rest of the section. A few chloritized fractures transect the section.

17 (76B) All grains on this slide are less than 0.25 mm in diameter. Pink-green pleochroic orthopyroxene and greenish augite both make up 15% of the section and are poikilitic with small inclusions of plagioclase feldspar. There is a trace of ilmenite, 5% brown biotite, and 45% slightly sericitized or clear plagioclase. Hornblende and symplectite are both absent.

18 (159A) In this medium-grained slide all grains are less than 1 mm in diameter. The specimen is composed of pink-green pleochroic orthopyroxene (40%), 15% greenish augite, 15% green-brown hornblende, a small amount of brown biotite, about 30% twinned plagioclase, much of which is sericitic, and 10% quartz. There is also a trace of magnetite. Some slightly larger pyroxene grains are associated with quartz-feldspar-rich granitic bands which are also hornblende deficient. A symplectite composed of feldspar, pyroxenes, hornblende, biotite, and oxides forms a relatively thick border around most grains. Pyroxenes, in places, are altered to biotite or hornblende. Some of the orthopyroxene is poikiloblastic and optically continuous for distances up to 1 cm.

20 (222C) This medium-grained amphibolite is composed of equal amounts (30%) of pink-green pleochroic orthopyroxene and greenish augite, 35% slightly sericitized plagioclase, and 5% magnetite and ilmenite associated with the pyroxenes. A vein of quartz and feldspar transects the slide and contains pink garnet, brown hornblende, magnetite, and hornblendized augite. Hornblende and magnetite are associated with shear zones which intersect the vein.

22 (232A) This is a moderately coarse-grained section (< 5 mm) composed of equal amounts (20%) of pink-green pleochroic orthopyroxene and greenish augite, both poikiloblastic and forming optically continuous regions. Hornblende (15%) is restricted to a narrow band and exhibits a symplectic intergrowth at its edges which is composed of hornblende, plagioclase, pyroxenes, and oxides. Ilmenite, commonly with magnetite grains in contact, makes up 5% of the slide. Slightly sericitized plagioclase (40%) is present, with many grains exhibiting polysynthetic twinning.

23 (234) This medium-grained amphibolite contains a quartz-feldspar granitic portion with associated coarse grains (some larger than 5 mm in diameter) of garnet and pyroxenes. The remainder of the slide is composed of 20% pink non-pleochroic orthopyroxene, 30% greenish augite with curved deformation lamellae, some altered to hornblende, 5% magnetite and ilmenite, traces of quartz, potassium feldspar, and hornblende. The remainder of the amphibolitic portion is composed of plagioclase which is commonly polysynthetically twinned.

24 (236A) Deformation lamellae containing oriented oxide rodlets are common in the pink-green pleochroic orthopyroxene (10%) and greenish augite (30%) of this section. These minerals and green-brown hornblende (20%) all exhibit symplectic edges, the pyroxenes altering slightly to serpentine (orthopyroxene) and hornblende (augite). Chlorite is found along a fracture through the specimen. Plagioclase (40%) is commonly twinned. There is also a trace of ilmenite, magnetite, and pyrite in this medium-coarse-grained amphibolite.

25 (236B) This is a medium-to-coarse-grained section with some grains larger than 5 mm. Subequal amounts (25%) of pink-green pleochroic orthopyroxene and greenish augite are present plus 5% augite in

the form of larger grains exhibiting curved relict planes of deformation lamellae filled with rodlets of opaque oxides. The relict planes are more or less equally spaced with the rodlets in any one area having the same orientation. The apparent width of the planes varies from a line to broad bands depending on the orientation of the plane with respect to the plane of section. The larger augite grains are slightly hornblendized and are associated with about 5% quartz. Greenish-brown hornblende, noticeably absent in the vicinity of the larger pyroxene grains, makes up about 20% of the section. There is also approximately 20% plagioclase present which is commonly twinned. Most grain boundaries are a fine-grained oxide-rich symplectite with plagioclase, pyroxenes, and hornblende present in lesser amounts. There are also traces of magnetite, ilmenite, and pyrite throughout the slide.

26 (259F) This medium-grained specimen (1 mm in diameter grains) is comprised of 20% pink-green pleochroic orthopyroxene which is poikilitic and optically continuous for distances up to 1 cm. Greenish augite (35%), 5% green-brown hornblende, 5% magnetite and ilmenite, and 35% well-twinned plagioclase make up the rest of the slide. Symplectite is noticeably absent from this hornblende-rich section.

27 (260A) In this medium-grained (0.5 - 1 mm) amphibolite, green-brown hornblende (35%), subequal amounts (20%) of greenish augite, and poikilitic, optically continuous pink-green pleochroic orthopyroxene with much included magnetite, plus 25% clear plagioclase, are present. Traces of ilmenite and magnetite are commonly seen as adjacent grains. Symplectite is also noticeably absent from this hornblende-rich section.

28 (260B) The equigranular minerals in this medium-fine-grained slide are all approximately 0.5 mm in diameter. The slide is composed of 5% pink-green pleochroic orthopyroxene, 40% greenish augite, 50% well-twinned plagioclase, and 5% magnetite. Much of the magnetite appears as irregular inclusions in the orthopyroxene and in fractures with traces of biotite. There are also traces of hematite and limonite in the section. Symplectite, as well as hornblende, are absent.

APPENDIX B

Photographic Plates and Legends

PLATE 1.

Fig. 1. Large poikiloblastic orthopyroxene porphyroblast approximately 1.5 cm in diameter. All light gray reticulated areas in this field of view are optically continuous. Poikiloblastic pyroxenes are not associated with migmatitic zones. Plane polarized light. Specimen no. 14 (515). 12.5X.

Fig. 2. Large poikiloblastic orthopyroxene. All areas exhibiting dark reticulated structure are optically continuous. Augite grains in the same section are clearer and less obviously optically continuous. Plane polarized light. Specimen no. 26 (259F). 12.5X.

Fig. 3. Similar to Fig. 2, but the orthopyroxene is even more altered and contains more inclusions. Note the absence of symplectite in this and the other hornblende-bearing section (Fig. 2) from the Parishville-Colton area. Plane polarized light. Specimen no. 27 (260A). 12.5X.

Fig. 4. Low power photo of the migmatized portion of an amphibolite showing larger, non-poikiloblastic augites and a few smaller orthopyroxenes all containing relict planes of oxide inclusions (after deformation lamellae). Note the hornblende-free aureole in the amphibolite adjacent to the clearer quartz-feldspar zone. Plane polarized light. Specimen no. 25 (236B). 3X.

Fig. 5. Amphibolite with quartz veinlets surrounded by larger than average (for this section) augite grains within a hornblende-free aureole. The contact between the quartz and pyroxenes is a zone of hornblendization of the augite. Plane polarized light. Specimen no. 15 (88B). 3X.

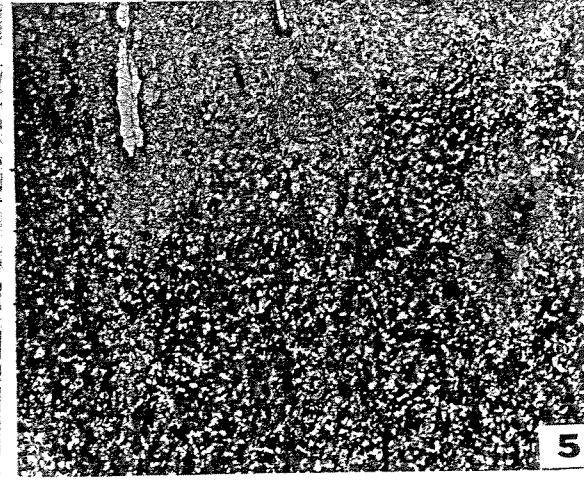
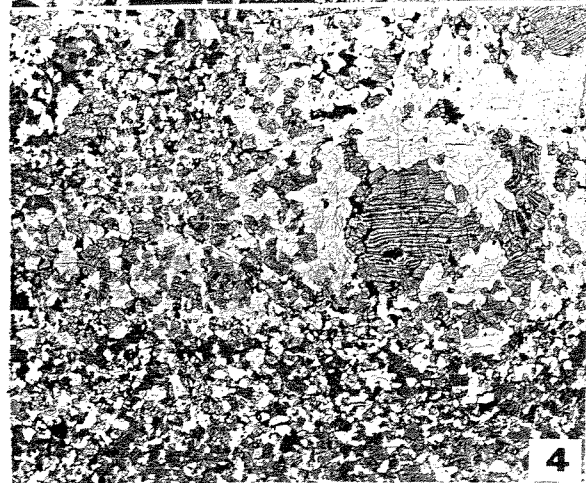
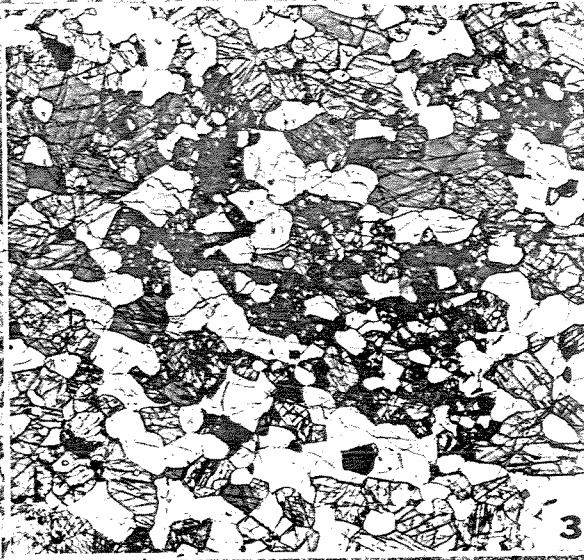
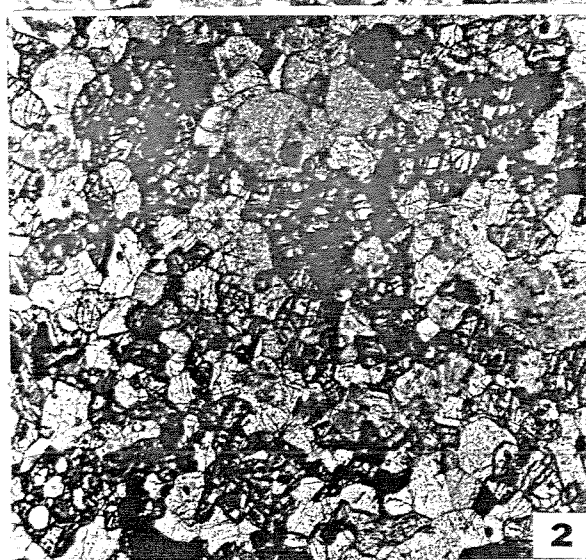
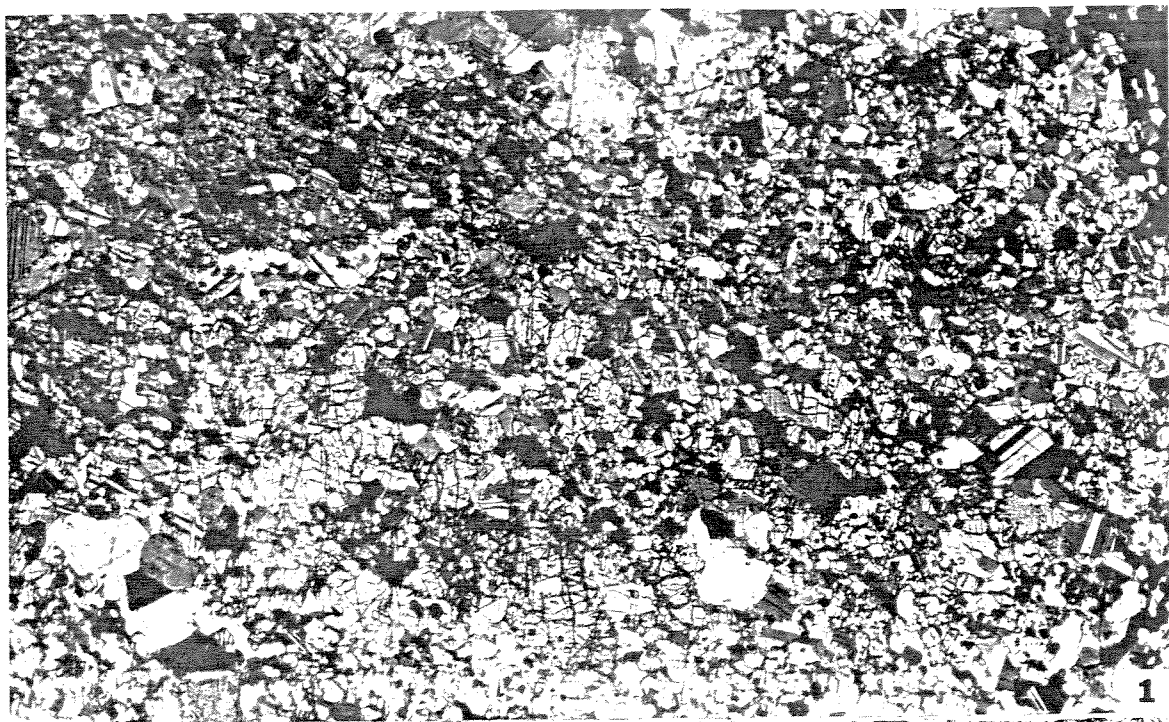


PLATE 2.

Fig. 1. Large, non-poikiloblastic orthopyroxene within the granitic portion of a migmatized amphibolite. Alteration to serpentine(?) has occurred along relict planes (after deformation lamellae). Plane polarized light. Specimen no. 2 (520). 9X.

Fig. 2. Altered augite grain exhibiting relict planes and partially replaced by hornblende. Plane polarized light. Specimen no. 23 (234). 30X.

Fig. 3. Large, non-poikiloblastic orthopyroxene grain associated with the granitic portion of a migmatized amphibolite. Deformation lamellae appear under crossed polars and exhibit undulatory extinction a few degrees from the rest of the grain. Note that the lamellae taper toward both ends and terminate within the grain. Polarized light. Specimen no. 10 (156C). 35X.

Fig. 4. Same as Fig. 3, but under plane polarized light. Some opaque oxide rodlets may be seen as relict planes of inclusions after deformation lamellae. Plane polarized light. Specimen no. 10 (156C). 35X.

Fig. 5. Enlarged view of a portion of a non-poikiloblastic augite porphyroblast seen in Plate 1, Fig. 4. Some portions of the deformation lamellae are extinguished under crossed polars, but most of the area shown is crystallographically continuous. Most of the deformation lamellae are outlined by relict planes of oxide rodlet inclusions. Polarized light. Specimen no. 25 (236B). 30X.

Fig. 6. Same as Fig. 5, but in plane polarized light. Polarized light. Specimen no. 25 (236B). 30X.

