Manitoba
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Geological Report GR82-3

The Fox River Sill, Northeastern Manitoba - A Major Stratiform Intrusion

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Winnipeg, 1990

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INTRODUCTION

FOX RIVER BELT

The Fox River Belt forms a segment of the Circum-Superior Belt (Baragar and Scoates, 1981), a sequence of Proterozoic supracrustal rocks of similar age, stratigraphy and lithologies, that occurs around the margin of the Archean Superior Province (Fig. 1). The belt borders the northeast edge of the Superior Province craton in Manitoba for approximately 300 km, and forms a portion of the Churchill-Superior boundary zone. It consists of sedimentary rocks, large differentiated sills, and ultramafic to mafic volcanic rocks (Table 1) (Scoates, 1977; 1981), which together form a north-facing, homoclinal sequence that is interpreted to have been deposited upon Superior Province crust (Scoates, 1981; Fig. 2). Fox River Belt rocks have suffered low to very low grade metamorphism. Pumpellyite and prehnite are widespread in the volcanic rocks (Scoates, 1981). Metamorphic grade increases to the south, with stratigraphic depth.

FOX RIVER SILL

The Fox River Sill, a stratiform ultramafic-mafic complex, forms an integral part of the Fox River Belt. In the western part of the Belt, the Sill comprises two lobes or segments, each approximately 70 km long and separated by a gap of 12 km. Distinctive aeromagnetic anomalies, east of the eastern segment, indicate that ultramafic rocks extend for another 120 km eastward, beneath Paleozoic cover rocks of the Hudson Bay Lowland (Fig. 3). Thus the west lobe of the Sill, examined in this report, represents only a part of a much larger, stratiform intrusion that is more than 250 km in length. The thickness of the western segment averages slightly more than 2 km, at the present erosional surface.

The Sill, which intruded a sequence of siltstone, sandstone, argillite and shale (Middle sedimentary formation), is subdivided into four zones (Fig. 4): Marginal Zone (MZ - 270 m), Lower Central Layered Zone (LCLZ - 875 m), Upper Central Layered Zone (UCLZ - 925 m), and Hybrid Roof Zone (HRZ - 50 m). Thicknesses were determined from different areas using outcrop and drill hole data; individual zones display a variation in thickness from place to place along strike. Each zone is characterized by distinctive lithologic units, and except for the HRZ, by distinctive cyclic arrangement of units. The intrusion is predominantly ultramafic in composition; more than 75 percent of the Sill consists of olivine-rich cumulate rocks.

MZ rocks occur along the south margin of the Sill, and, with the exception of one drill hole, have been found along the entire length of the west lobe of the intrusion. The zone ranges in thickness from several metres to several hundred metres and is distinguished by repetitions of olivine, clinopyroxene and plagioclase cumulate layers that constitute cyclic units. The LCLZ succession, which has been found along the entire length of the west lobe of the intrusion, is composed predominantly of cyclic repetitions of paired dunite and olivine clinopyroxenite layers. Each cyclic unit is considered to represent an interruption in the process of fractional crystallization caused by an influx of fresh magma into the chamber that, in turn, caused a resetting or starting over of the fractional crystallization process. UCLZ rocks are distinguished from LCLZ rocks by the presence of orthopyroxene in olivine, clinopyroxene and plagioclase cumulate rocks, and by the presence of plagioclase cumulate rocks, that form the uppermost layers of many UCLZ cyclic units. UCLZ rocks are widespread, although they appear to be absent in the easternmost part of the west lobe of the Sill. The HRZ separates UCLZ cyclic units from overlying rocks of the Middle sedimentary formation. The rocks of the HRZ are a mixture of Sill and roof rocks, caused by incorporation of roof rocks into the Sill magma.

The intrusion is characterized by well developed compositional layering reflecting the predominant cumulus phases. A composite section, in the western part of the intrusion, is composed of a minimum of 70 layers. This total does not include layers less than 1 m thick, small-scale rhythmic layers, macrorhythmic layers, nor grain size graded layers. The layers belong to cyclic units each comprising two or three layers. The successive layers of a cyclic unit are composed of cumulus minerals that correspond to the order of appearance of phases that crystallize from basic magma with decreasing temperature. Thirty-five cyclic units have been identified in the composite section.

Observation of shallower dips in LCLZ and UCLZ succession, compared with the near vertical dip of MZ rocks, as measured in the Great Falls outcrop area, suggests that the intrusion may possess a lopolithic or funnel shape in cross section.

Chemical variations emphasize the differences between the four major subdivisions of the intrusion. Each of the major subdivisions of the intrusion, in addition to possessing diagnostic layers and cyclic units, is distinguished also by characteristic MgO/MgO + FeO ratios. MZ rocks range from 0.62 to 0.73 and average 0.67. The lowermost 60 m of the LCLZ succession displays a sharp increase from 0.78 to 0.87, and the succeeding 700 m of LCLZ stratigraphy displays a gradual progressive increase from 0.87 to 0.92. Individual LCLZ cyclic units display slight progressive increase in MgO/MgO ± FeO from base to top. The LCLZ succession, apart from the lower 60 m, displays little variation in MgO/MgO + FeO.

The dramatic change in size and composition of cyclic units that occurs at the LCLZ-UCLZ contact is reflected in a change of MgO/MgO + FeO. UCLZ rocks display a range from 0.72 to 0.89, and there is a decrease in MgO/MgO + FeO from base to top of individual cyclic units. The HRZ displays a range from 0.47 to 0.59.

The dramatic change in the character of the main layered succession at the LCLZ-UCLZ contact represents a significant event in the magmatic history of the intrusion. The changes in composition of the cyclic units imply changes in composition of the magma that produced the UCLZ cyclic units. These changes in magma composition may reflect changes in the composition of introduced magma batches and/or mixing of those batches with the overlying residual magma column.

Volcanic rocks overlie the Sill and are separated from the intrusion by several hundred metres of sedimentary rocks. The volcanic sequence (Upper volcanic formation, Scoates, 1981) ranges in thickness from 2500 to 3500 m and consists of a lower zone of olivine-bearing, layered, differentiated flow units and komatiitic basalt flows, a middle zone of pillowed olivine clinopyroxenite and massive layered flows and an upper zone of massive and pillowed basalt. The lavas display a progressive change in mineralogical and chemical composition with stratigraphic height that suggests derivation of the lavas from a subvolcanic chamber in which differentiation was taking place. Various ternary chemical diagrams illustrate the relationship between the progressive change in liquidus minerals in the Sill magma and the character of the evolved liquids as demonstrated by the progressive chemical changes in the associated Upper volcanic formation lavas. The lavas are interpreted to represent samples of the residual magma column of the Fox River Sill magma chamber at different times in its evolution (Scoates, 1981, 1984).

Disseminated magmatic sulphides are common accessory phases in parts of the MZ, UCLZ and HRZ succession, and are rare in LCLZ rocks. Pyrrhotite, pentlandite, chalcopyrite, pyrite, cubanite, and mackinawite have been identified. Awaruite, pentlandite and heazlewoodite have been identified as rare fine grained minerals in LCLZ serpentinized dunite.

The presence of locally abundant magmatic sulphides in cyclic units above the LCLZ-UCLZ contact is considered especially noteworthy. Their association with UCLZ orthopyroxene and plagioclase-bearing orthocumulates suggests that these zones of disseminated sulphides may be potentially significant for