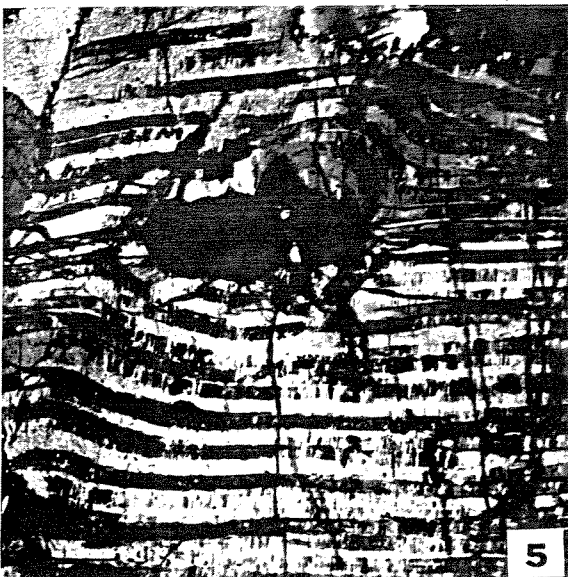
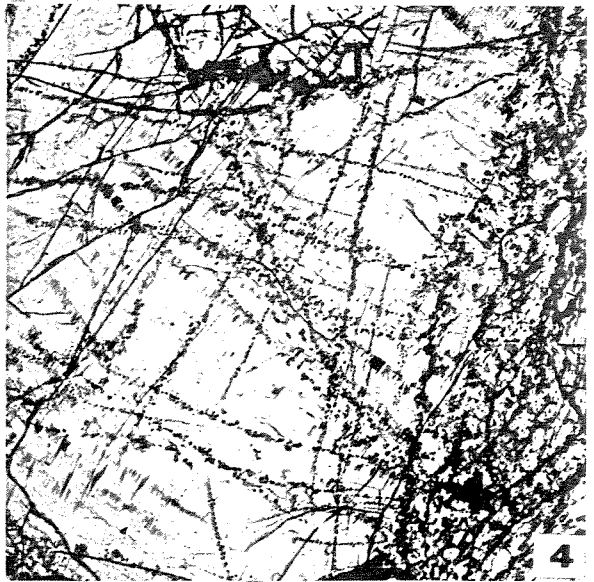
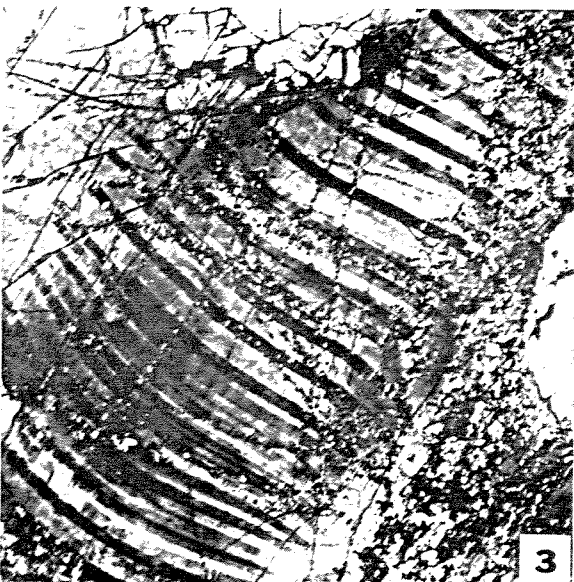
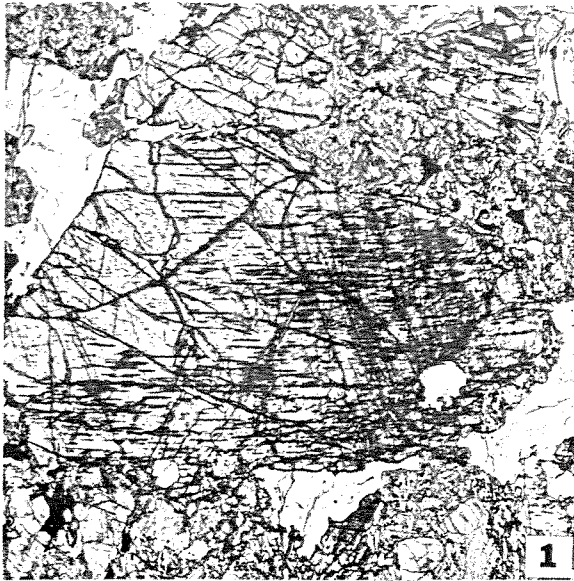


PLATE 3.

Fig. 1. Typical appearance of relict planes of oxide inclusions after deformation lamellae within pyroxene (augite) porphyroblasts. Plane polarized light. Specimen no. 24 (236A). 40X.

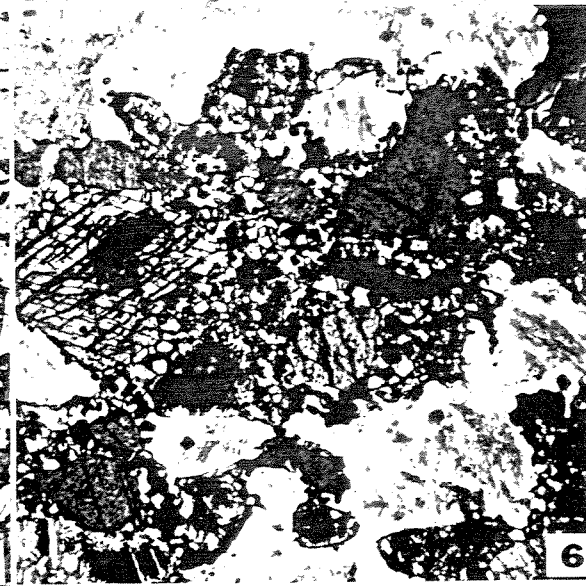
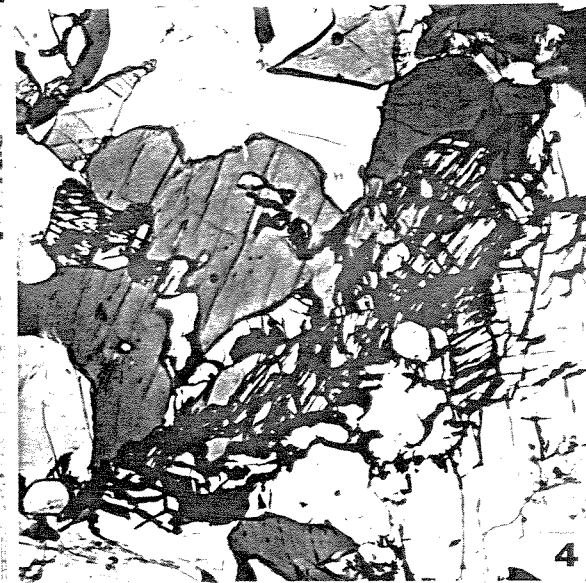
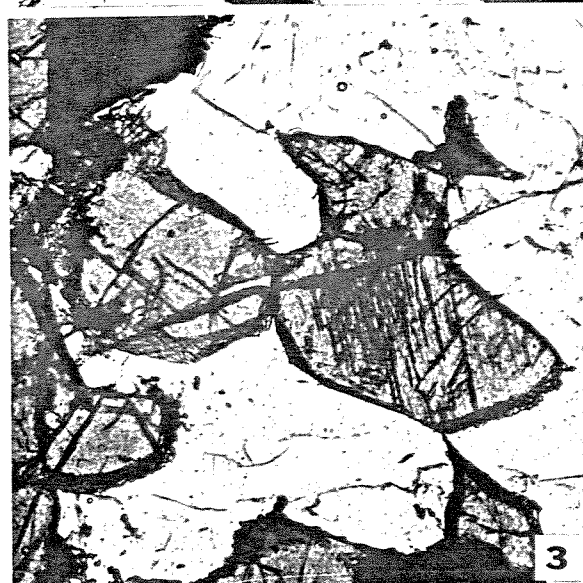
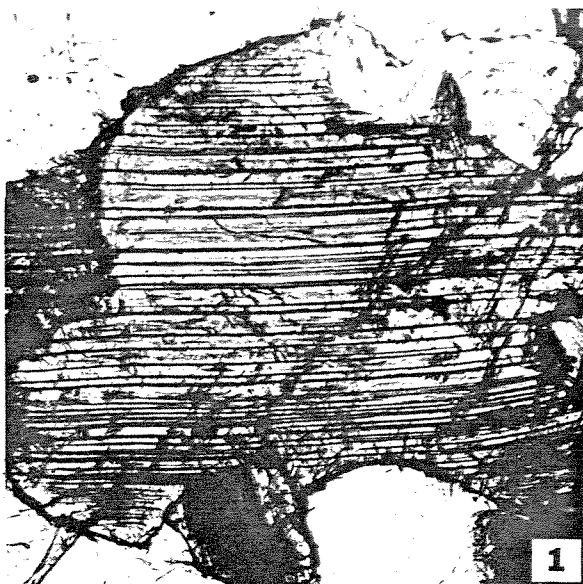
Fig. 2. Several grains of augite (as seen in Plate 1, Fig. 4). Each grain contains several relict planes of oxide rodlet inclusions at different orientations to the plane of section. Note orientation of rodlets differs from grain to grain. Plane polarized light. Specimen no. 25 (236B). 30X.

Fig. 3. Smaller pyroxene grains, not associated with migmatitic zones, exhibiting (in core) relict planes of oxide inclusions after deformation lamellae. Plane polarized light. Specimen no. 6 (534). 55X.

Fig. 4. Nearly completely altered orthopyroxene grain associated with magnetite and unusual green hornblende suggestive of retrograde metamorphism. Plane polarized light. Specimen no. 5 (505). 30X.

Fig. 5. Symplectite consisting of pyroxenes, plagioclase, hornblende, and oxides appearing as black intergrowth at most grain edges. Plane polarized light. Specimen no. 25 (236B). 35X.

Fig. 6. Very coarse granular symplectite at the boundary of most grains in this amphibolite. Plane polarized light. Specimen no. 15 (88B). 30X.



APPENDIX C

Materials and Methods

A relatively large suite of rock specimens (348) collected in the Adirondack Lowlands during the summer of 1978 was combined with 39 specimens gathered by Roger Hewins in a reconnaissance survey of the area during the previous summer. These were all macroscopically examined to determine approximate modal mineral assemblages, and listed by number according to quadrangle, map symbol (Geologic Map of New York State; Isachsen and Fisher, 1970), and into which metamorphic zone it falls according to Buddington (1963), DeWaard (1969a), and Engel and Engel (1962a). Selected specimens were slabbed at right angles to the foliation (if any), thin-sectioned, and studied to determine the presence of mineral pairs (orthopyroxene-augite and iron-titanium oxides) suitable for microprobe analysis. One-centimeter-thick slabs measuring 3 X 4 centimeters were sent to; Mann Petrographics, 326 Mimbres (White Rock), Los Alamos, New Mexico 87544, or to; D. M. Organist, Petrographic Laboratory, Post Office Box 176, Newark, Delaware 19711, at a cost of \$10.75 per polished section. These were carbon coated and examined at the American Museum of Natural History, New York City, using an Applied Research Laboratories (ARL) SEMQ electron microprobe. The microprobe has six fixed (Si, T, Al, Fe, Mg, Ca) and three variable spectrometers tuned to the appropriate K α wavelengths and operating, for pyroxenes, at an accelerating voltage of 15KV and a specimen current of 0.2 NA. The counting interval for the peak and background was 20 seconds each. Compositions for pyroxene molecular formulae are on the basis of six oxygen atoms and four cations (see Table 2).

Beam diameter was kept at a minimum (approximately 1 micron) and specimens were focused in reflected light prior to each counting interval. Standards used for the wavelength dispersive analysis of augite and orthopyroxene were;

A209	Si, Ti, Al, Fe, Mg, Ca, Na
Hyjon	Cr
Heden	Mn
Corun	Si background
Qtz	Ti, Al, Cr, Fe, Mn, Mg, Ca, Na background.

Raw counts for standards and unknowns were corrected for background by subtracting the averages of high and low background counts measured at equally-spaced wavelengths on either side of a given peak. The data were corrected for atomic number effect, absorption, fluorescence, and system dead time (1.5 microseconds) using the data reduction method of Bence and Albee (1968) and the correction factors of Albee and Ray (1970). Analyses are considered to be accurate to within two relative percent.

The probe, standardized for pyroxenes, could also be utilized to accurately determine the composition of hornblende associated with the coexisting pyroxenes.

Most photographs were taken with a Zeiss Photomicroscope using Kodak 35 mm Plus-X Pan film. Plate 1, Figs. 1-3 and Plate 2, Fig. 1 were obtained from 10.2 X 12.7 cm Plus-X Pan film negatives produced by projecting the entire image of the polished section positioned in a photographic enlarger. Plate 1, Figs. 4-5 were printed from contact negatives of the polished sections on 35 mm Plus-X Pan film. All prints are on Agfa-Gevaert Rapidoprint FP 1-2 projection paper.

APPENDIX D

Pyroxene quadrilateral plots of compositions of coexisting orthopyroxene and augite determined by microprobe analysis. Numeration as in Fig. 3. Occasional hornblende plots fall very close to Wo-30%.

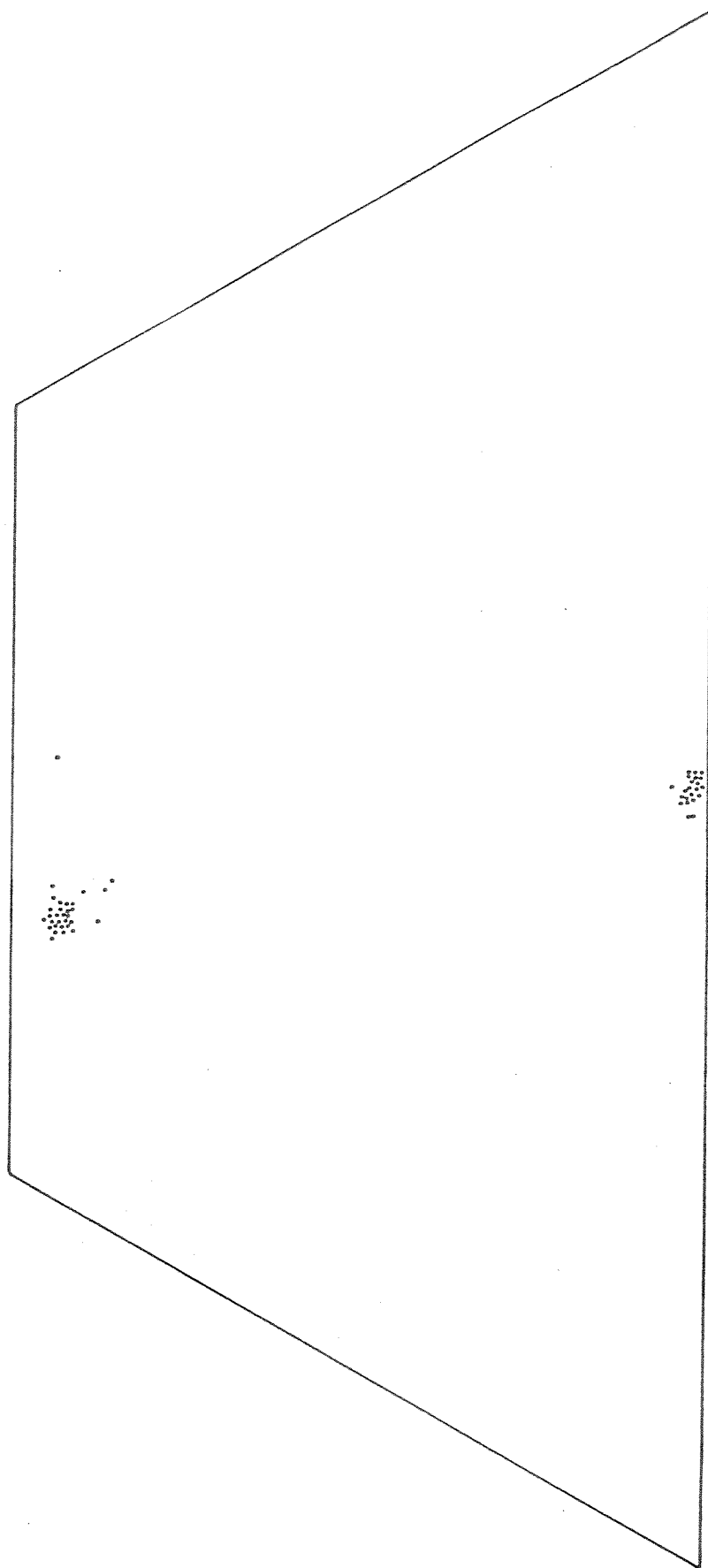


Fig. D-1. Plot of pyroxene compositions from specimen 1.