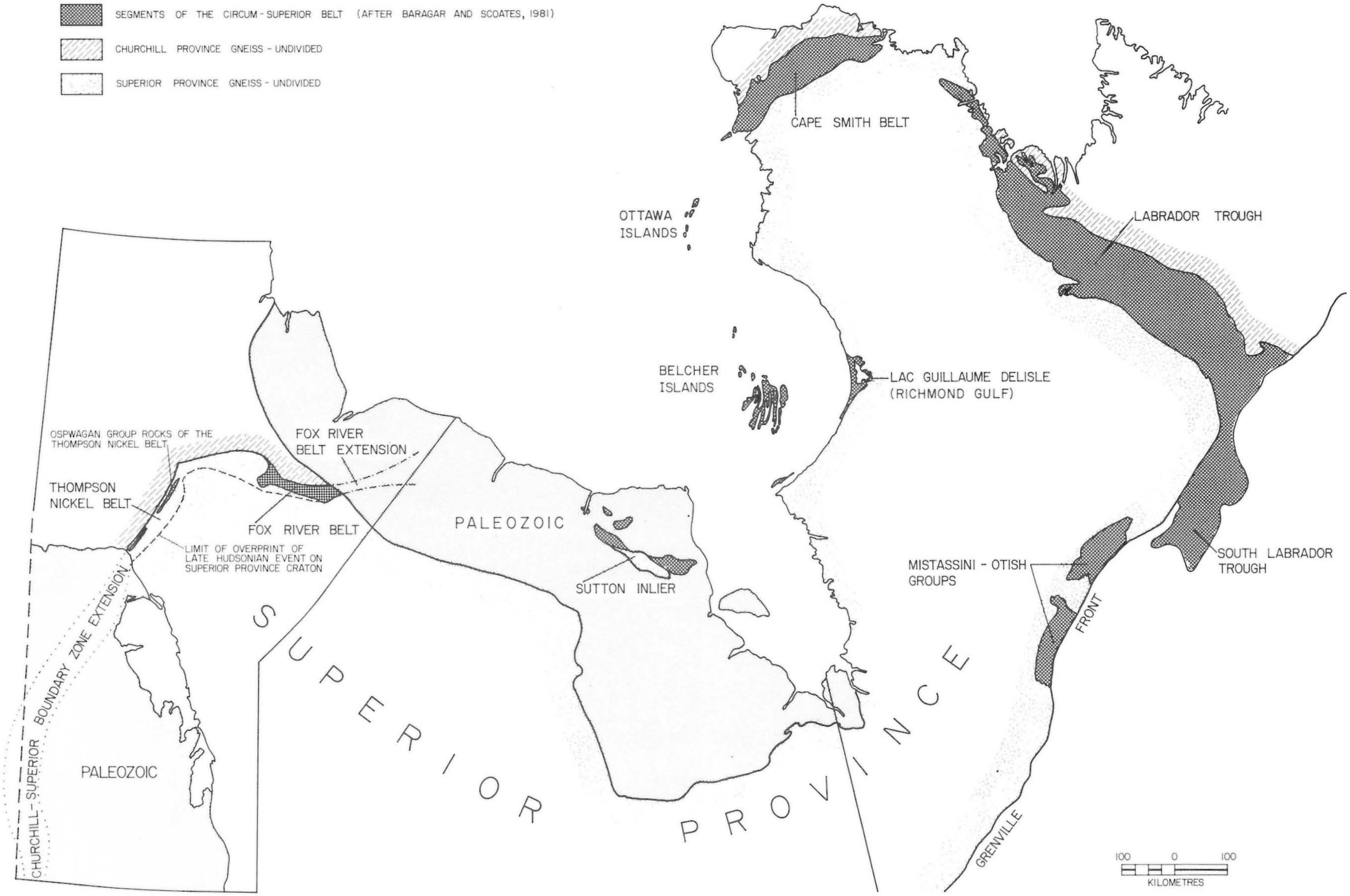


Figure 1: *Relation of Fox River Belt to northern part of Circum-Superior Belt.*

Era	METAMORPHIC ROCKS	FOX RIVER BELT: SEDIMENTARY AND VOLCANIC ROCKS		FOX RIVER BELT: INTRUSIVE ROCKS	
PRECAMBRIAN – PROTEROZOIC – APHEBIAN	[1]Paragneiss of the Churchill Province (Northern Gneiss)				
	contact with Fox River Belt rocks exposed in DDH 38505 — faulted contact? — contact with Archean gneiss not exposed-faulted contact?				
			[1]contact with Churchill Province paragneiss exposed in DDH 38505 — faulted contact?		
		Upper sedimentary formation	[2](1.0-2.0 km) argillite, shale, carbonaceous shale		
			contact exposed in DDH 38507 — conformable?		intrusive contact
		Upper volcanic formation	[2](2.5-3.4 km) massive and layered komatiitic basalt, pillowed and massive olivine clinopyroxenite, pillowed and massive basalt	Fox River Sill	[2](2.0 km) differentiated, stratiform, ultramafic-mafic intrusion (intrusive into Middle sedimentary formation rocks and interpreted to be time equivalent with the extrusion of Upper volcanic formation lavas)
			contact exposed in DDH 38579 and 11921 — conformable?		intrusive contact
		Middle sedimentary formation	[2](0.3-0.8 km) quartz-bearing siltstone, sandstone and argillite (host to Fox River Sill)		
			contact not exposed — conformable?		intrusive contact
		Lower volcanic formation	[2](2.0-2.5 km) massive and layered komatiitic basalt, pillowed and massive olivine clinopyroxenite, pillowed and massive basalt	Lower differentiated intrusions	[2](0.8 km) differentiated ultramafic-mafic intrusions (intrusive into Lower sedimentary formation rocks and interpreted to be time equivalent with the extrusion of Lower volcanic lavas)
			contact exposed in DDH 13214 — conformable?		intrusive contact
		Lower sedimentary formation	[3](4.0-4.5 km) argillite, siltstone, shale, sandstone, dolomite and iron formation (host to Lower differentiated instructions)		
			contact with Superior Province Archean gneiss not exposed — faulted contact?		
	contacts between Archean gneiss and Churchill Province paragneiss, and Fox River Belt rocks not exposed — faulted contacts?				
ARCHEAN	Archean gneiss of the Superior Province craton (Southern Gneiss)				

1) The age relation between Churchill Province paragneiss and Fox River Belt rocks is uncertain. The paragneiss may be older than is shown. It may be time equivalent with, or older than Fox River Belt rocks.
2) Thickness estimate.
3) True thickness probably less than this as there is evidence of folding toward the base of the formation.

TABLE 1: Table of Formations

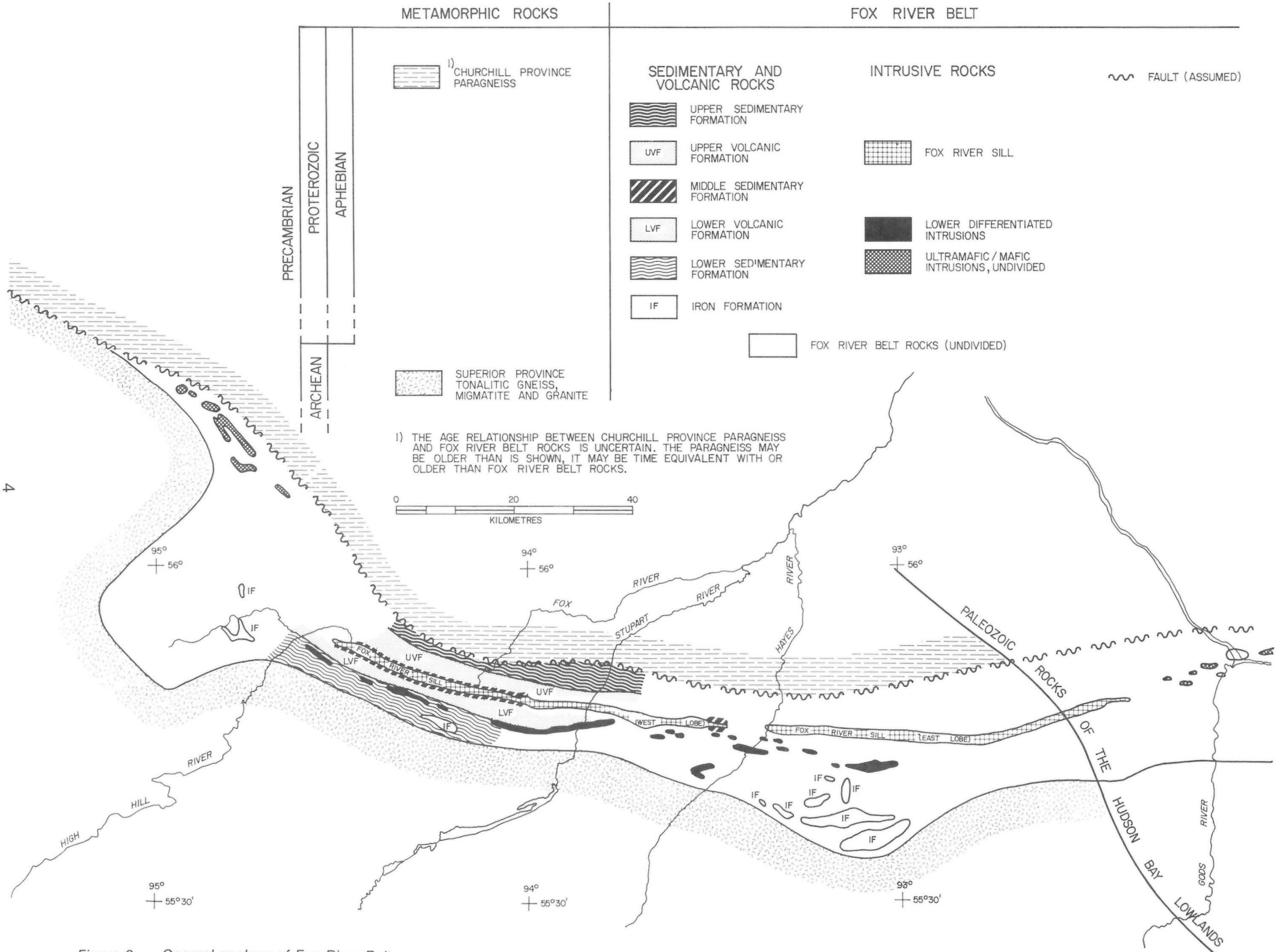
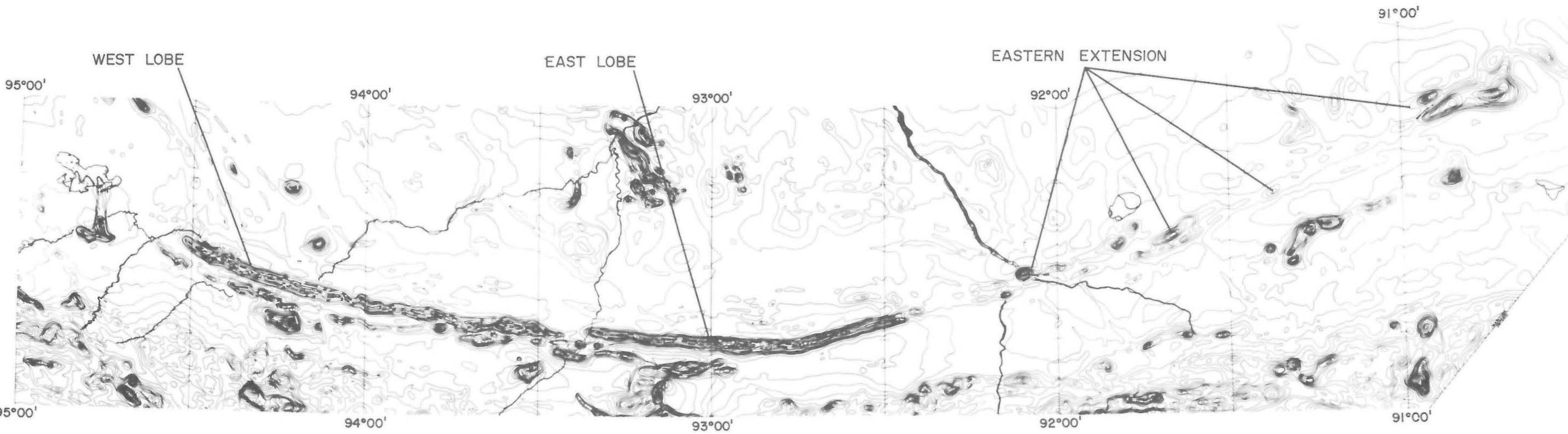
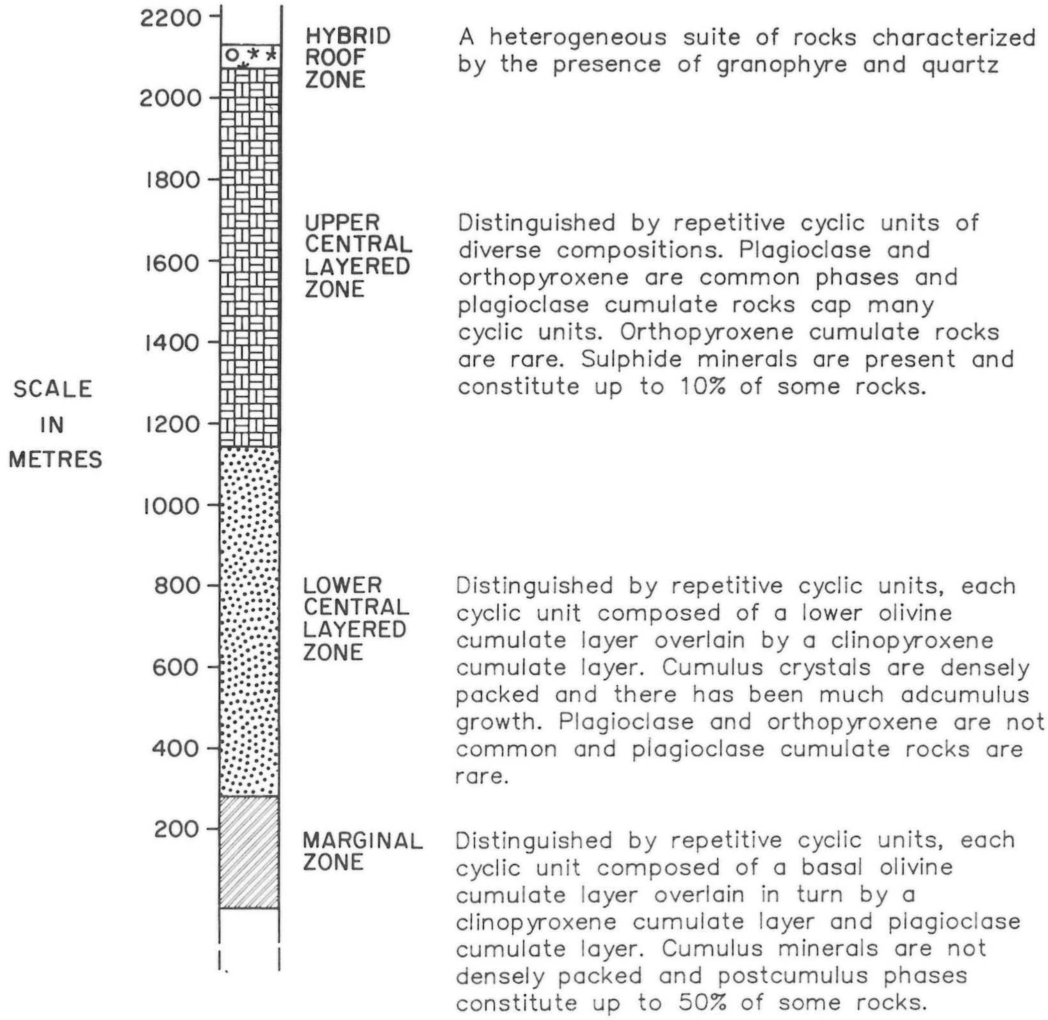