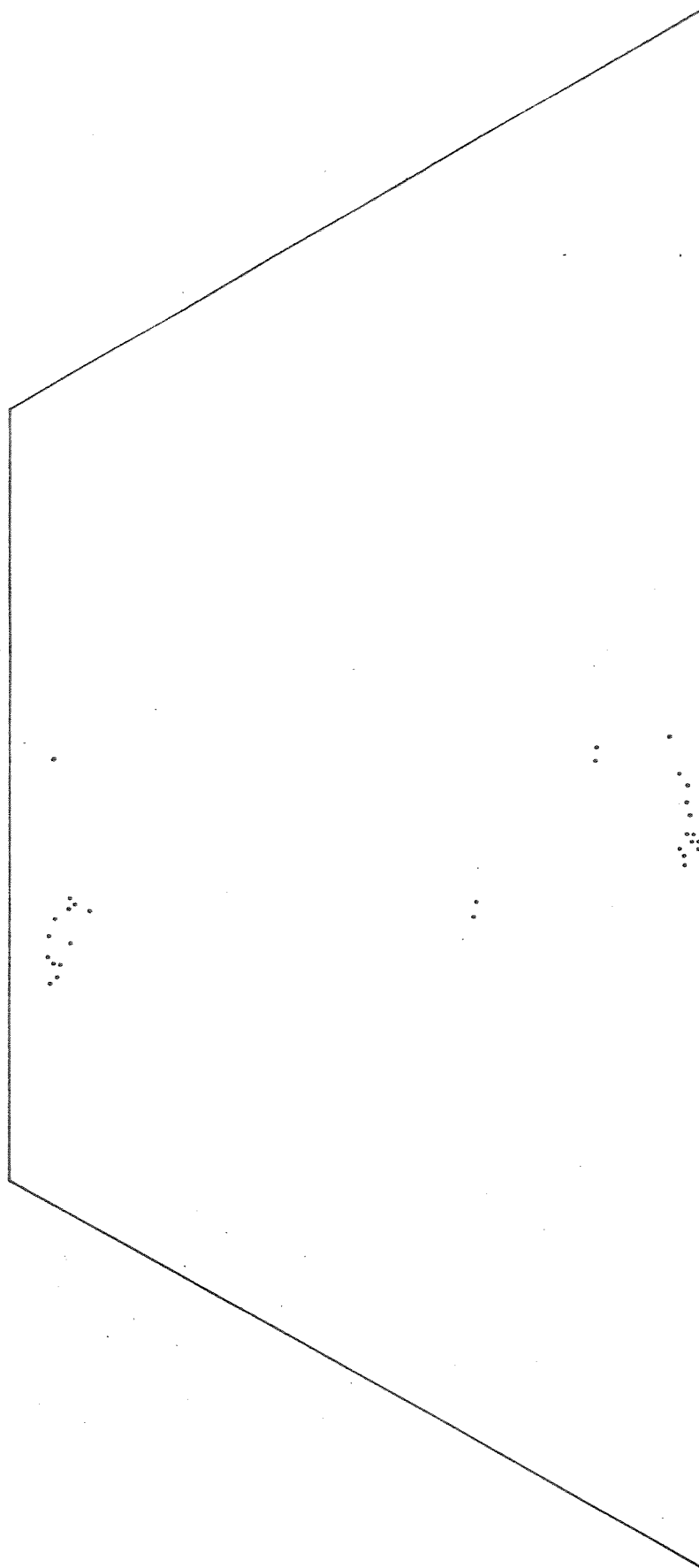


Fig. D-2. Plot of pyroxene compositions from specimen 2.

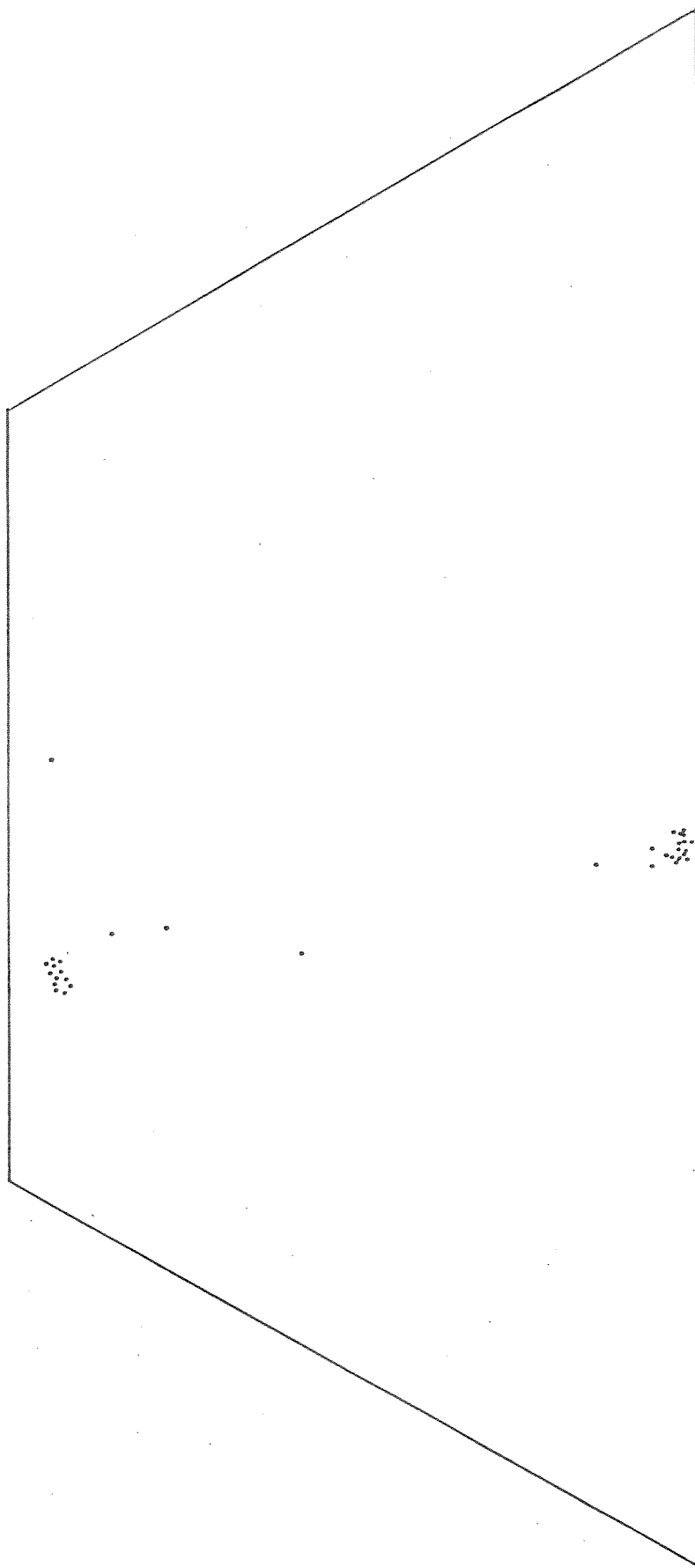


Fig. D-3. Plot of pyroxene compositions from specimen 3.

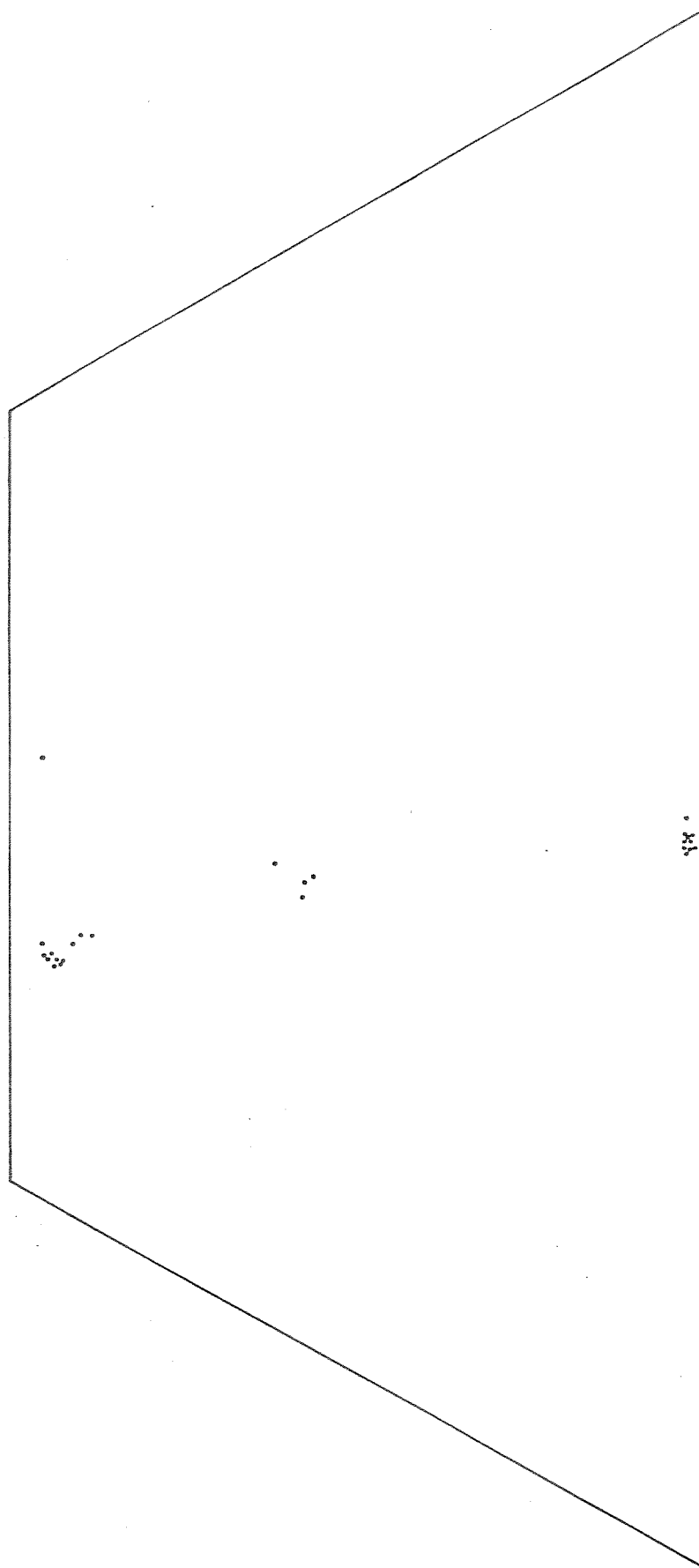


Fig. D-5. Plot of pyroxene compositions from specimen 5.

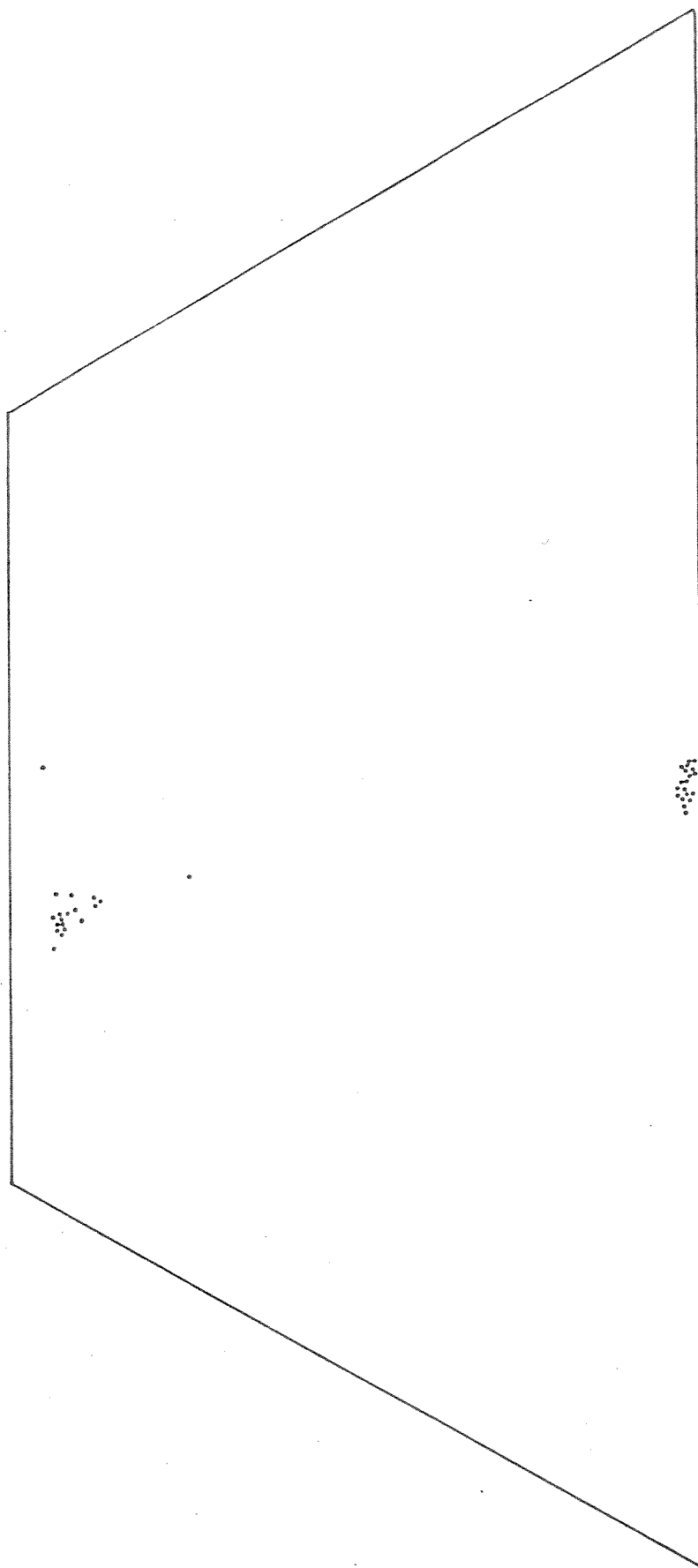


Fig. D-6. Plot of pyroxene compositions from specimen 6.

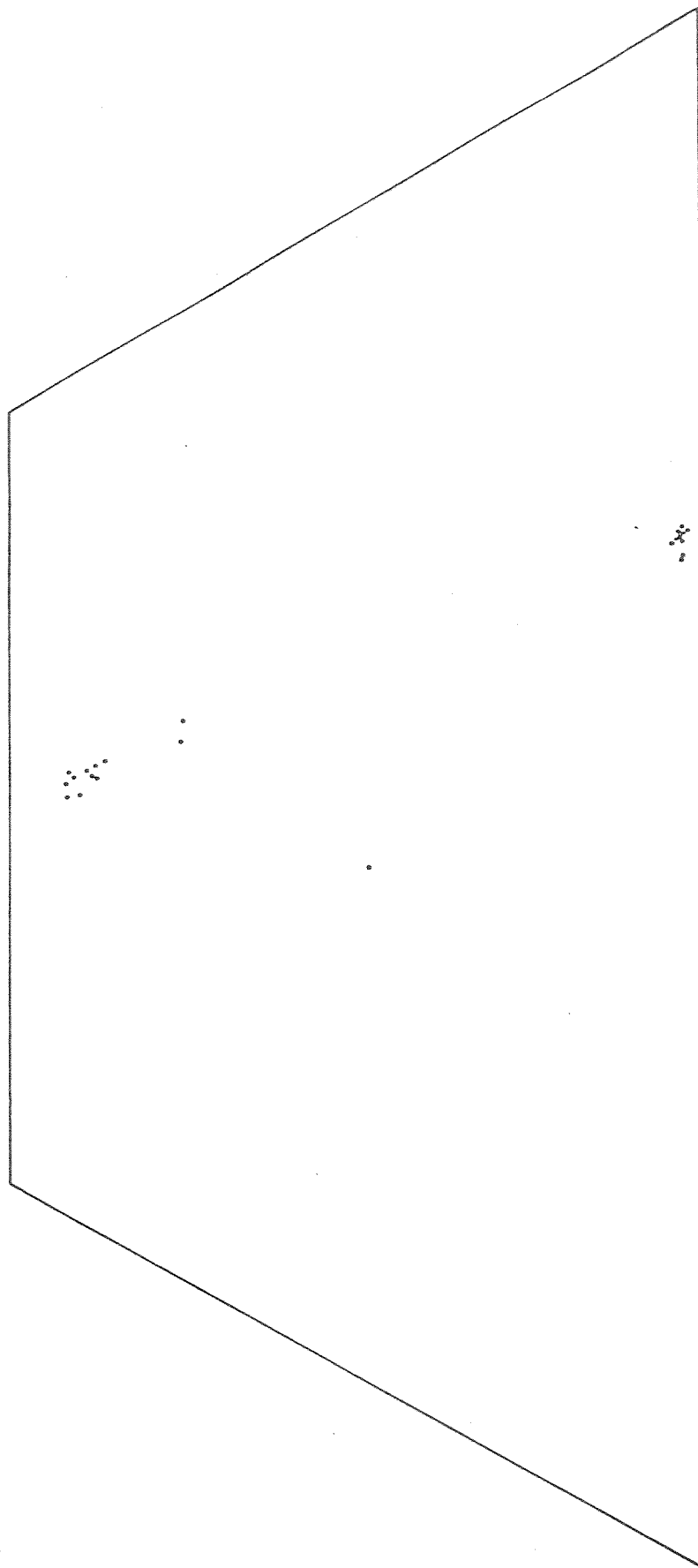


Fig. D-7. Plot of pyroxene compositions from specimen 7.

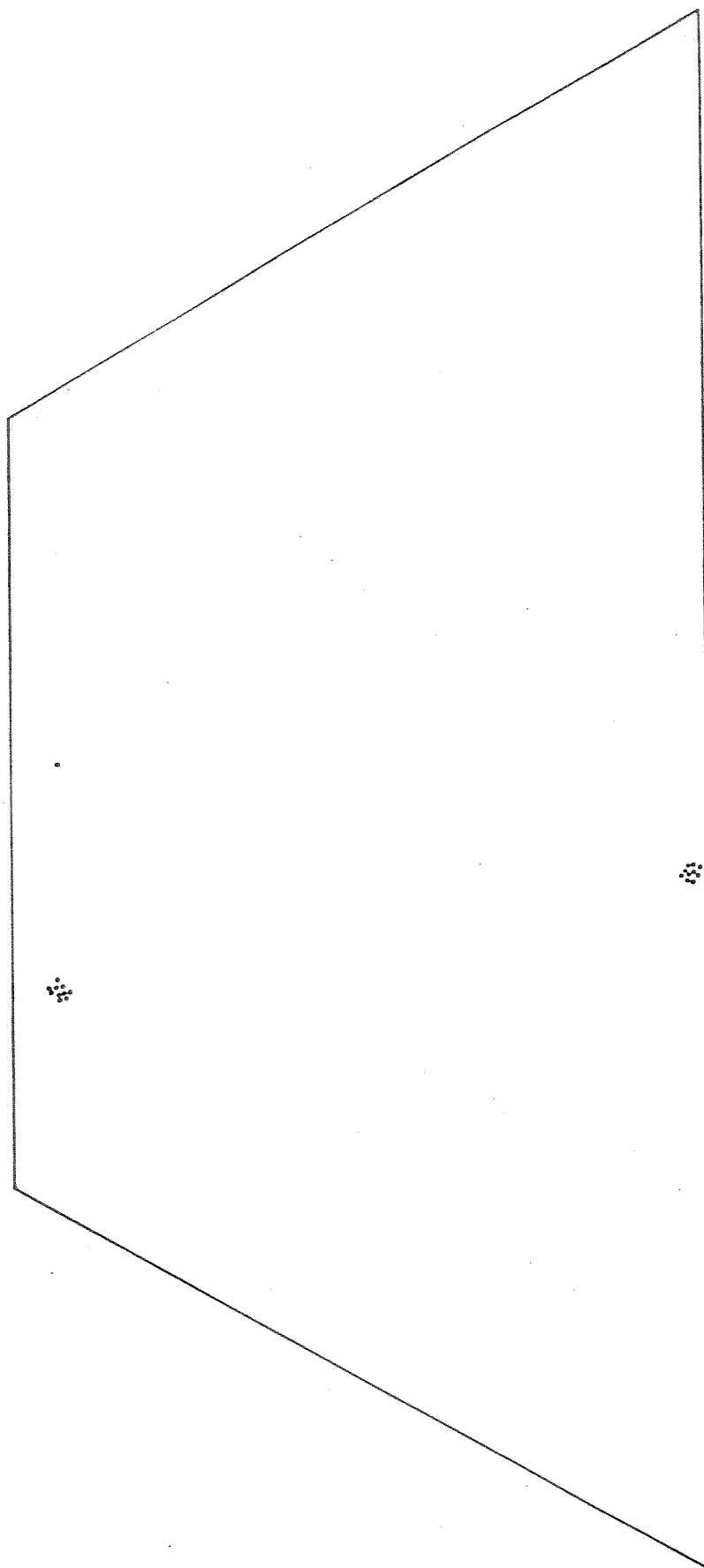


Fig. D-9. Plot of pyroxene compositions from specimen 9.

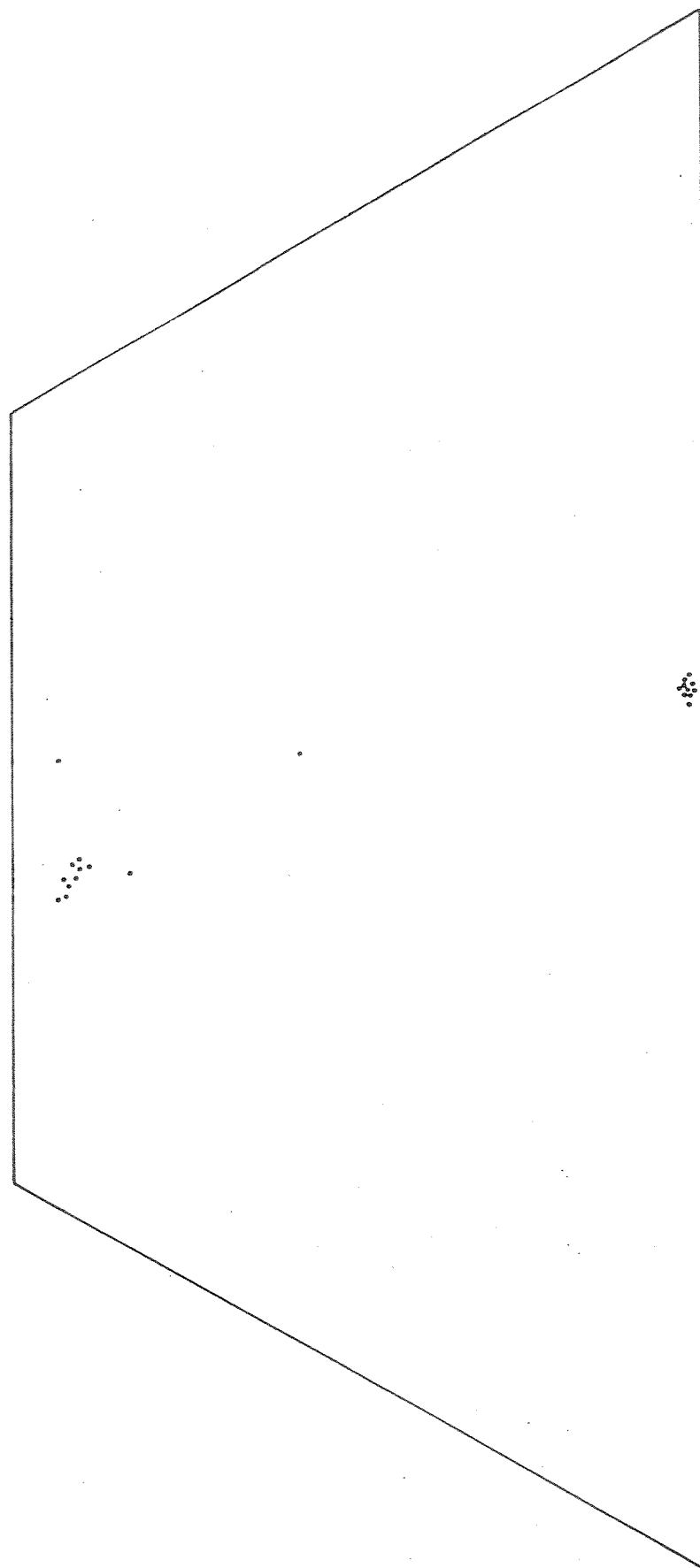


Fig. D-10. Plot of pyroxene compositions from specimen 10.

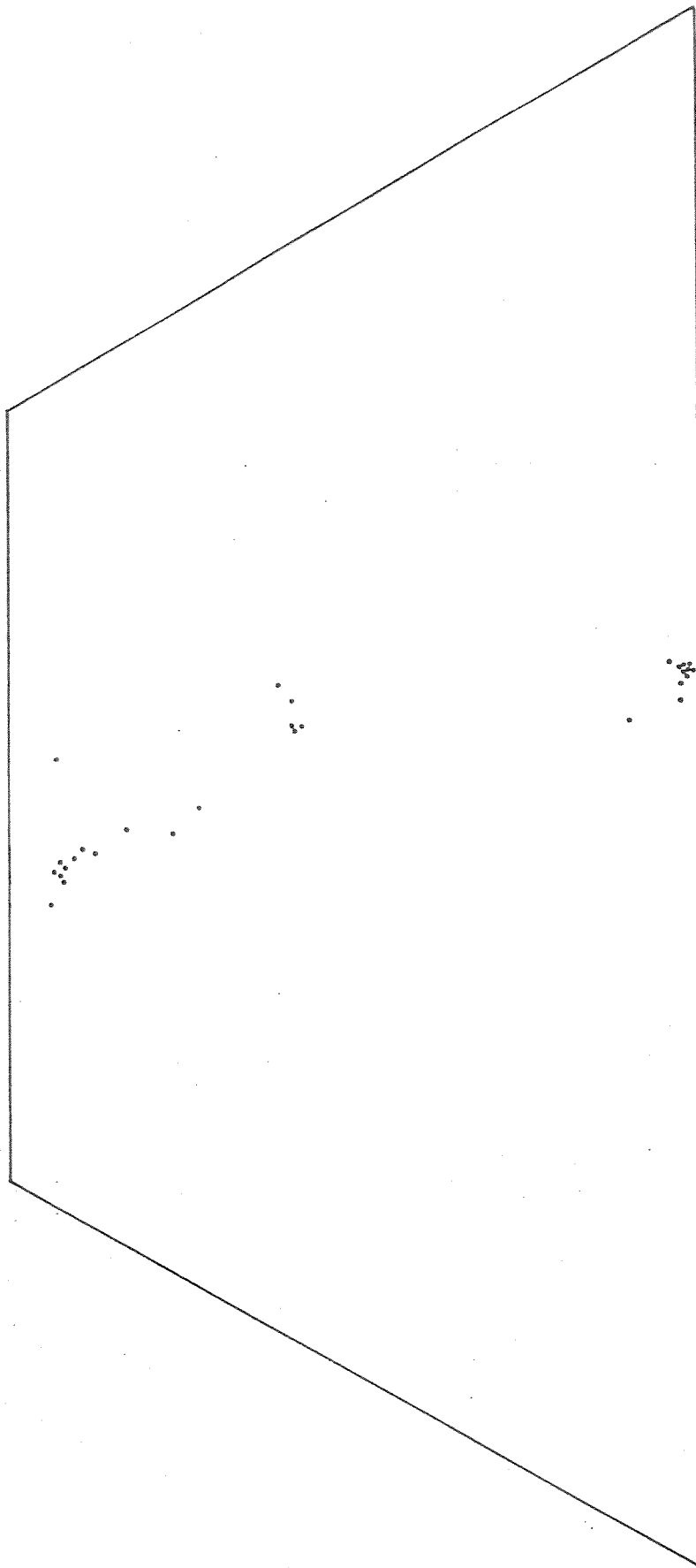


Fig. D-11. Plot of pyroxene compositions from specimen 11.

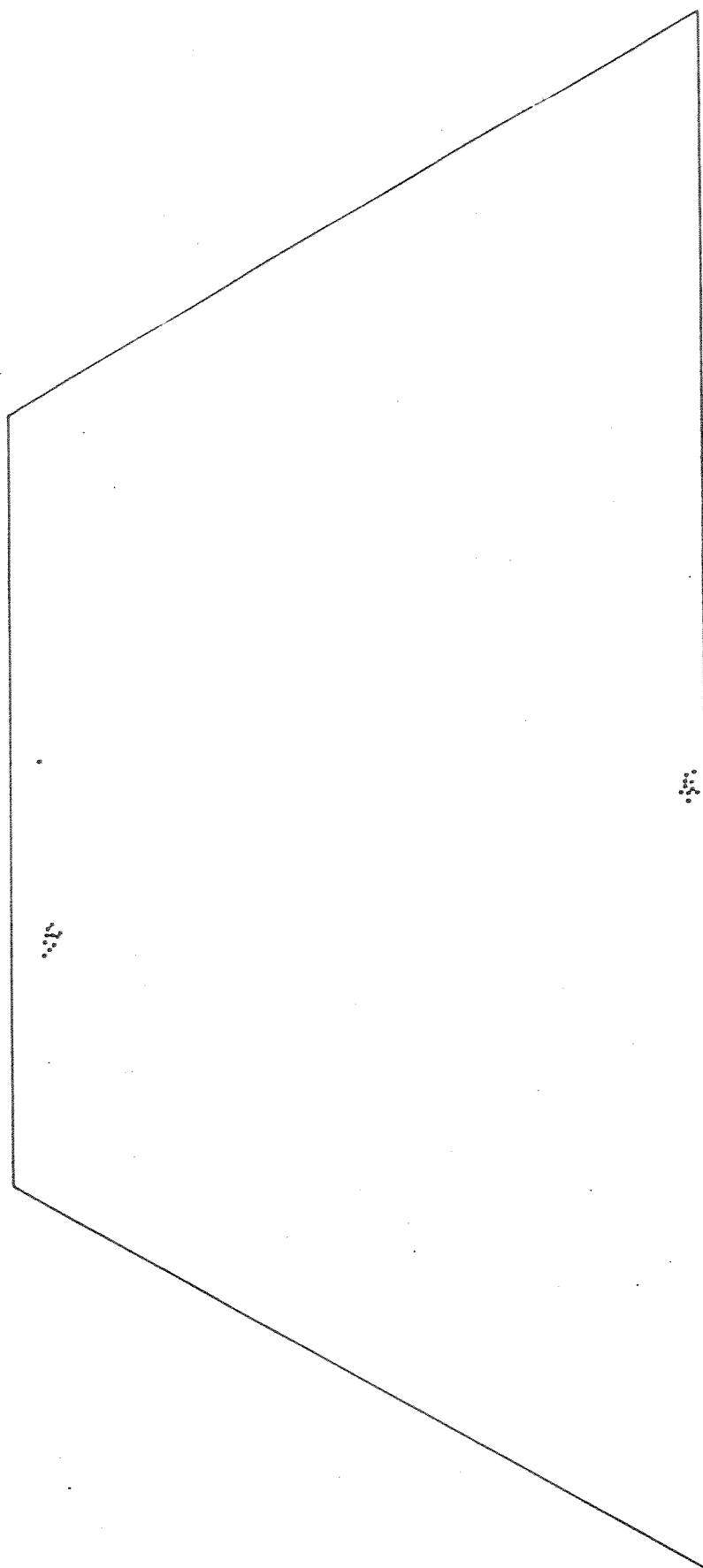


Fig. D-12. Plot of pyroxene compositions from specimen 12.