Figure 2: General geology of Fox River Belt.



AEROMAGNETIC EXPRESSION OF FOX RIVER SILL

Figure 3: Aeromagnetic expression of Fox River Sill.



This is a generalized stratigraphic section based on outcrop and drill hole data from areas west of the "pinch and swell" structure of the west lobe of the Sill. Individual zones display variations in thickness and in number of cyclic units from place to place along strike.

Figure 4: General stratigraphic section - Fox River Sill.

concentrations of platinum group elements, by analogy with platiniferous horizons in other major stratiform intrusions.

Chromite is a widely distributed primary cumulus phase in olivine cumulate rocks of the intrusion. Locally, it displays anomalous concentrations (more than 4 percent) as either heavy disseminations or more rarely as mm-scale layers.

MAJOR STRATIFORM INTRUSIONS

The Fox River Sill is comparable in size to other major layered intrusions; because of its relative inaccessibility and the paucity of outcrop it has been poorly known prior to the present study. The Bushveld Complex, the largest known layered intrusion, underlies about 67 000 km^2 of the Kaapvaal Craton of South Africa (Vermaak and Lees, 1981). The Jurassic Dufek intrusion of Antarctica is a differentiated, stratiform mafic igneous complex that has an areal extent of 24 000-34 000 km^2, and a thickness estimated to be 8 to 9 km (Ford, 1976). The Great Dyke of Zimbabwe is 480 km in length and averages 8 km in width (Wilson, 1982). The Stillwater Complex, as exposed in the Beartooth Mountains of Montana, is 44 km long and 6 km thick, although its topmost units have been eroded (Todd *et al.*, 1982). The Muskox Intrusion in the Bear Province of the Canadian Shield is approximately 120 km long. The southern half of this length is a narrow (150 to 500 m) segmented, vertical dyke. The intrusion, which disappears northward under cover rocks, can be traced by its associated aeromagnetic anomaly for a further 30 km. An associated gravity anomaly extends northward for 230 km (Irvine, 1979). The Duluth Complex of Minnesota, exposed sporadically along an arcuate belt for slightly more than 200 km, has approximately 15 km of section exposed (Weiblen and Morey, 1980). The dyke-like Jimberlana Intrusion in Western Australia extends for 180 km and has a maximum width of 2.5 km (Campbell *et al.*, 1970).

AGE RELATIONSHIPS

The age relationships between Fox River Belt rocks and paragneiss of the adjacent Churchill Province to the north are not clear. The low grade rocks of the Belt could have been deposited after the peak metamorphism and deformation of adjacent Churchill Province rocks.

Alternatively, as the Churchill Province and Fox River Belt are interpreted to be in fault contact, the metamorphism and deformation of the former could have taken place at some distance from the Fox River Belt prior to the event that led to their juxtaposition. The low grade metamorphism of Fox River Belt rocks may represent the effect of the Hudsonian metamorphism of adjacent Churchill Province rocks or alternatively it may reflect the event that led to the juxtaposition of the Fox River Belt and Churchill Province assemblages. A similarity of Rb-Sr ages (about 1740 Ma, Scoates and Clark, in prep.) from Fox River Belt rocks and Churchill Province paragneiss suggests that either of the last two explanations may be viable. The radiometric ages suggest deposition of Fox River Belt rocks prior to 1740 Ma.

Recent U-Pb zircon age determinations (Heaman *et al.*, 1986) for the Fox River Sill (1882.9 $\pm$ 1.5 Ma) and Molson dykes (1883.0 $\pm$ 1.0, 1883.2 +1.5/-1.0 Ma) indicate that the suggestion that the Sill and Molson dykes represent a consanguineous magmatic suite (Scoates and Macek, 1978, Scoates, 1981) is valid.

Contact metamorphism produced by the Sill in rocks of the Lower volcanic formation and the Middle sedimentary formation, and the lack of such contact metamorphism in rocks of the Upper volcanic formation, suggest that intrusion of the Sill postdated Lower volcanic formation and Middle sedimentary formation, was coeval with Upper volcanic formation rocks and, consequently, predated deposition of rocks of the Upper sedimentary formation.

EXPLORATION ACTIVITY

Canadian Nickel Company Limited (Inco) actively explored the area through diamond drilling between 1955 and 1957, and between 1969 and 1972. More than 100 drill holes, totalling in excess of 30 000 m of core, were drilled; 49 of those drill holes penetrated Fox River Sill rocks. Sherritt Gordon Mines Limited drilled 8 holes in the area in 1956 and 1957. Permits for airborne electromagnetic surveys in the Fox River area were granted to International Nickel Company in 1957 and 1970. As the area was covered by both airborne electromagnetic and magnetic surveys, drill targets were likely determined on the basis of coincident electromagnetic and magnetic anomalies.

Geochemical and geophysical surveys over the western portion of the Fox River Sill were conducted during 1976 by the Exploration Operations Branch of the Manitoba Mineral Resources Division (Clue, 1976). Vertical loop electromagnetic bedrock conductors were found to coincide with anomalous concentrations of sulphide minerals witn little or no enrichment in Cu, Ni and Cr. This pattern was interpreted as reflecting the presence of barren sulphide in the area (Clue, *op. cit.*).

PREVIOUS WORK

Bell (1879), Brock (1911) and Merritt (1925) surveyed the Fox River area, and Merritt made the first reference to ultramafic rocks on the Fox River. Springer (1946) traversed the Fox, Bigstone and Stupart Rivers, and noted volcanic and sedimentary rocks. Quinn (1955a, 1955b) made reference to a layered ultramafic sill exposed in rapids of the Fox River. He did not distinguish between Fox River volcanic rocks, and volcanic rocks exposed on High Hill, Utik and Knee lakes, all of which he termed Hayes River Group after Wright (1932). Similarly, Potter (1962) tentatively correlated volcanic rocks of the Fox River Belt, and a belt of volcanic rocks exposed on the Semmens and Gods rivers, with Hayes River Group volcanic rocks. He also suggested that the ultramafic rocks exposed on the Stupart River were the eastern extension of the ultramafic sill described by Quinn (*op. cit.*) on the Fox River.

Bell (1971) proposed that the ultramafic rocks of the Fox River Belt occupied a tectonic position similar to the ultramafic rocks of the Thompson Nickel Belt. He further speculated that the entire Fox River Belt "complex" may correlate with rocks of the Circum-Ungava geosyncline. This followed a suggestion by Dimroth *et al.* (1970), that rocks of the Circum-Ungava geosyncline extend through the Belcher Islands, to the Sutton Lake area of northern Ontario, and west to the Churchill-Superior boundary zone of Manitoba. Gibb and Walcott (1971) also postulated a correlation between the Thompson, Fox River and Circum-Ungava belts on the basis of gravity anomalies. Thomas and Gibb (1977) introduced the term Circum-Superior suture to apply to the boundary between the Churchill and Superior Provinces. Baragar and Scoates (1981) introduced the term Circum-Superior Belt to refer to the discontinuous segments of Aphebian supracrustal rocks that circumscribe the Archean Superior Province craton. The Fox River Belt is one of those segments.

ACKNOWLEDGEMENTS

Field work was carried out in the Fox River area by R.F.J. Scoates in 1969, 1975, 1976 and 1977. D.L. Trueman rendered outstanding assistance in 1969 under arduous conditions, and M.T. Corkery, J.J. Macek and W. Weber assisted with helicopter operations in 1975. J.J. Macek assisted with helicopter work in 1976,and W.D. McRitchie and W. Weber provided assistance in 1977. All of these geologists have contributed enormously, not only in the collection of field data, but also in helpful and critical discussion of aspects of the local and regional geology.