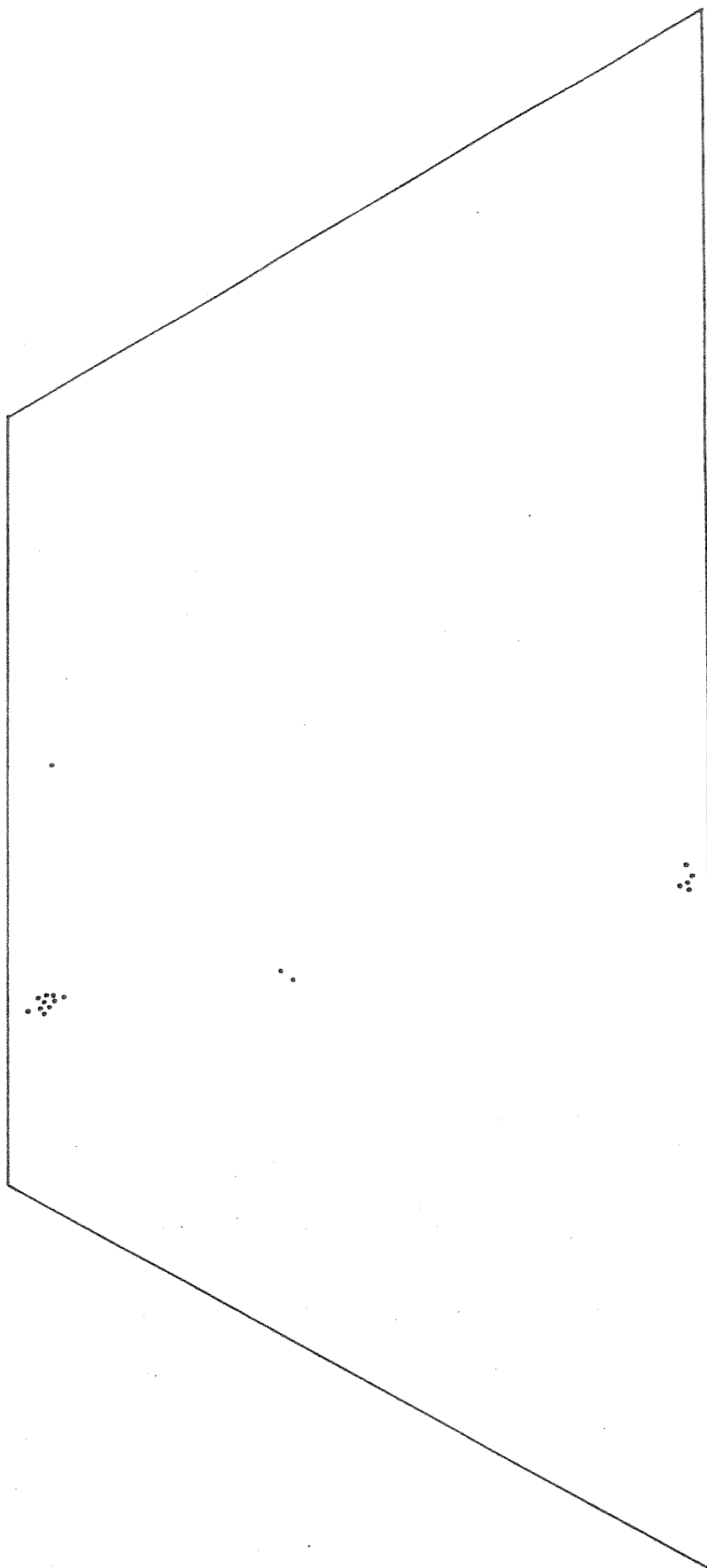


Fig. D-13. Plot of pyroxene compositions from specimen 13.

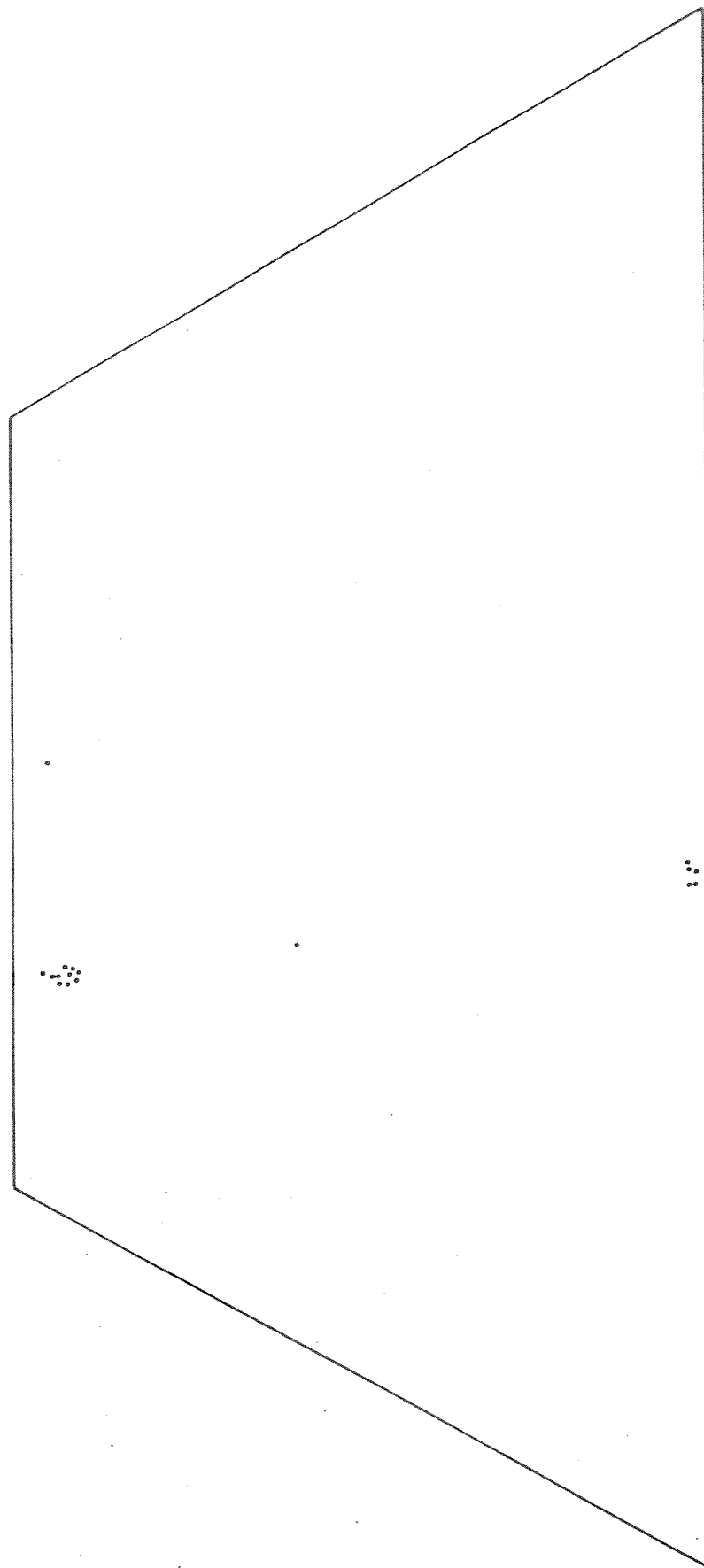


Fig. D-14. Plot of pyroxene compositions from specimen 14.

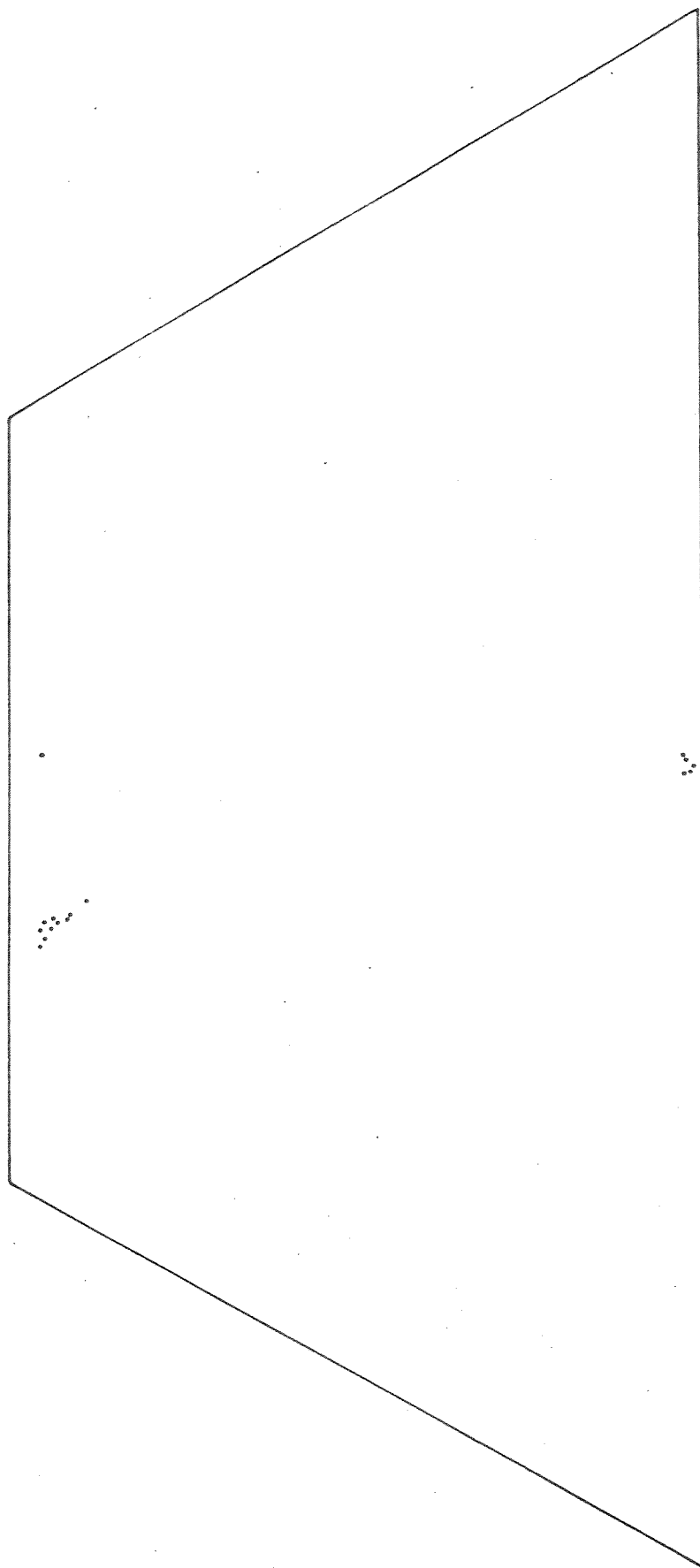


Fig. D-15. Plot of pyroxene compositions from specimen 15.

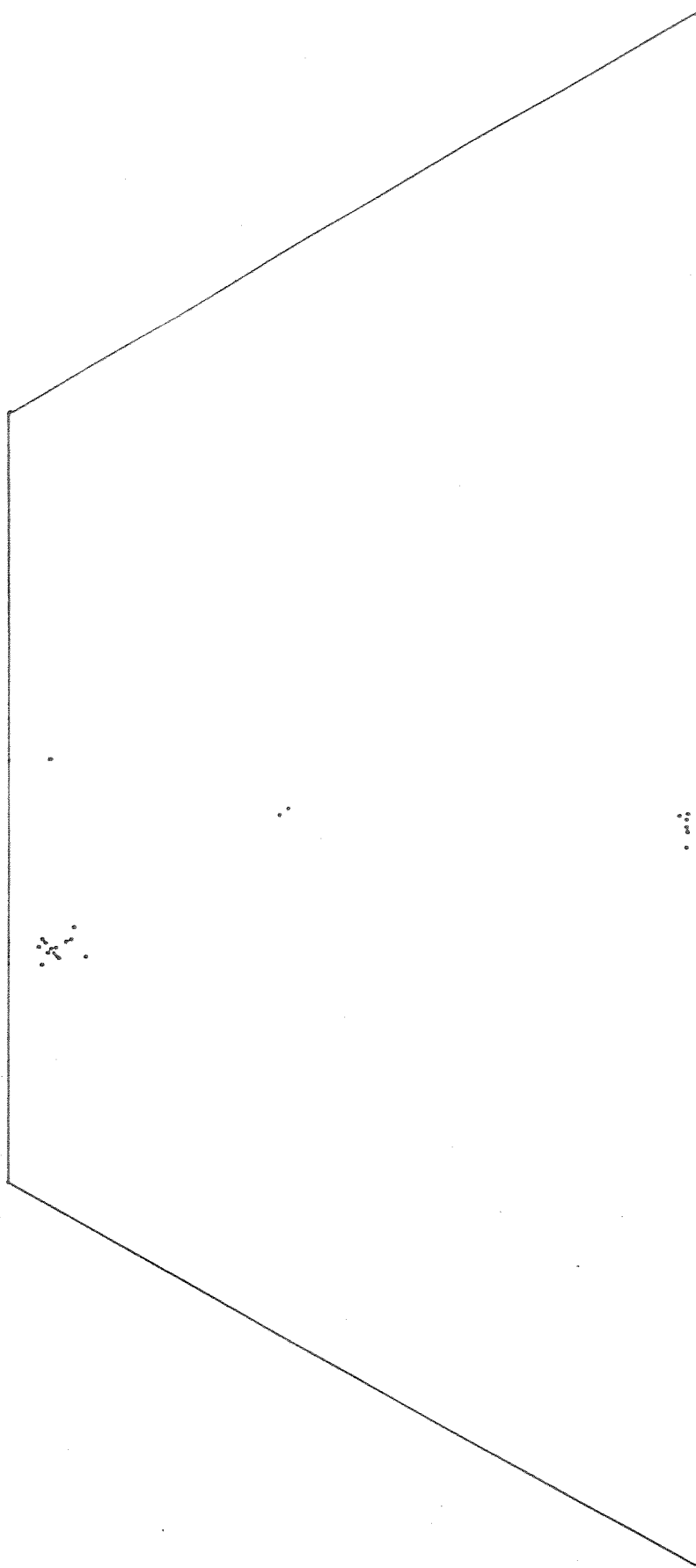


Fig. D-16. Plot of pyroxene compositions from specimen 16.

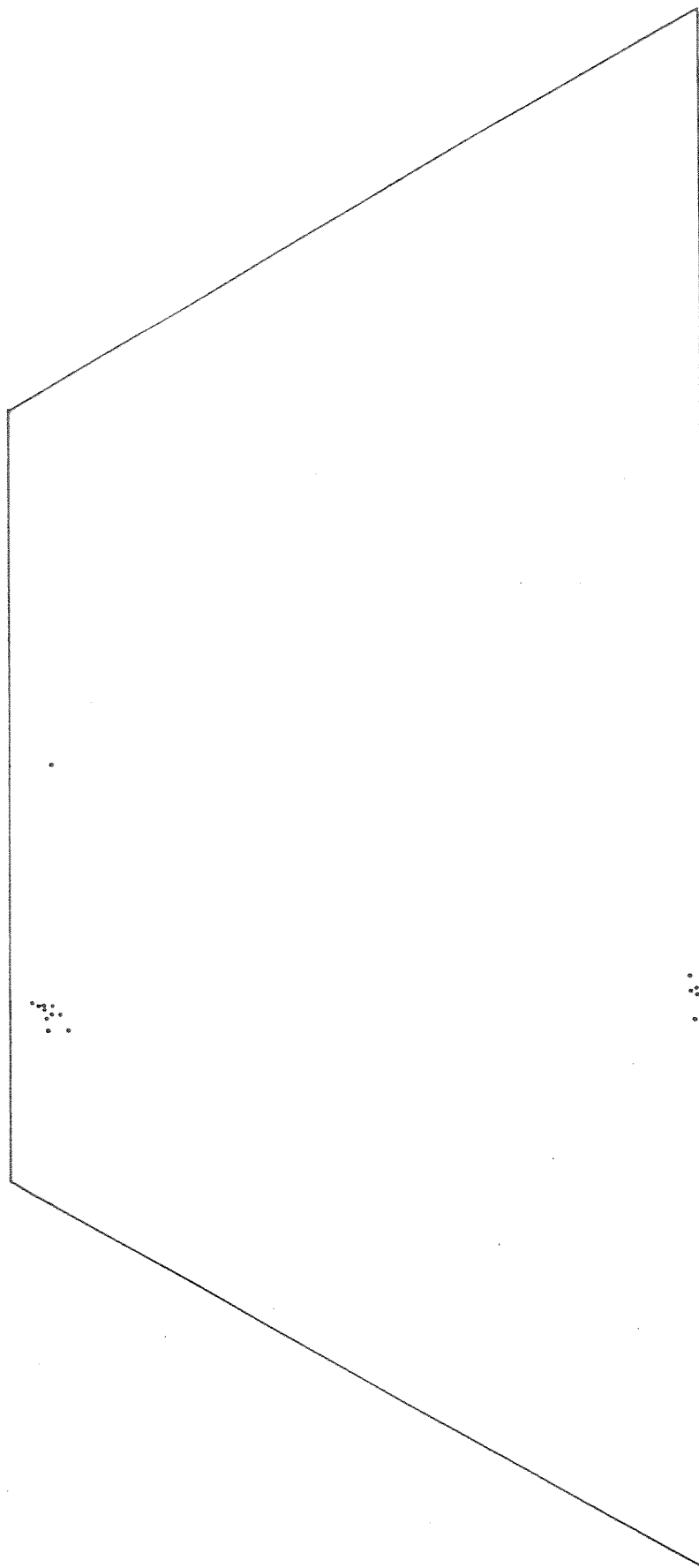


Fig. D-17. Plot of pyroxene compositions from specimen 17.

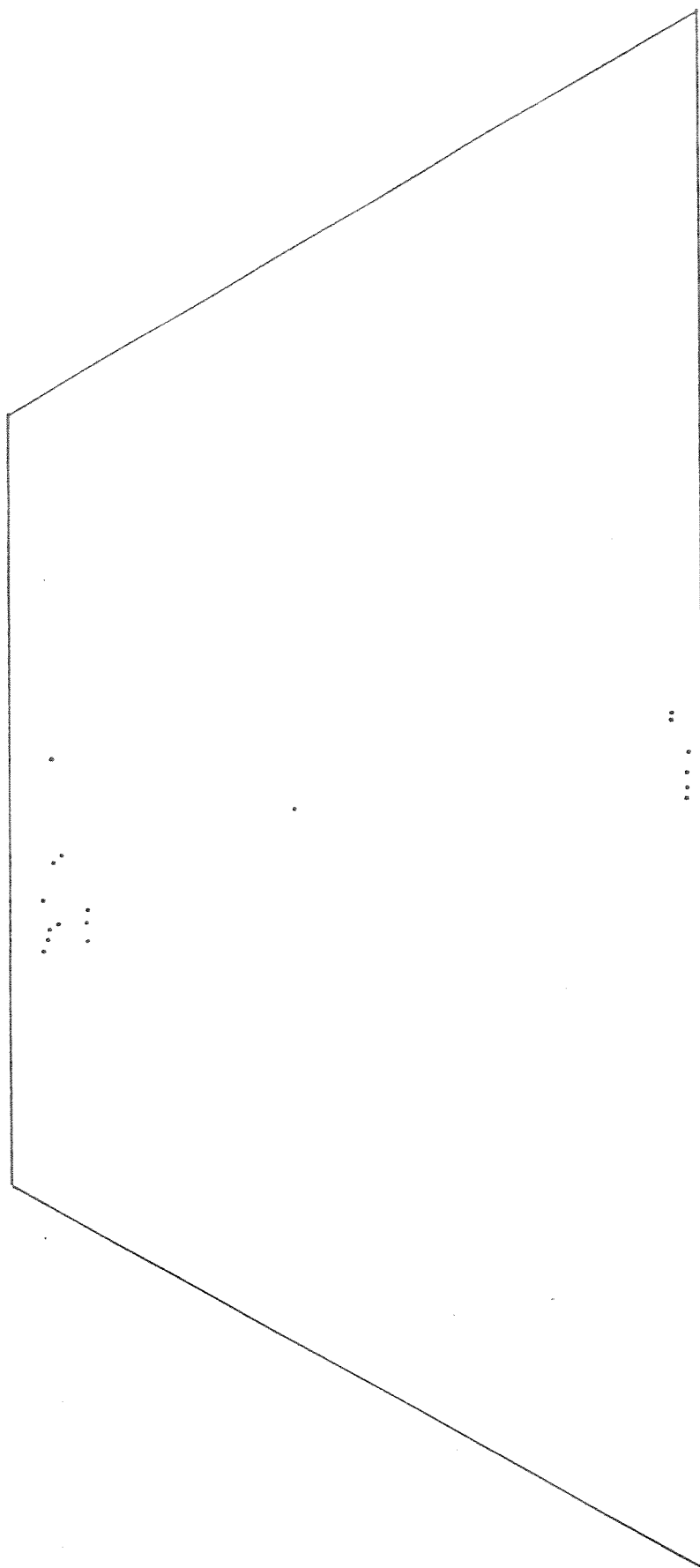


Fig. D-18. Plot of pyroxene compositions from specimen 18.

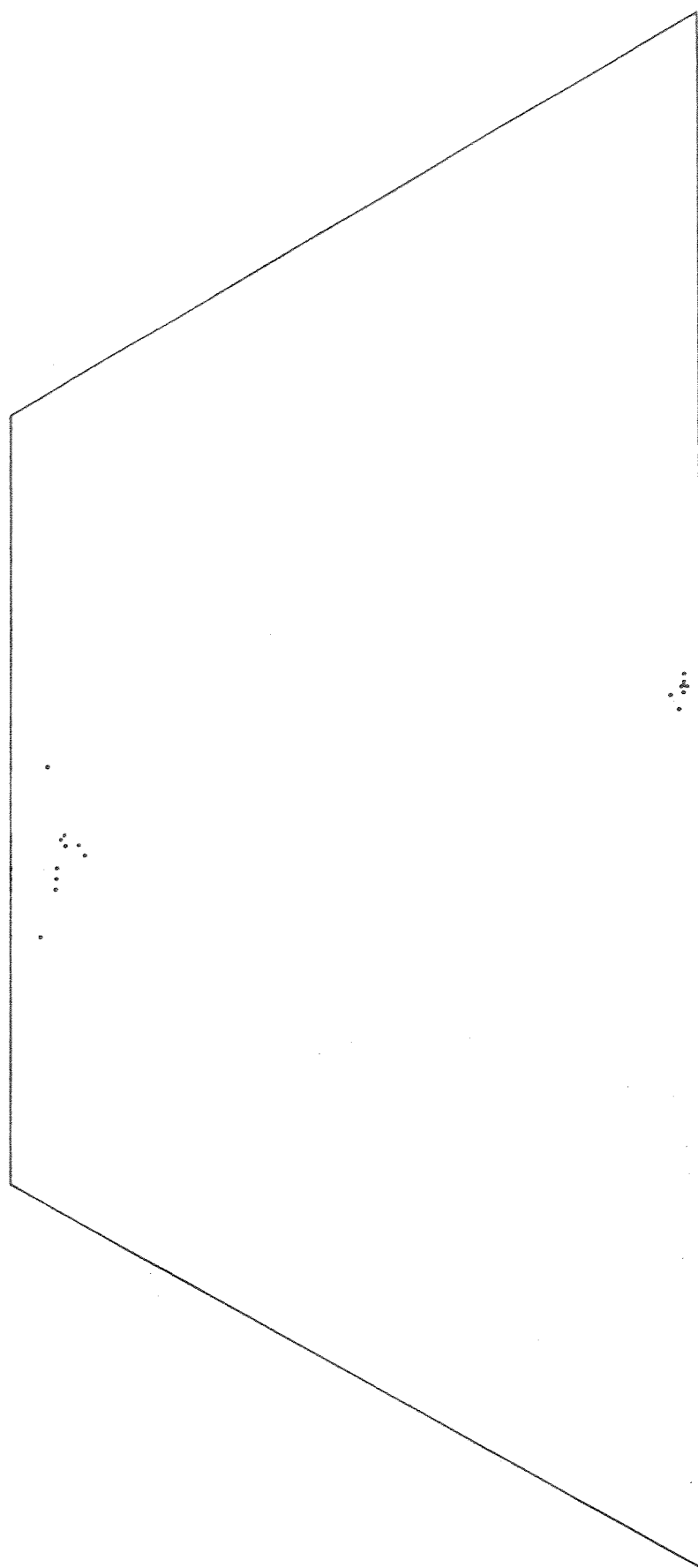


Fig. D-20. Plot of pyroxene compositions from specimen 20.

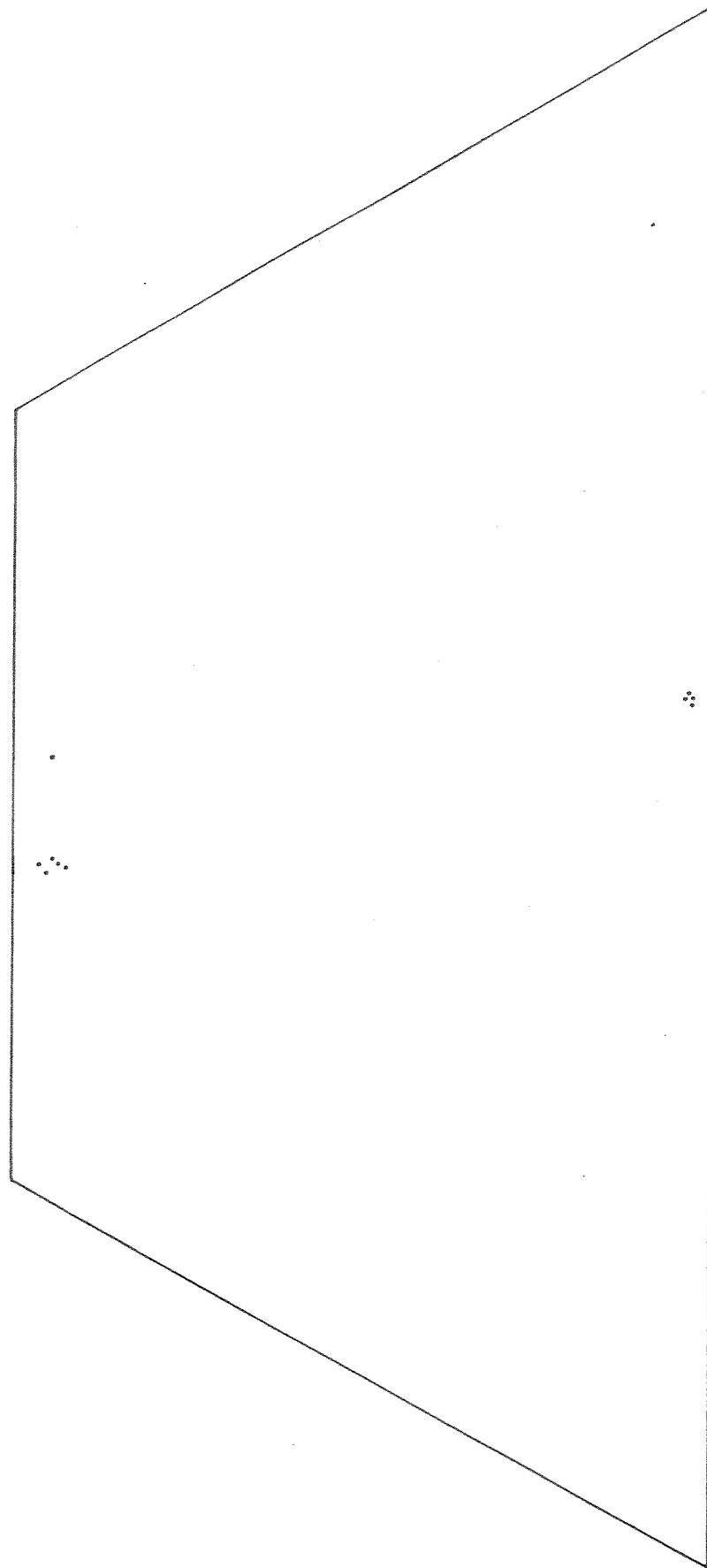


Fig. D-22. Plot of pyroxene compositions from specimen 22.

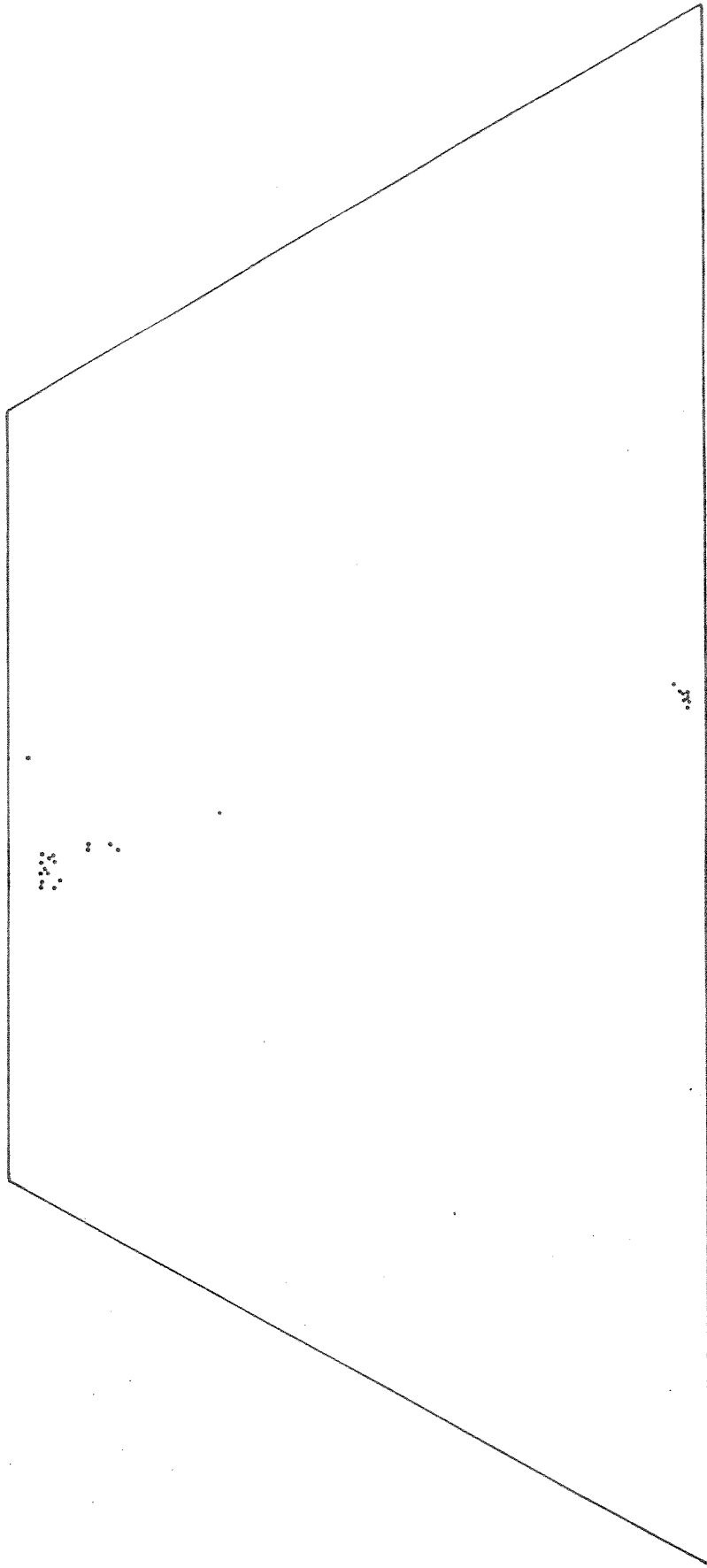


Fig. D-23. Plot of pyroxene compositions from specimen 23.