This project has benefited immeasurably by the contribution of drill core from the Fox River area by Inco (formerly International Nickel Company of Canada Limited). Access to this core (101 drill holes representing approximately 30 000 m of core) has added a critical dimension to this investigation, particularly with outcrop being scarce in the area. The generous cooperation of INCO officers and staff is acknowledged with sincere appreciation.

The drill core was logged and sampled by R.F.J. Scoates, J.J. Macek assisted with helicopter work in 1976, and W.D. McRitchie and Parker and W. Mackenzie provided excellent assistance in 1972 and 1973, respectively. R.F.J. Scoates and M.T. Corkery completed the logging and sampling of drill core in 1974.

M.T. Corkery provided structural logs for the drill holes through careful re-examination of the core, and J.J. Macek, P.G. Lenton and C.R. McGregor provided mineral identifications and compositional determinations. J. Timchak assisted with the mineralogical work in 1976, and D. Barchyn assisted with aeromagnetic interpretations in 1975.

Chemical analyses were made by staff of the Analytical Laboratory of the Mineral Resources Division.

Colleagues of the Geological Services Branch are acknowledged for their support and critical counsel, particularly J.J. Macek and M.T. Corkery, who were directly involved in field work and other aspects of the project, and A.H. Bailes, W.D. McRitchie and W. Weber who provided much insight by way of discussion into critical problems of the local and regional geology. O.R. Eckstrand, D.C. Findlay and J.M. Franklin of the Geological Survey of Canada are thanked for their continued interest in the project. The assistance of J.S. Scoates in making the final revisions to the manuscript is greatly appreciated. J.M. Duke of the Geological Survey of Canada critically reviewed a portion of the manuscript and B.B. Bannatyne and D.A. Baldwin, with assistance from S. Weselak, of Manitoba Energy and Mines carefully edited the completed manuscript.

Diagrams were prepared by Cartographic Services staff, particularly Mark Timcoe; K. Chase, G.G. Leibrecht and J. Malyon prepared the photomicrographs. L. Chudy, D. Navitka and B. Thakrar typed earlier revisions of this report. S. Weselak prepared the final typed manuscript.

MARGINAL ZONE

Marginal Zone (MZ) rocks occur along the south margin of the Sill, and, with the exception of one locality, have been found along the entire length of the west lobe of the intrusion. Cyclic and noncyclic varieties have been observed, the former being composed of olivine, clinopyroxene and plagioclase cumulate layers. Non-cyclic MZ rocks are less widespread, with olivine cumulates and plagioclase cumulates being observed. MZ rocks range from several metres to several hundred metres thick. Drill holes and outcrops where MZ sequences are exposed are illustrated in Figure 5.

CLASSIFICATION OF MZ ROCKS

Classification of MZ rocks is complicated by their heterogeneous character, and the wide range in grain size of both cumulus and postcumulus phases. The sporadic distribution of large poikilitic and plate-like orthopyroxene crystals also contributes significantly to the heterogeneous nature of MZ rocks. Some rocks are substantially altered. As a result of these factors, visual estimates of cumulus and postcumulus minerals were made and used to classify the rocks according to Streckeisen (1976). Thus rock types are based on estimated total modal mineralogy, irrespective of whether the mineral phases were originally cumulus or postcumulus. The method of categorizing rocks of layered intrusive complexes using their cumulus phases and total primary mineralogy has been discussed by Jackson (1967, 1970).

The cumulus or postcumulus nature of primary minerals is an important factor in distinguishing individual layers, and layers are consequently referred to by the principal or predominant cumulus phase. Determining whether a primary mineral was originally cumulus or postcumulus is based on crystal shapes and textural relationships. In some rocks, original cumulus crystals have changed shape and have had their textural relationships modified through postcumulus growth. In other rocks, original cumulus crystals have had their crystal shape modified through reaction with liquid to form new, postcumulus minerals. Thus, distinguishing original cumulus from original postcumulus phases is not necessarily a straightforward process. The terminology used in describing MZ and other Fox River Sill rocks is that of Jackson (1967, 1970), which is, in part, a modification of the terminology of Wager *et al.* (1960).

GREAT FALLS OUTCROP AREA

Rocks of the MZ are exposed in scattered outcrops in the Great Falls rapids area of the Fox River, where they occur within and along the channels and on the numerous islands separating the channels (Fig. 6 and Plate 1). The island outcrops are low and weathered, whereas the channel outcrops are water-washed and clean. Part of one of the largest islands was burned prior to 1969 and in 1975 new growth obscured small outcrops of low relief. In 1969 unusually low water level allowed traversing the smaller channels on foot. The larger channels and isolated islands were mapped and sampled in 1975 utilizing a helicopter for support. The uneven distribution of outcrop necessitates extrapolation of some layers over several hundred metres.

MZ rocks were originally interpreted as representing the upper part of the intrusion (Scoates, 1969), based mainly on the abundance of gabbro. Logging of drill core in 1972 and 1973, and further mapping in 1975 led to the recognition of the north-facing character of the Sill (Scoates, 1975c).

The MZ is approximately 270 m thick in the Great Falls area where it comprises three repetitive cyclic units (Fig. 6). The term cyclic unit or cycle is used in the sense of Jackson (1961) who introduced the term to describe similarly repeated stratigraphic divisions in the Stillwater Complex, Montana. The cyclic units are numbered northwards from the south contact to the contact with LCLZ rocks. Each cyclic unit is composed of three distinctive layers that have resulted from fractional crystallization and differentiation of basic magma. Each unit comprises an olivine cumulate layer, succeeded in turn by a clinopyroxene cumulate layer, and a plagioclase cumulate layer. In addition, a chilled margin separates the first cycle (cycle 1) from Middle sedimentary formation siltstones at the contact.

Originally the rocks were mapped as peridotite, websterite and gabbro (Scoates, 1969 and 1975c). Individual layers of cyclic units can

Plate 1: Braided stream complex, Great Falls outcrop area. This oblique aerial photograph (looking south) displays the upstream portion of the braided stream complex underlain by MZ rocks. The contact between MZ and LCLZ rocks passes through the north end of the wooded island at the right centre of the photo. Great Falls outcrop area, Fox River.

be readily distinguished in the field. However, because all rocks originally contained olivine, clinopyroxene, orthopyroxene, plagioclase and hornblende as primary silicate minerals, many of the rocks from various layers of cyclic units are (hornblende-bearing) olivine melagabbronorite.

CYCLIC UNIT 1

Chilled zone

A sharp contact between the Fox River Sill and Middle sedimentary formation quartz-rich siltstone is exposed in a few low outcrops. The siltstone has the fine grained, baked appearance of hornfels and is brecciated and veined by chilled zone material up to 20 cm from the contact. The chilled zone extends up to 6 m north of the contact. The rock is dark grey, very fine grained, and contains small irregular patches of quartz; numerous inclusions of Middle sedimentary formation quartz-rich siltstone impart a heterogeneous character to the zone.

The rock was originally composed of fine grained plagioclase that occurs as randomly oriented lath-like crystals (0.15 x 0.01 mm) and elongate crystals (0.7 x 0.05 mm) that form bundles of subradially disposed laths. The coarser grained plagioclase is associated with quartz inclusions. Fine grained, nearly isotropic chlorite fills the irregularly shaped areas between the plagioclase crystals. Larger areas (up to 0.7 mm in size), displaying more regular, almost prismatic shapes, now occupied by chlorite with anomalous brown to Prussian blue birefringence, are interpreted to have been pyroxene. Quartz occurs as irregular masses and patches (up to 6 mm in size), and as discontinuous veinlets with chlorite, sphene and sulphide as common associated minerals. All quartz grains display strain extinction. Irregularly shaped sulphide grains (up to 1 mm) are associated with the quartz-rich areas.

The abundance of plagioclase and the probable original presence of pyroxene suggests that the liquid phase of the initial magmatic batch was gabbroic in composition. The quartz in the zone is considered to represent reconstituted inclusions of quartz-rich siltstone from the Middle sedimentary formation.

Olivine cumulate layer

The contact between the chilled zone and the olivine cumulate layer is not exposed. The olivine cumulate layer near the contact weathers rusty brown and is brownish green on fresh surface. The rock has a spotted appearance due to the sporadic distribution of poikilitic orthopyroxene. Toward the upper part of the layer the rock weathers reddish brown and has a dark greenish-black fresh surface. The rock is medium- to coarse-grained and granular, and is well jointed, developing the rectangular blocks that are typical of many ultramafic outcrops.

Toward the base of the layer, which is approximately 50 m thick, the rock has been substantially recrystallized and colourless- to pale green-hornblende is a common constituent. Although recrystallization has obliterated much of the original character of the rock, the following features are considered to be diagnostic. Fine grained (0.1 to 0.7 mm), granular to polyhedral olivine appears to have been a cumulus phase. Clinopyroxene formed equidimensional crystals and irregularly shaped grains, and also occurred as grains consisting of aggregates of crystals. It also was a cumulus phase in the lower part of the layer where it was the most abundant single constituent, although it never exceeds 40 percent of the rock. Plagioclase, orthopyroxene and ubiquitous red-brown hornblende originally formed poikilitic and interstitial crystals.

Olivine has been completely replaced by colourless hornblende and chlorite. Original crystal shapes are best preserved where olivine was poikilitically enclosed by hornblende crystals. Orthopyroxene has been pseudomorphously replaced by chlorite displaying anomalous birefringence in grey blue to Prussian blue. Plagioclase has been replaced by chlorite displaying anomalous grey-brown birefringence and by fine grained mixtures of saussurite, colourless hornblende and epidote, and rarely by albite and epidote. Red-brown hornblende is considered a primary phase and it commonly has successive overgrowths of pale green hornblende and colourless hornblende.

In the middle part of the layer, polyhedral olivine, euhedral chromite and equidimensional to irregularly shaped clinopyroxene crystals are cumulus phases. Polycrystalline clinopyroxene grains consisting of aggregates of crystals are also prominent, and are similar to 'clinopyroxene multigrain aggregates' described from some Molson swarm dykes (Scoates and Macek, 1978). Some clinopyroxene crystals have been modified by postcumulus crystallization, and as a result possess irregular outlines and/or inclusions of olivine near their margins. Plagioclase and red-brown hornblende occur as poikilitic crystals containing numerous olivine inclusions. Orthopyroxene forms large (4 mm) irregular, plate-like poikilitic crystals that include clinopyroxene and euhedral chromite.