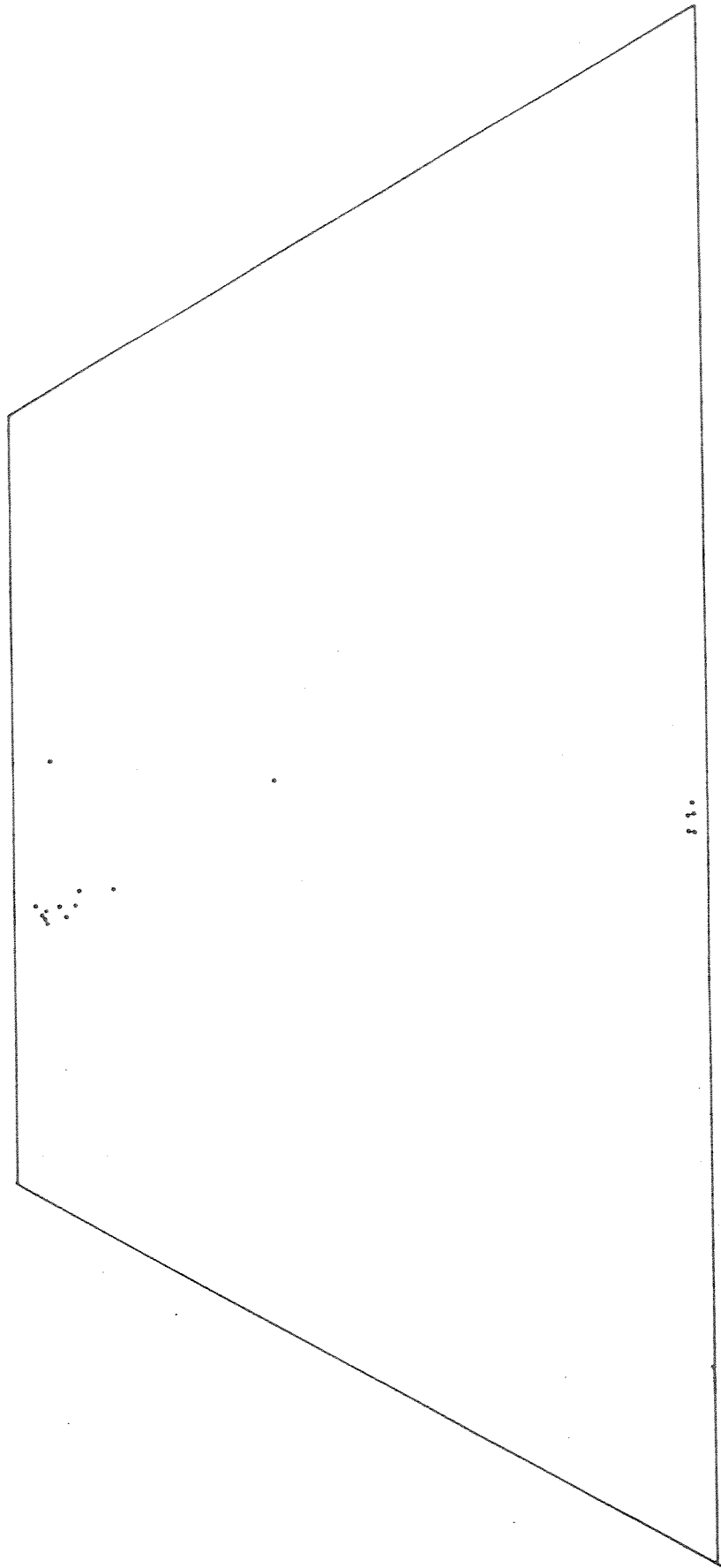


Fig. D-24. Plot of pyroxene compositions from specimen 24.



Fig. D-25. Plot of pyroxene compositions from specimen 25.

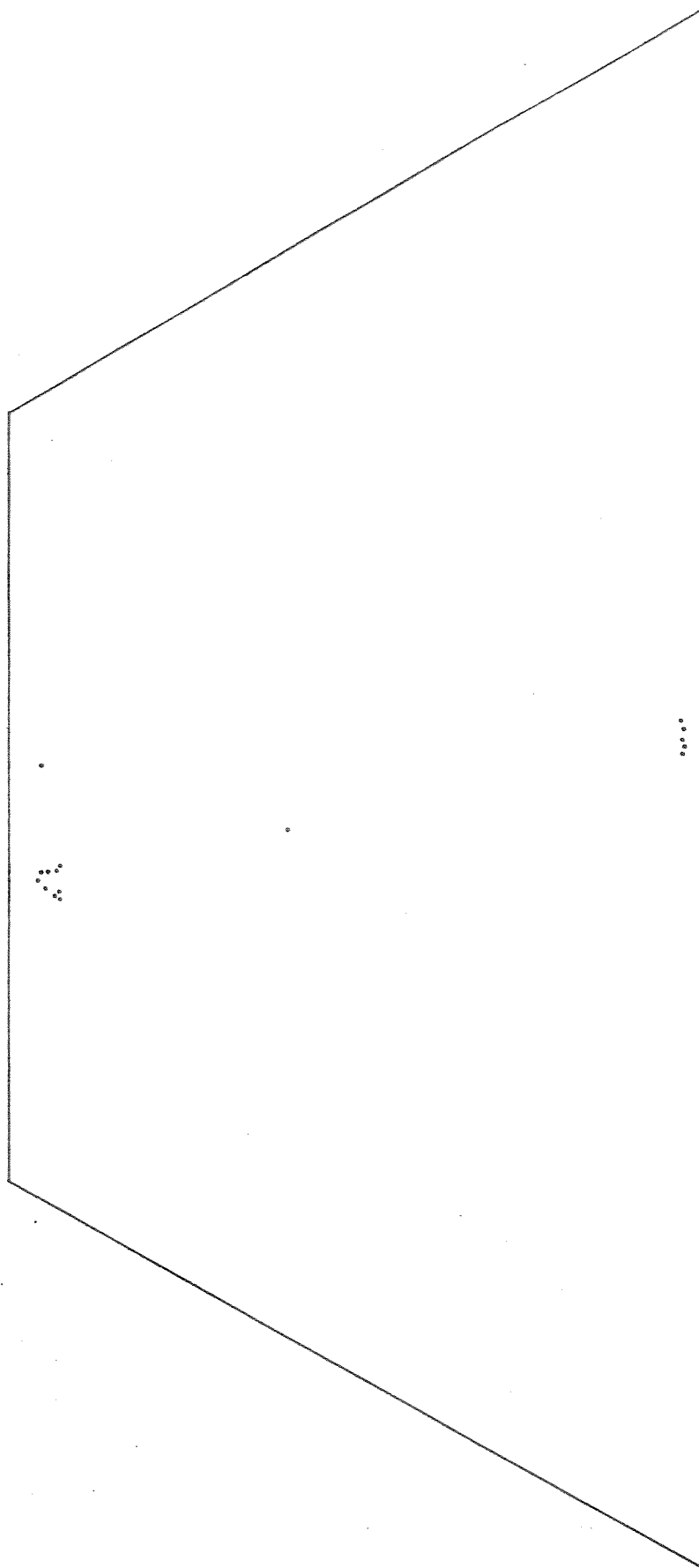


Fig. D-26. Plot of pyroxene compositions from specimen 26.

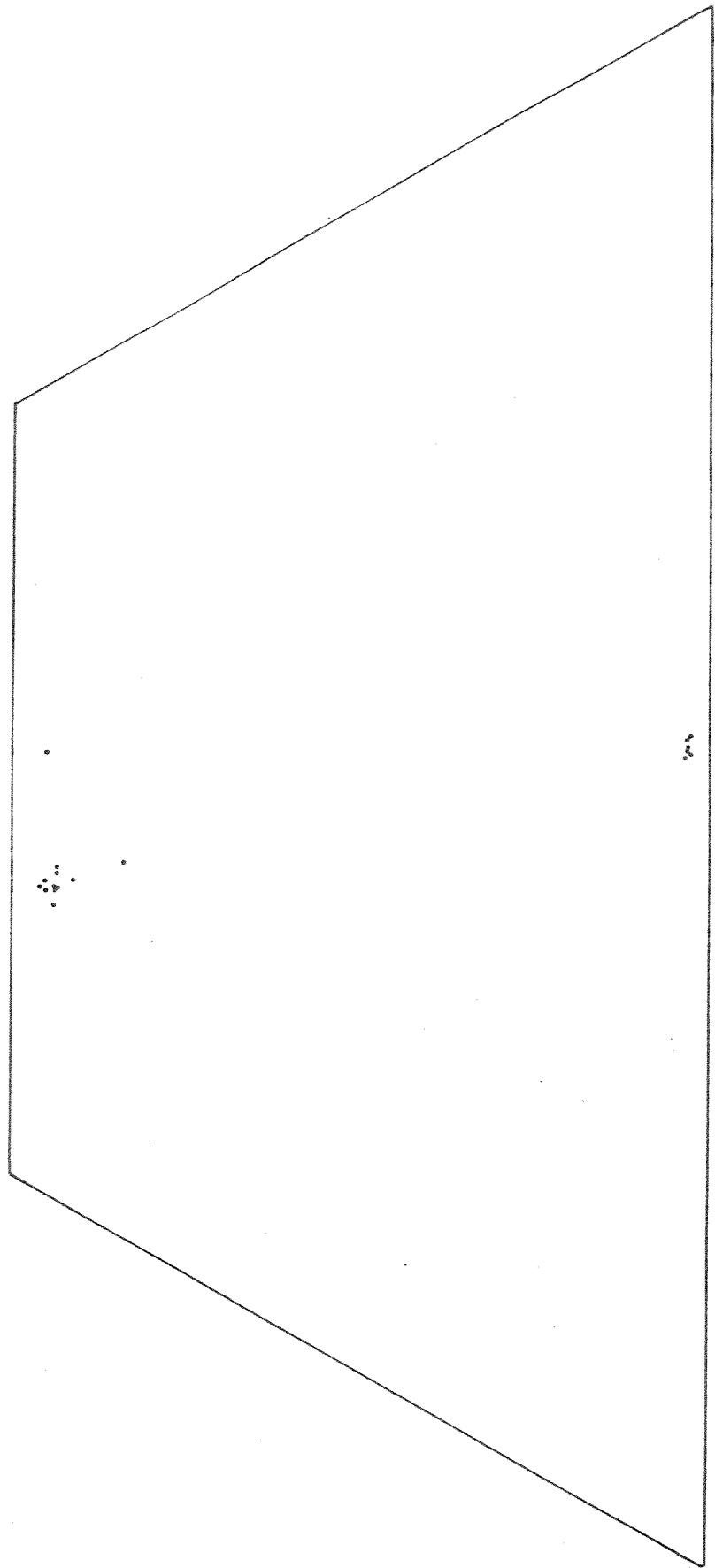


Fig. D-27. Plot of pyroxene compositions from specimen 27.

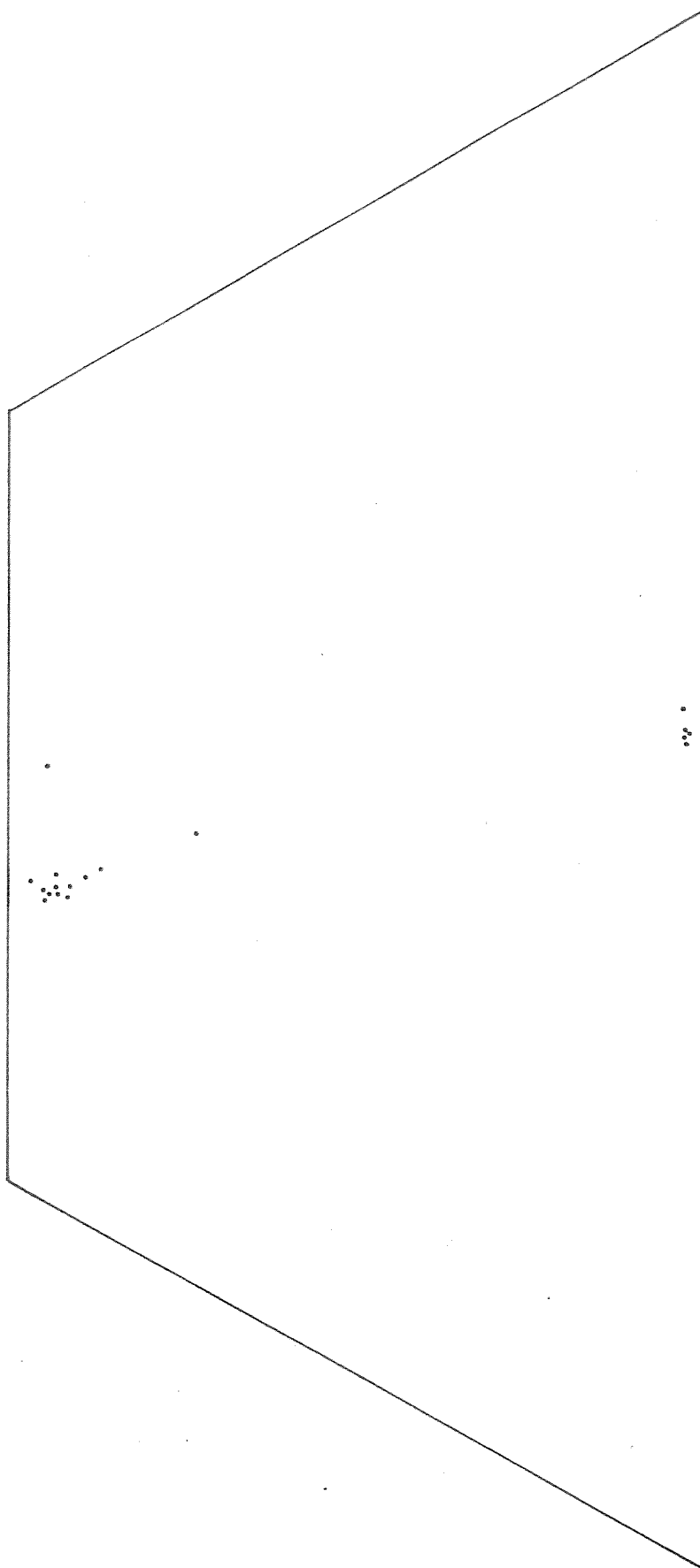


Fig. D-28. Plot of pyroxene compositions from specimen 28.

APPENDIX E

Sample Locations*

- 156C (10) Hermon quadrangle. On road, 1.78 km. north-northwest of Fairbanks Corners.
- 159A (18) Hermon quadrangle. Just south of Devils Corners on Rt.
159E (11) 87, 0.68 km. northwest of BM 707.
- 512 (1) Hermon quadrangle. On Rt. 87, 1.70 km. northwest of
514 (14) bridge across Grass River just south of Russell.
515 (13)
- 201B (12) Hermon quadrangle. On Rt. 87, 1.25 km. northwest of
bridge across Grass River just south of Russell.
- 519 (3) Hermon quadrangle. Along northeast portion of Rt. 87,
520 (2) just south of Devils Elbow.
- 524 (7) Hermon quadrangle. On road, 0.38 km. south of Fairbanks
525 (9) Corners.
- 505 (5) Harrisville quadrangle. On road to Balmat, northwest of
Geers Corners, 0.70 km. northwest of BM 797.
- 76B (17) Harrisville quadrangle. On road between Geers Corners
and Harrisville, 0.28 km. south of BM 772.
- 88B (15) Lake Bonaparte quadrangle. 0.54 km. east-northeast of
eastern end of road at north end of Hitchcock Bay.
- 222C (20) Pierrepoint quadrangle. On Clare Road, 0.8 km. northwest
of the intersection with Allen Road.
- 232A (22) Pierrepoint quadrangle. On road, 2.8 km. southwest of
road intersection in Pierrepoint.
- 234 (23) Pierrepoint quadrangle. On road, 2.25 km. southwest of
road intersection in Pierrepoint.
- 236A (24) Pierrepoint quadrangle. On road, 1.35 km. southwest of
236B (25) road intersection in Pierrepoint.
236C (16)
- 534 (6) Pierrepoint quadrangle. On road, 1.25 km. southwest of
road intersection in Pierrepoint.
- 260A (27) Colton quadrangle. 2.4 km. north of St. Patricks Church.
260B (28)

259F (26) Colton quadrangle. 0.5 km. north of BM 797 which is on road, 1.25 km. northeast of Pleasant Mound Cemetery.