Olivine in the central part of the layer has been replaced by fibrous serpentine, some displaying a criss-cross pattern. Bipartite serpentine veinlets are common. Strongly coloured, yellow-brown serpentine

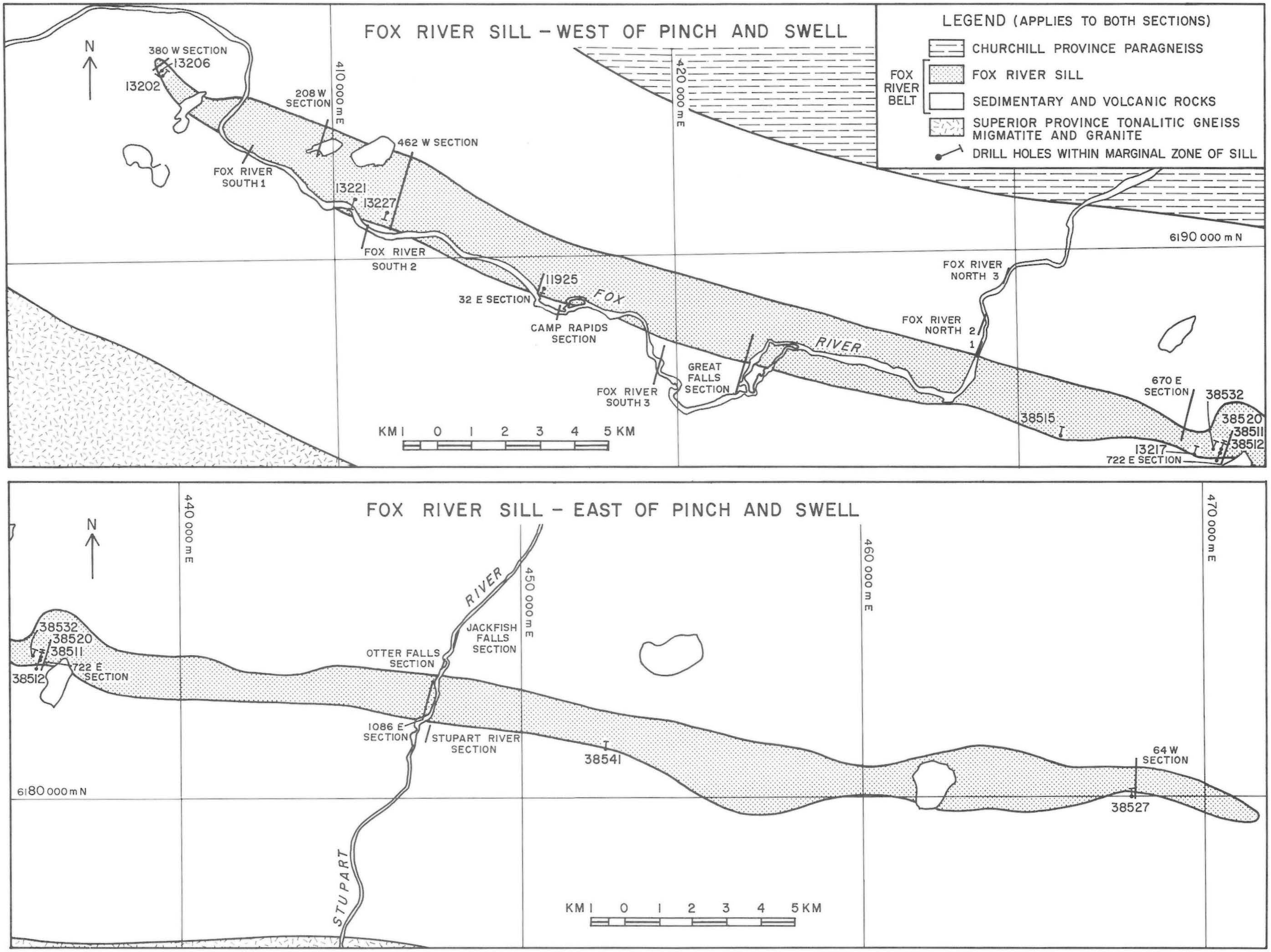


Figure 5: Drill hole and outcrop locations, Marginal Zone.

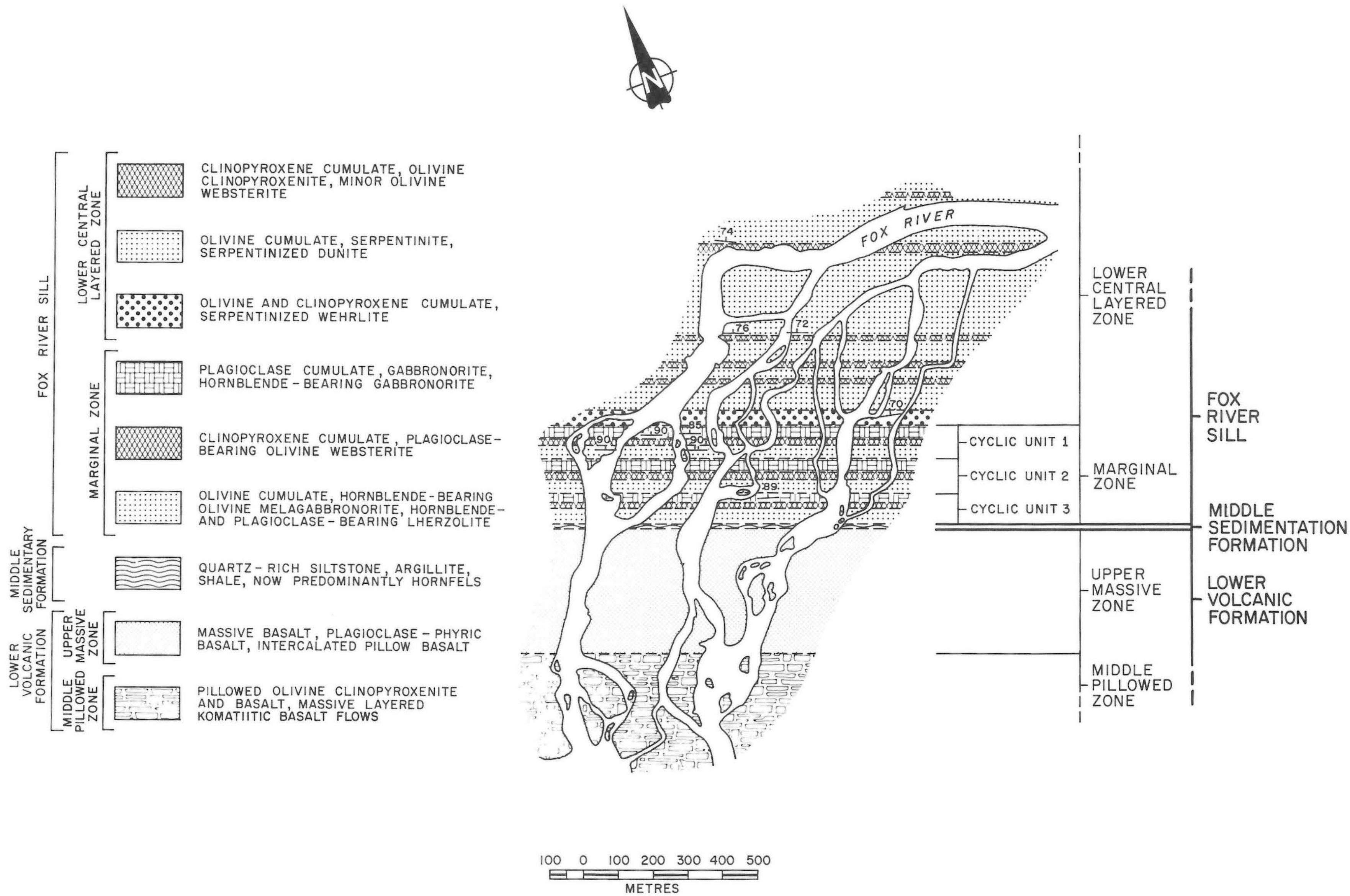


Figure 6: Geology of the Great Falls outcrop area.

forms discontinuous veinlets, and pseudomorphously replaces olivine adjacent to the veinlets. Coloured serpentine grades into colourless serpentine along the veinlets. Fine grained, nearly isotropic chlorite, in places displaying a faint blue-grey birefringence, replaces original poikilitic and interstitial plagioclase crystals. Colourless hornblende overgrows, and is in optical continuity with, red-brown hornblende. Clinopyroxene displays incipient pseudomorphous replacement by colourless tremolite. Talc ± colourless tremolite replaces orthopyroxene. A very fine grained, high relief mineral forms mat-like patches in the talc in some areas.

The upper part of the layer is composed of polyhedral olivine and euhedral chromite as cumulus crystals, and clinopyroxene, orthopyroxene, plagioclase and red-brown hornblende as intercumulus phases. Euhedral chromite occurs as inclusions in all minerals, and olivine occurs as inclusions in clinopyroxene, orthopyroxene, plagioclase and hornblende. Clinopyroxene occurs as inclusions in orthopyroxene. These textures indicate that crystallization of plagioclase commenced after the crystallization of orthopyroxene, but before crystallization of hornblende. Faintly pleochroic phlogopite is a rare intercumulus phase.

The rocks become coarser grained toward the top of the layer where olivine ranges from 0.15 to 3 mm and averages 0.8 mm in long axis dimension, compared with an average of 0.4 mm near the base of the layer. Intercumulus minerals are also coarser grained toward the top of the layer. The rocks become more olivine-rich toward the top, olivine commonly making up more than 50 percent of the rock, whereas it constitutes less than 25 percent of the rock toward the base. Most rocks are olivine melagabbronorite (Streckeisen, 1976), although some approach and hornblende-bearing plagioclase-bearing lherzolite in composition toward the top of the layer.

Primary phases other than plagioclase are partly preserved in the upper part of the layer. Olivine has been partly replaced in a pseudomorphous fashion. Some serpentine in veinlets possesses a weak pleochroism in pale yellow to yellow brown. Orthopyroxene is partly replaced by talc, serpentine, and colourless tremolite mixtures, and plagioclase has been completely converted to fine grained nearly isotropic chlorite.