* All distances given are straight-line as measured on the respective quadrangle. All place names as given on the respective quadrangle.

APPENDIX F

Table 2. Mineral analyses and structural formulae for coexisting pyroxenes from the Adirondack Lowlands.

Table 2. Mineral analyses and structural formulae for coexisting pyroxenes.

No. anal. in aver.	1(512)			2(520)			3(519)			5(505)		
	C	O		C	O		C	O		C	O	
SiO ₂	51.372	51.063		52.237	52.070		52.199	51.317		52.079	51.351	
TiO ₂	0.178	0.068		0.210	0.104		0.173	0.090		0.111	0.045	
Al ₂ O ₃	2.026	1.095		1.470	0.835		1.474	0.922		1.599	0.862	
Cr ₂ O ₃	0.126	0.126		0.064	0.056		0.154	0.096		0.062	0.043	
FeO	11.407	29.715		10.818	28.832		9.560	28.242		9.970	27.911	
MnO	0.362	0.935		0.209	0.407		0.217	0.503		0.441	1.055	
MgO	11.840	16.854		12.399	18.100		13.141	18.501		12.698	17.876	
CaO	21.987	0.584		22.056	0.612		22.140	0.652		22.457	0.506	
Na ₂ O	0.413	0.024		0.199	0.010		0.310	0.013		0.407	0.000	
TOTAL	99.711	100.464		99.662	101.026		99.368	100.336		99.824	99.649	
Molecular formulae on the basis of 6 oxygen atoms												
Si	1.938	1.967		1.971	1.978		1.967	1.963		1.961	1.978	
Ti	0.005	0.002		0.006	0.003		0.005	0.003		0.003	0.001	
Al	0.090	0.050		0.065	0.037		0.065	0.042		0.071	0.039	
Cr	0.004	0.004		0.002	0.002		0.005	0.003		0.002	0.001	
Fe	0.362	0.959		0.342	0.914		0.301	0.904		0.314	0.899	
Mn	0.012	0.030		0.007	0.013		0.007	0.016		0.014	0.034	
Mg	0.669	0.969		0.697	1.025		0.738	1.055		0.713	1.026	
Ca	0.894	0.022		0.892	0.025		0.894	0.027		0.906	0.021	
Na	0.030	0.002		0.015	0.001		0.023	0.001		0.030	0.000	
TOTAL	3.984	4.005		3.997	3.998		4.005	4.014		4.014	3.999	
en	34.77	49.65		36.11	52.11		38.17	53.13		36.85	52.70	
fs	18.77	49.11		17.68	46.93		15.59	45.53		16.30	46.19	
wo	46.43	1.24		46.19	1.27		46.25	1.35		46.90	1.07	

Table 2 (contd.).

No. anal. in aver.	6(534)			7(524)			9(525)			10(156C)		
	C 18	O 19	C 10	O 10	C 10	O 10	C 10	O 10	C 9	O 10	C 9	O 10
SiO ₂	51.152	50.929	50.128	49.093	50.128	49.093	52.692	52.170	51.769	50.634	51.769	50.634
TiO ₂	0.246	0.076	0.131	0.083	0.131	0.083	0.142	0.082	0.155	0.076	0.155	0.076
Al ₂ O ₃	2.062	0.953	1.254	0.573	1.254	0.573	1.178	0.587	1.775	0.808	1.775	0.808
Cr ₂ O ₃	0.110	0.096	0.076	0.064	0.076	0.064	0.121	0.077	0.062	0.076	0.062	0.076
FeO	11.751	30.131	17.175	37.986	17.175	37.986	9.252	27.370	13.474	33.571	13.474	33.571
MnO	0.269	0.617	0.433	0.988	0.433	0.988	0.309	0.733	0.450	1.030	0.450	1.030
MgO	11.800	16.842	8.859	11.088	8.859	11.088	13.302	19.096	11.137	14.682	11.137	14.682
CaO	21.657	0.557	20.824	0.713	20.824	0.713	22.472	0.582	21.936	0.599	21.936	0.599
Na ₂ O	0.418	0.014	0.289	0.164	0.289	0.164	0.376	0.012	0.359	0.093	0.359	0.093
TOTAL	99.465	100.215	99.169	101.331	99.169	101.331	99.844	100.709	101.117	101.569	101.117	101.569

Molecular formulae on the basis of 6 oxygen atoms

Si	1.946	1.969	1.962	1.973	1.962	1.973	1.975	1.979	1.953	1.967	1.953	1.967
Ti	0.007	0.002	0.004	0.003	0.004	0.003	0.004	0.002	0.004	0.002	0.004	0.002
Al	0.092	0.043	0.029	0.027	0.029	0.027	0.052	0.026	0.079	0.037	0.079	0.037
Cr	0.003	0.003	0.003	0.002	0.003	0.002	0.004	0.002	0.002	0.002	0.002	0.002
Fe	0.374	0.974	0.562	1.277	0.562	1.277	0.290	0.868	0.425	1.091	0.425	1.091
Mn	0.009	0.020	0.014	0.034	0.014	0.034	0.010	0.024	0.014	0.034	0.014	0.034
Mg	0.669	0.971	0.517	0.664	0.517	0.664	0.743	1.079	0.626	0.850	0.626	0.850
Ca	0.883	0.023	0.873	0.031	0.873	0.031	0.902	0.024	0.886	0.025	0.886	0.025
Na	0.031	0.001	0.022	0.002	0.022	0.002	0.027	0.001	0.026	0.007	0.026	0.007
TOTAL	4.014	4.006	3.986	4.013	3.986	4.013	4.007	4.005	4.015	4.015	4.015	4.015
en	34.74	49.33	26.50	33.80	26.50	33.80	38.39	54.76	32.30	43.25	32.30	43.25
fs	18.41	49.50	28.80	64.80	28.80	64.80	14.98	44.05	21.93	55.49	21.93	55.49
wo	46.84	1.12	44.80	1.56	44.80	1.56	46.64	1.20	45.75	1.27	45.75	1.27

Table 2 (contd.).

No. anal. in aver.	11(159E)			12(201B)			13(515)			14(514)		
	C	9	O 10	C 10	O 10		C 10	O 5		C 10	O 5	
SiO ₂	51.409		50.299	52.184	50.896		52.324	51.896		51.437	50.778	
TiO ₂	0.150		0.073	0.193	0.086		0.178	0.073		0.158	0.080	
Al ₂ O ₃	1.637		0.788	1.751	0.790		1.297	0.998		1.300	1.037	
Cr ₂ O ₃	0.056		0.073	0.086	0.063		0.140	0.087		0.092	0.096	
FeO	13.497		33.398	10.761	29.456		8.466	26.348		9.643	27.072	
MnO	0.443		1.036	0.365	0.900		0.277	0.663		0.302	0.696	
MgO	10.773		14.145	11.969	16.595		13.397	18.459		12.883	18.709	
CaO	21.489		0.641	22.278	0.570		22.306	0.516		21.758	0.552	
Na ₂ O	0.419		0.045	0.394	0.041		0.207	0.006		0.220	0.003	
TOTAL	99.873		100.498	99.981	99.397		98.592	99.046		97.793	99.023	

Molecular formulae on the basis of 6 oxygen atoms

Si	1.963	1.975	1.966	1.981	1.978	1.990	1.971	1.962
Ti	0.004	0.002	0.006	0.003	0.005	0.002	0.005	0.002
Al	0.066	0.036	0.078	0.036	0.058	0.045	0.059	0.047
Cr	0.002	0.002	0.003	0.002	0.004	0.003	0.003	0.003
Fe	0.431	1.097	0.339	0.959	0.268	0.845	0.309	0.875
Mn	0.014	0.035	0.012	0.030	0.009	0.021	0.010	0.023
Mg	0.613	0.828	0.672	0.963	0.755	1.055	0.736	1.077
Ca	0.879	0.027	0.899	0.024	0.903	0.021	0.893	0.023
Na	0.031	0.003	0.029	0.003	0.015	0.001	0.016	0.000
TOTAL	4.003	4.005	4.004	4.001	3.995	3.983	4.002	4.012
en	31.87	42.42	35.19	49.41	39.19	54.92	37.97	54.54
fs	22.41	56.22	17.76	49.30	13.90	43.98	15.95	44.28
wo	45.72	1.39	46.58	1.22	46.93	1.10	46.10	1.16

Table 2 (contd.).

No. anal. in aver.	15(88B)			16(236C)			17(76B)			18(159A)		
	C	10	O	5	C	13	O	6	C	10	O	6
SiO ₂	51.489		50.853		51.567		51.646		52.260		51.619	
TiO ₂	0.189		0.066		0.309		0.092		0.278		0.202	
Al ₂ O ₃	1.662		0.794		2.406		1.135		1.693		1.668	
Cr ₂ O ₃	0.082		0.083		0.310		0.322		0.280		0.216	
FeO	11.075		29.791		10.497		29.152		7.773		11.786	
MnO	0.346		0.777		0.314		0.760		0.133		0.333	
MgO	11.608		15.834		12.350		18.216		13.660		11.524	
CaO	21.711		0.523		22.103		0.548		22.401		21.634	
Na ₂ O	0.357		0.009		0.499		0.119		0.497		0.477	
TOTAL	98.519		98.730		100.355		101.990		98.975		99.459	
									99.166			99.597

Molecular formulae on the basis of 6 oxygen atoms

Si	1.971	1.993	1.936	1.953	1.963	1.975	1.964	1.970
Ti	0.005	0.002	0.009	0.003	0.008	0.002	0.006	0.003
Al	0.075	0.037	0.106	0.051	0.075	0.044	0.075	0.043
Cr	0.003	0.003	0.009	0.010	0.008	0.008	0.006	0.007
Fe	0.354	0.977	0.330	0.922	0.244	0.713	0.375	0.992
Mn	0.011	0.026	0.010	0.025	0.004	0.009	0.011	0.026
Mg	0.662	0.925	0.691	1.027	0.765	1.223	0.653	0.926
Ca	0.890	0.022	0.889	0.022	0.902	0.018	0.882	0.031
Na	0.026	0.001	0.036	0.009	0.036	0.011	0.035	0.006
TOTAL	3.997	3.986	4.016	4.022	4.005	4.003	4.007	4.004
en	34.72	48.08	37.18	52.08	40.01	62.60	34.18	47.50
fs	18.60	50.76	17.25	46.78	12.78	36.52	19.64	50.88
wo	46.68	1.14	46.56	1.13	47.19	0.90	46.17	1.61

Table 2 (contd.).

No. anal. in aver.	20(222C)				22(232A)				23(234)				24(236A)			
	C	9	0	7	C	5	0	4	C	12	0	8	C	9	0	5
SiO ₂	51.127		50.621		51.070		50.556		51.250		51.097		51.343		51.114	
TiO ₂	0.198		0.082		0.211		0.109		0.237		0.077		0.314		0.058	
Al ₂ O ₃	1.949		1.001		2.127		1.059		1.840		0.884		2.739		1.161	
Cr ₂ O ₃	0.049		0.045		0.050		0.042		0.083		0.080		0.070		0.043	
FeO	13.773		33.706		13.186		33.330		12.930		32.289		11.630		28.506	
MnO	0.343		0.843		0.405		0.947		0.375		0.933		0.379		0.862	
MgO	10.626		14.603		10.501		15.031		10.451		14.535		11.384		17.593	
CaO	21.931		0.719		22.204		0.618		21.815		0.616		22.017		0.514	
Na ₂ O	0.176		0.118		0.618		0.244		0.446		0.041		0.529		0.033	
TOTAL	100.172		101.728		100.372		101.936		99.427		100.552		100.405		99.884	
Molecular formulae on the basis of 6 oxygen atoms																
Si	1.949		1.963		1.943		1.955		1.962		1.989		1.935		1.969	
Ti	0.006		0.003		0.006		0.003		0.007		0.002		0.009		0.002	
Al	0.088		0.046		0.095		0.048		0.083		0.041		0.122		0.053	
Cr.	0.002		0.001		0.001		0.001		0.003		0.003		0.002		0.001	
Fe	0.439		1.093		0.419		1.078		0.414		1.051		0.367		0.918	
Mn	0.011		0.028		0.013		0.031		0.012		0.031		0.012		0.028	
Mg	0.604		0.844		0.596		0.866		0.596		0.843		0.640		1.010	
Ca	0.896		0.030		0.905		0.026		0.895		0.026		0.889		0.021	
Na	0.013		0.009		0.045		0.018		0.033		0.003		0.039		0.003	
TOTAL	4.008		4.017		4.023		4.026		4.005		3.989		4.015		4.005	
en	31.12		42.90		31.00		44.00		31.29		43.91		33.77		51.80	
fs	22.66		55.57		21.86		54.70		21.72		54.73		19.33		47.10	
wo	46.20		1.52		47.14		1.30		46.96		1.34		46.92		1.09	

Table 2 (contd.).

No. anal. in aver.	25(236B)			26(259F)			27(260A)			28(260B)		
	C	10	O	5	C	9	O	5	C	10	O	5
SiO ₂	51.308		51.241		51.126		50.747		51.123		51.786	
TiO ₂	0.275		0.092		0.309		0.067		0.321		0.301	
Al ₂ O ₃	2.631		1.274		2.543		1.261		2.404		2.344	
Cr ₂ O ₃	0.060		0.065		0.081		0.082		0.071		0.089	
FeO	12.252		29.782		12.621		31.415		12.267		12.616	
MnO	0.370		0.868		0.339		0.779		0.388		0.325	
MgO	11.139		16.991		10.741		15.458		11.009		11.091	
CaO	22.027		0.504		21.830		0.621		21.927		22.254	
Na ₂ O	0.508		0.034		0.463		0.047		0.458		0.434	
TOTAL	100.570		100.854		100.053		100.477		99.968		101.240	
												101.504

Molecular formulae on the basis of 6 oxygen atoms

Si	1.936	1.965	1.942	1.969	1.941	1.967	1.943	1.971
Ti	0.008	0.003	0.009	0.002	0.009	0.003	0.008	0.003
Al	0.117	0.058	0.114	0.058	0.108	0.063	0.104	0.058
Cr	0.002	0.002	0.003	0.002	0.002	0.002	0.003	0.003
Fe	0.387	0.955	0.401	1.020	0.390	0.998	0.396	1.025
Mn	0.012	0.028	0.011	0.026	0.013	0.029	0.010	0.023
Mg	0.627	0.971	0.608	0.894	0.623	0.907	0.620	0.885
Ca	0.891	0.021	0.888	0.026	0.892	0.027	0.895	0.026
Na	0.037	0.003	0.034	0.004	0.034	0.003	0.031	0.004
TOTAL	4.017	4.006	4.010	4.001	4.012	3.999	4.010	3.998
en	32.89	49.88	32.03	46.08	32.73	46.95	32.46	45.64
fs	20.30	49.06	21.13	52.58	20.46	51.66	20.70	52.94
wo	46.77	1.06	46.83	1.33	46.84	1.38	46.83	1.36

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- 1961-67 New York State National Guard - United States Army Reserve.
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