Clinopyroxene cumulate layer

The poorly exposed contact between the olivine cumulate and clinopyroxene cumulate layers is gradational over one metre. Rocks of the clinopyroxene cumulate layer weather greyish brown to greyish green, are medium grained and have a granular appearance. They are dark brownish green on fresh surfaces and individual pyroxene crystals can be readily identified. The sporadic distribution of coarse grained orthopyroxene (up to 7 cm) imparts an inhomogeneous character to the rock.

Clinopyroxene occurs as equidimensional cumulus crystals that average 0.4 mm in size. The crystals are brownish green, and possess closely spaced parting. In some areas, numbers of individual crystals are joined together to form crystal aggregates similar to those described from the lower part of the olivine cumulate layer. Some crystal aggregates possess highly irregular shapes, and individual crystals that form parts of aggregates are coarser grained than cumulus crystals (Plate 2). The coarser grained crystals are colourless, do not possess parting and may contain numerous, fine grained, opaque inclusions. Many also display incipient alteration to colourless hornblende. Some of the colourless clinopyroxene crystals display an irregular, blebby, myrmekite-like exsolved phase (Plates 3 and 4). Individual crystals and crystal aggregates with this type of exsolution are identical to those found in some ultramafic and mafic Molson dykes (Scoates and Macek, 1978).

Orthopyroxene forms large (up to 7 cm) elongate to equidimensional, irregularly shaped, poikilitic, plate-like crystals. They contain clinopyroxene crystals as inclusions, but fewer than the orthopyroxene of the underlying olivine cumulate layer. The orthopyroxene has been replaced by fine grained colourless chlorite with a brownish-green anomalous birefringence.

Plagioclase forms large porphyritic crystals up to 5 cm in size. The crystals have optical continuity over several mm and up to 5 cm, and individual segments may be separated by the dense packing of cumulus phases. Plagioclase is a cumulus phase at the top of the layer. The original basic plagioclase has been pseudomorphously replaced by oligoclase.

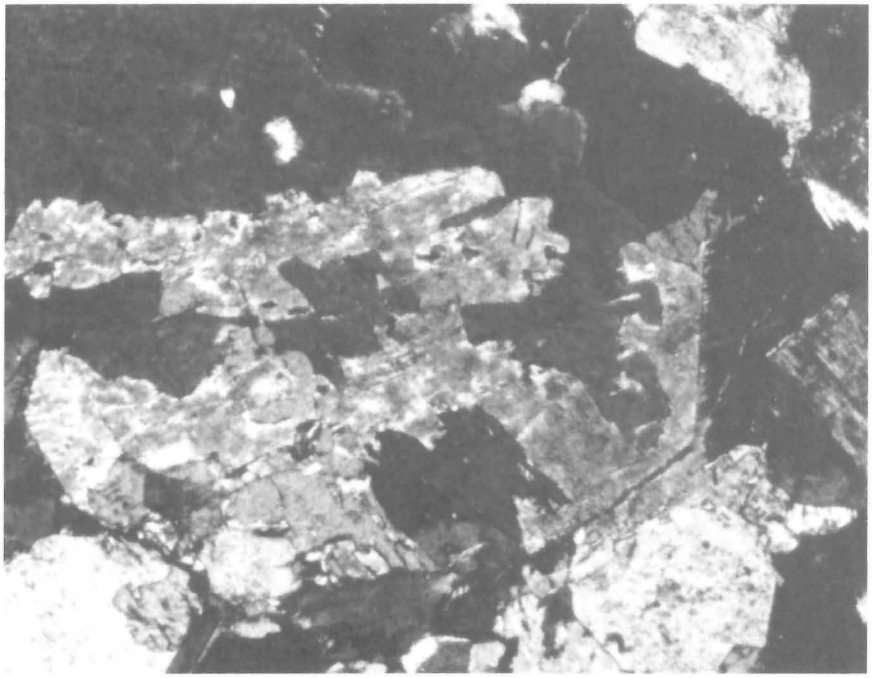
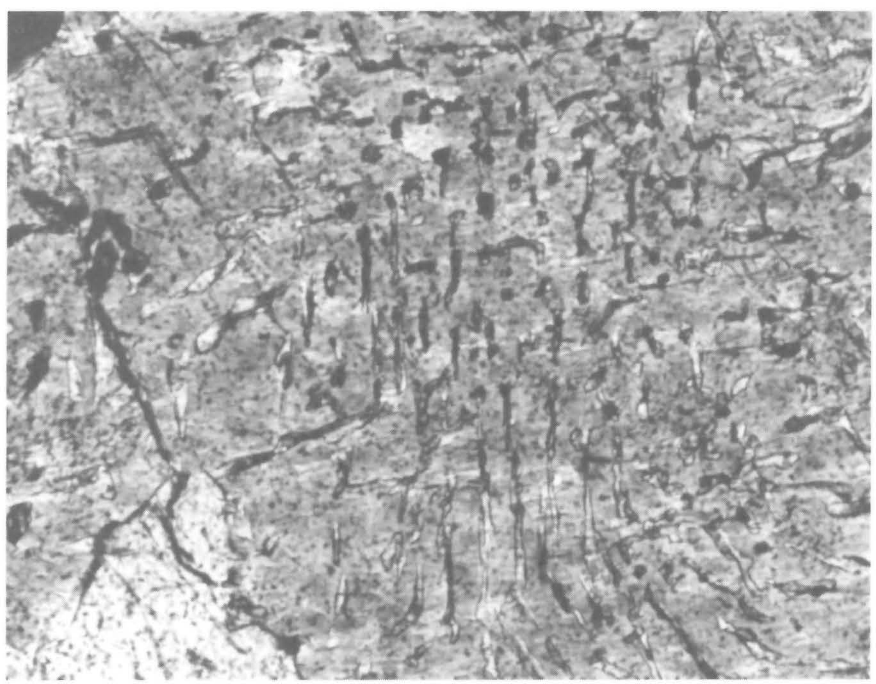


Plate 2: Clinopyroxene multigrain aggregate with complex interdigitated internal contacts. Similar crystals are characteristic of certain Molson swarm dykes (Scoates and Macek, 1978). Cycle 1, clinopyroxene cumulate layer, Great Falls area, Fox River, 03-75-68-1. XN.

Plate 3: *Clinopyroxene multigrain aggregate displaying blebby, vermicular, myrmekite-like exsolution. Similar exsolution has been described from clinopyroxene of Molson swarm dykes (Scoates and Macek, 1978). Cycle 1, clinopyroxene cumulate layer, Great Falls area, Fox River, 03-75-68-1. XN.*

Plate 4: *Detail of blebby, vermicular, myrmekite-like exsolution in clinopyroxene, 03-75-68-1. XN.*



Red-brown hornblende occurs as irregularly shaped interstitial crystals, which in places contain clinopyroxene inclusions. Some crystals are twinned, whereas others are zoned. The red-brown colour becomes less intense toward the crystal boundary.

Olivine, now pseudomorphously replaced by colourless chlorite with dark greyish-brown anomalous birefringence, originally formed cumulus crystals that occurred as inclusions in orthopyroxene, plagioclase and hornblende. Some originally polyhedral crystals have had their shape modified through postcumulus growth.

Opaque minerals include euhedral chromite crystals, and minor, fine grained sulphide crystals.

The clinopyroxene cumulate layer is characterized by an abundance of cumulus clinopyroxene crystals. Olivine remained a cumulus phase, and clinopyroxene and olivine were on the liquidus together. Orthopyroxene formed by reaction between earlier-formed clinopyroxene and olivine with liquid. Hornblende may also have formed through some reaction of clinopyroxene and olivine with liquid, and plagioclase represents crystallization of intercumulus liquid.

The rocks were originally hornblende-bearing melagabbronorites, although they approach and hornblende-bearing plagioclase-bearing websterite. They were mapped in the field as websterite.

Plagioclase cumulate layer

The contact between the clinopyroxene cumulate layer and the plagioclase cumulate layer is gradational over several metres. Rocks of the plagioclase cumulate layer are grey weathering, and brownish grey on fresh surface.

The rock originally consisted of randomly disposed laths (0.2 x 1.5 mm) and prism-like crystals (0.5 x 0.7 mm) of cumulus plagioclase and irregularly shaped, interlocking clinopyroxene crystals. The shape of individual clinopyroxene crystals is controlled by the surrounding plagioclase crystals, yet plagioclase inclusions in clinopyroxene are rare. This suggests that clinopyroxene was an original cumulus phase and that its shape was substantially modified by postcumulus growth.

The sporadic distribution of large (up to 5 mm), irregularly shaped, poikilitic orthopyroxene crystals gives the rock an inhomogeneous appearance. The orthopyroxene crystals are characterized by numerous inclusions of plagioclase and clinopyroxene crystals. Smaller areas of chlorite ± tremolite ± talc (up to 2 mm) are interpreted as representing original olivine crystals. Red-brown hornblende occurs as discrete intercumulus crystals and as partial overgrowths on clinopyroxene crystals. Some red-brown hornblende is replaced by colourless hornblende.

The opaque minerals are ilmenite and its alteration products and rare, very fine grained sulphide minerals.

Plagioclase has been recrystallized to a fine grained mat of chlorite ± epidote ± sphene ± muscovite ± albite ± quartz. Orthopyroxene has been replaced by greenish-grey chlorite ± tremolite that form bastite-like pseudomorphs.

Cumulus plagioclase increases in abundance toward the top of the layer at the expense of clinopyroxene, and orthopyroxene decreases in size and abundance upward.

The plagioclase cumulate layer is characterized by an increasing abundance of cumulus crystals toward the top of the layer, and by cumulus clinopyroxene crystals that have been substantially modified by postcumulus crystallization. Plagioclase and clinopyroxene ± olivine were liquidus minerals in the main part of the magma during the formation of the layer. As in other layers, orthopyroxene is an intercumulus phase, formed by reaction of early formed clinopyroxene (± olivine) and intercumulus magma. The rocks were originally gabbronorite in composition.

CYCLIC UNIT 2

Olivine cumulate layer

Rocks of the olivine cumulate layer weather dark reddish brown to black and have a dark greenish-black fresh surface. They are medium- to coarse-grained and possess a characteristic knobby or rubbly surface. The contact between olivine cumulate rocks and underlying cycle 1 rocks is exposed only in one area where it is seen to be sharp.

Cumulus olivine (0.3 to 2 mm) ranges from granular to polyhedral in shape. The granular olivine represents original polyhedral crystals whose shape has been modified by reaction with the intercumulus liquid to form clinopyroxene, orthopyroxene and red-brown hornblende. Clinopyroxene forms irregularly shaped, poikilitic crystals (up to 5 mm) with olivine and plagioclase inclusions. Plagioclase is a cumulus, as well as an intercumulus phase. As a cumulus phase it forms laths and prisms 0.2 to 0.4 mm long. As an intercumulus phase it forms large (up to 1 cm) irregularly shaped oikocrysts. Orthopyroxene occurs as large (up to 1 cm) sporadically distributed, irregularly shaped poikilitic crystals with numerous inclusions of olivine. Some crystals possess fine ruled-line exsolution lamellae. Red-brown hornblende forms large (up to 1.5 cm) irregularly shaped, oikocrysts that are similar in character to the clinopyroxene and plagioclase oikocrysts. Euhedral opaque chromite crystals occur as sporadically distributed discrete crystals and as crystal clusters. Fine gained, irregularly shaped sulphide crystals in the interstitial areas are rare.

Olivine is partly to completely replaced by bipartite serpentine veinlets, and finely interwoven mat-like serpentine. Plagioclase has been replaced by extremely fine grained, nearly isotropic saussurite. Orthopyroxene displays incipient alteration to talc-tremolite assemblages. Some red-brown hornblende crystals display colourless to pale green hornblende selvages. Magnetite, as dust-like patches, highly irregular drusy aggregates and irregular vein-like masses is a ubiquitous secondary mineral. It is associated dominantly with hornblende, and outlines and veins altered olivine.

The rock is similar in mineralogy and texture to the olivine-rich upper part of the olivine cumulate layer of cyclic unit 1.

Clinopyroxene cumulate layer

The contact between the clinopyroxene cumulate layer and underlying olivine cumulate layer is sharp. The rocks are similar to the clinopyroxene cumulate layer of cyclic unit 1. The clinopyroxene cumulate layer weathers light reddish brown and has a smooth weathered surface. The fresh surface is mottled green and brown. The rock was mapped in the field as websterite. It consists of an interlocking mosaic of fine grained (0.3 to 1.5 mm), brownish to colourless, irregularly shaped clinopyroxene crystals, some of which possess an irregular, myrmekite-like exsolved phase. Some of these colourless crystals form complex aggregate grains, some of which are composed of brownish and colourless crystals. The nature of the exsolved phase and the character of the aggregate crystals are very similar to the clinopyroxene multigrain aggregates of cycle 1 rocks and Molson swarm dykes (Scoates and Macek, 1978). Clinopyroxene may be incipiently altered to red-brown hornblende.

The inhomogeneous character of the rock is caused by the sporadic distribution of large (up to 6 mm) tremolite ± chlorite pseudomorphs after orthopyroxene with clinopyroxene inclusions.

Original cumulus, polyhedral olivine crystals (up to 0.8 mm) have been pseudomorphously replaced by a fine grained, mat-like intergrowth of chlorite + tremolite. Many olivine crystals originally formed crystal clusters.

Original intercumulus plagioclase crystals have been replaced by albite ± epidote ± chlorite ± muscovite. Plagioclase becomes a cumulus phase, as well as more abundant toward the top of the unit. Red-brown hornblende forms irregularly shaped intercumulus crystals and overgrowths on clinopyroxene and orthopyroxene. Euhedral ilmenite crystals and their associated alteration products are a disseminated phase. Prehnite and chlorite veinlets have been observed.

Plagioclase cumulate layer

The contact between the plagioclase cumulate layer and underlying clinopyroxene cumulate layer is not exposed. Rocks of the plagioclase cumulate layer are medium- to fine-grained with a whitish, weathered surface and grey fresh surface. Cumulus, euhedral plagioclase laths (up to 3 x 0.5 mm) commonly occur as crystal clusters. The plagioclase has been altered to a mixture of chlorite ± epidote ± sphene ± tremolite.

Polyhedral to granular olivine, in crystals pseudomorphously replaced by finely intergrown mat-like chlorite + tremolite, is a cumulus phase. Clinopyroxene is distinguished by irregularly shaped crystals with margins that contain inclusions of olivine and plagioclase. The lack of inclusions in the core suggests that the clinopyroxene was a cumulus phase that became enlarged through postcumulus growth. Many crystals display incipient alteration to red-brown hornblende and/or colourless, ragged to shredded tremolite.

Orthopyroxene formed large (up to 6 mm) poikilitic, plate-like crystals with plagioclase and olivine inclusions. Clinopyroxene also occurs as inclusions, but is not as common as plagioclase. The orthopyroxene crystals have been replaced by fine grained tremolitic amphibole ± chlorite that form bastite-like pseudomorphs.

Red-brown hornblende forms interstitial crystals with numerous inclusions of plagioclase ± olivine. Many of the crystals are zoned; the cores are medium to dark red-brown and the colour becomes less intense toward the grain boundary. A colourless- to pale green-selvage rims some crystals. Some crystals display incipient alteration to colourless, ragged tremolite at their margins.

Irregular blebs of ilmenite are a rare disseminated phase.

The rocks are characterized by fractures that display evidence of movement. Some of the fractures have been filled by chlorite ± quartz ± tremolite ± sphene and one contains albite ± epidote.

CYCLIC UNIT 3

Olivine cumulate layer

Rocks of the olivine cumulate layer have rusty to brown weathering, medium- to coarse-grained and possess a greenish-black fresh surface. The contact with the underlying plagioclase cumulate layer is gradational over several metres.

Cumulus, granular to polyhedral olivine (averaging 0.7 mm in long axis dimension) is the dominant mineral. It is estimated to compose 55 percent of the rock at the base of the layer and decreasing to approximately 35 percent at the top. It occurs as clusters of crystals and as inclusions in later formed intercumulus phases. Olivine crystals tend to be smaller, and granular to spherical where they occur as inclusions in pyroxene and hornblende. They have been partly to completely replaced pseudomorphously by bipartite fibrous serpentine veinlets. In some samples the bipartite veinlets display a preferred orientation that imparts a visible fabric to the rock.

Clinopyroxene commonly forms oikocrysts with numerous olivine inclusions. Some display a crude rectangular outline, others are equidimensional and some possess highly irregular shapes. Many are twinned and some possess a well developed parting. Clinopyroxene appears to have been a cumulus phase in a few rocks where its shape has been modified by postcumulus growth. The cumulus clinopyroxene commonly forms crystal aggregates composed of several crystals. In some rocks, there appears to be two ages of clinopyroxene: an early cumulus variety and a later postcumulus variety. Most clinopyroxene is well preserved; however, some crystals display incipient alteration to colourless tremolite.

Orthopyroxene occurs as sporadically distributed, large (up to 1.5 cm), poikilitic, plate-like crystals with numerous inclusions of granular olivine crystals. Clinopyroxene, plagioclase and red-brown hornblende are also found as inclusions, but are much less common than olivine. Orthopyroxene crystals have been partially to completely converted to an aggregate of tremolite ± serpentine ± talc that form bastite-like pseudomorphs. The sporadic distribution of these coarse crystals imparts a spotted appearance to many of the rocks.

Plagioclase originally occurred as oikocrysts up to several centimetres in size. The area over which the plagioclase occurs is distinguished by numerous polyhedral- to granular-olivine crystals. Plagioclase has been completely replaced by a fine grained, nearly isotropic mat of chlorite and clay minerals ± epidote ± muscovite. Pumpellyite was observed as a replacement of plagioclase in one sample. Plagioclase also forms a cumulus phase in a few rocks, and the presence of cumulus and intercumulus plagioclase implies both early and late plagioclase crystallization. The lath-like cumulus plagioclase crystals occur as inclusions in clinopyroxene and orthopyroxene.

Red-brown hornblende, a postcumulus phase, forms partly continuous oikocrysts up to 5 mm across. It is well preserved, although commonly cut by serpentine ± magnetite veins. In some samples it displays incipient alteration to colourless hornblende.

Disseminated euhedral chromite crystals (0.15 mm) are common, though not abundant (less than 1 percent), and occur as inclusions in all minerals. They occur as discrete crystals, and as clusters of several crystals. Sulphide minerals are uncommon; a few crystals are associated with serpentine ± magnetite veinlets.

Clinopyroxene cumulate layer

The contact between the clinopyroxene cumulate layer and the underlying olivine cumulate layer is gradational over 1.5 m. A sample collected close to the contact with the underlying olivine cumulate layer contains abundant cumulus olivine and consequently has the textural features of an olivine cumulate. The rocks of the clinopyroxene cumulate layer are brownish weathering and are mottled green and brown on the fresh surface.

The rocks are characterized by an aggregation of individual clinopyroxene crystals (0.7 mm) and clusters of clinopyroxene multigrain aggregates. Large (up to 6 mm) poikilitic orthopyroxene crystals have been pseudomorphously replaced by a fine grained intergrowth of chlorite and tremolite. Plagioclase, altered to tremolite and chlorite, is a postcumulus phase as is red-brown hornblende. Opaque minerals make up less than 1 percent of the rock and include euhedral chromite crystals and fine grained, irregularly shaped, ragged masses of magnetite and sulphide.

Plagioclase cumulate layer

The contact between the plagioclase cumulate layer and the underlying clinopyroxene cumulate layer is gradational over 2 m. The plagioclase cumulate layer consists of white to greyish brown to slightly pinkish weathering rocks that display a light grey fresh surface. Alternating layers display pinch-and-swell features and truncation, which indicate deposition of crystals from a moving magma. The unit, mapped in the field as gabbro, is similar to the other plagioclase cumulate layers.

The rocks are characterized by abundant cumulus plagioclase that occurs as clusters of lath-like (0.15 x 1 mm) and prismatic (1 x 1.5 mm) crystals. Plagioclase is altered to albite ± epidote ± chlorite ± muscovite ± prehnite, and much of the alteration occurs as a fine grained, nearly isotropic, mat-like intergrowth. Primary plagioclase (An_{90})[1] crystals are preservedin a few rocks.

Clinopyroxene occurs both as irregularly shaped crystals and as clusters of crystals that form a partly continuous phase. Some crystals appear to have been originally cumulus, but their shapes are modified by postcumulus crystallization. These crystals possess clear cores, and margins characterized by inclusions of plagioclase laths. Other clinopyroxene crystals contain plagioclase inclusions throughout and appear to be entirely postcumulus in character.

Olivine is a sporadically distributed cumulus phase that has been extensively altered to chlorite ± tremolite ± quartz. Rare magnetite and sulphide grains are commonly associated with altered olivine crystals.

Orthopyroxene, that forms irregularly shaped poikilitic crystals containing inclusions of clinopyroxene and plagioclase, has been partly to completely altered to talc ± tremolite ± chlorite. In one sample, orthopyroxene occurs as clusters of equidimensional (0.75 mm) and rhombic crystals (1.5 x 0.75 mm) and appears to have been a cumulus phase. Red-brown hornblende is a rare intercumulus phase. Opaque minerals make less than 1 percent of the rock and are composed dominantly of ilmenite crystals and their alteration products.

[1] Plagioclase compositions were determined using the universal stage and Nakamura plate, and the Becke-Becker or Fedorov methods were followed depending on the orientation of the plagioclase being measured. In the case of the Fedorov method, Nikitin's diagram, modified by Fediuk (1961) was utilized for determining the composition.

OTHER ROCK TYPES

Gabbroic pegmatite

In one area, a rusty weathering, sulphide-bearing zone of gabbroic pegmatite occupies the contact between the olivine cumulate and clinopyroxene cumulate layers of cyclic unit 3. Clinopyroxene crystals up to a centimetre in size are separated by areas occupied by chlorite ± epidote ± colourless garnet (A_0 = 11.848). Apatite and zircon are minor constituents. The highly altered areas are considered to have been plagioclase. Chromite forms large (2 mm) crystals and chalcopyrite occurs as irregularly shaped grains associated with clinopyroxene.

LAYERING

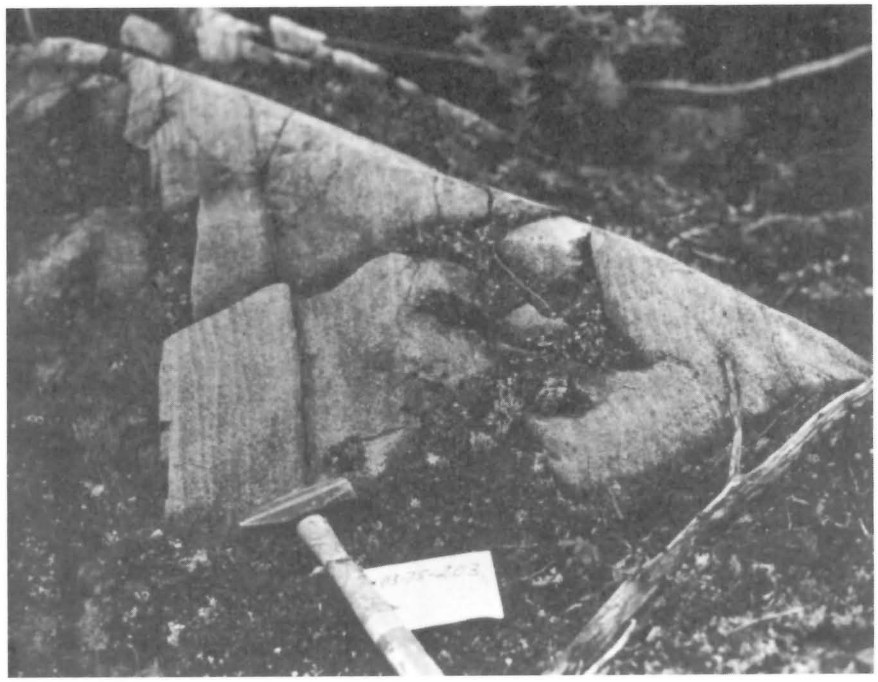
Some olivine cumulate outcrops display a well developed fabric caused by the parallel arrangement of serpentine veinlets. The veinlets are parallel with the overall direction of layering of the units (Plate 5). Plagioclase cumulate rocks display centimetre-scale rhythmic layering through alteration of light (plagioclase-rich) and dark (clinopyroxene-rich) layers. Truncation of layers suggests current-derived crossbedding (Plate 6 and Fig. 7).

722E SECTION - DRILL HOLES 38511, 38512, 38513, 38520, 38531 AND 38532

The information for geologic cross-section 722E is based on 6 drill holes (Fig. 8). Drill holes 38512, 38511 and 38520 were collared on section line 722E. Drill holes 38531 and 38532 are on a section line some 240 m west of 722E, and drill hole 38513 is 240 m east of 722E. All drill holes have been projected (at right angles) onto section line 722E (Fig. 9).

Plate 5: Well developed primary lamination enhanced by parallel serpentine veinlets, cycle 1 olivine cumulate layer, LCLZ, Great Falls outcrop area, Fox River. (03-75-44).

Plate 6: *Fine-scale rythmic layering, cycle 3 plagioclase cumulate layer, MZ, Great Falls outcrop area, Fox River. (03-75-203).*



Because of lack of outcrop in the area, structural relations are based on correlation of units among drill holes and measurement of structural attitudes in drill core. It is assumed that the holes were drilled at right angles to the strike of the units; however, the strike may vary locally and account for change in dip of some layers from hole to hole.

The contact with Middle sedimentary formation rocks is interpreted to be steep (88°) to the north. Cycle 1 layers dip steeply to the north (88-89°). Cycle 2 layers are interpreted to dip less steeply to the north (85-70°) and the change of dip appears to be progressive. The dip of layering in LCLZ rocks is interpreted to be approximately 56° to the north. It is the apparent progressive change in layer dip through MZ rocks into LCLZ rocks that has led to the interpretation of a lopolithic, cross-sectional shape for the Fox River Sill.

The MZ rocks and Middle sedimentary formation siltstone and argillite appear to be discordant on the basis of a 20° difference in angles of primary structures to the core axis. The discordance may be due to a difference in dip, as Middle sedimentary formation rocks are concordant with the MZ rocks in the Great Falls area.

CYCLIC UNIT 1

Cyclic unit 1 consists of an olivine cumulate layer in contact with Middle sedimentary formation siltstone and argillite, overlain in turn by a clinopyroxene cumulate layer and a plagioclase cumulate layer. A chilled margin, estimated to be 35 cm wide, separates olivine cumulate rocks proper from Middle sedimentary formation rocks. Rocks of the chilled margin were not observed in the telescoped core, and are interpreted to be present on the basis of Inco drillholelogs.

Olivine cumulate layer

The olivine cumulate layer is estimated to be 128 m thick, as exposed in drill holes 38512 and 38511, and it is therefore approximately 2.5 times thicker than the olivine cumulate layer of the equivalent cycle in the Great Falls area, some 14 km to the west.

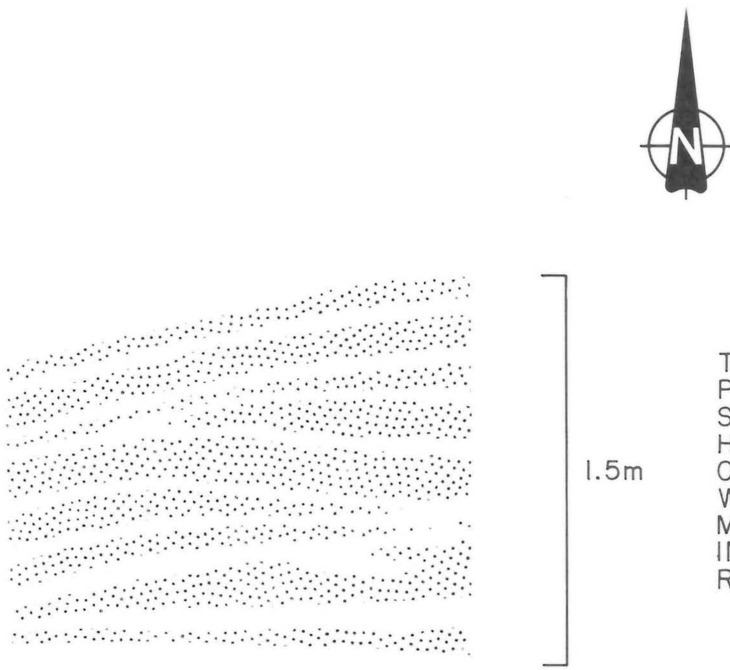
HORNBLENDE-RICH UNIT

Adjacent to the chilled margin is a massive granular, hornblende-rich unit, 11 m thick, as intersected in drill hole 38512 (Fig. 9). Red-brown, pleochroic hornblende is relatively abundant as a postcumulus phase and some grains display a progressive zoning from red-brown cores to colourless or pale green margins. The hornblende contains pseudomorphs after original cumulus olivine and some contain tremolitic pseudomorphs after regular, rectangular, lath-like plagioclase crystals. Thus there is an indication that plagioclase was a cumulus phase near the base of the layer. Colourless hornblende partly to completely replaces clinopyroxene.

Clinopyroxene originally occurred as individual crystals (up to 3 mm) and clusters of crystals, some displaying concentrations of serpentine $\pm$ tremolite pseudomorphs after original olivine inclusions. Fine grained (0.05 mm), euhedral chromite crystals are associated with some serpentine pseudomorph inclusions. Irregularly shaped, highly altered plagioclase crystals occupy interstitial areas. The plagioclase has been altered by an almost isotropic, finely interwoven chlorite mat. Chlorite displaying grey to grey-blue birefringence pseudomorphously replaces orthopyroxene, some of which may represent an original cumulus phase.

Relict primary textures are not well preserved; however, olivine and chromite were original cumulus phases. Clinopyroxene, orthopyroxene and plagioclase may have been cumulus phases near the base of the unit but are intercumulus phases elsewhere. Red-brown hornblende is an intercumulus phase, as is red-brown pleochroic phlogopite. The latter may represent a primary phase that has been substantially modified by secondary recrystallization.

The hornblende-rich unit is considered to represent an original clinopyroxene-rich rock, with clinopyroxene constituting up to 50 percent of the rock near the base of the unit. The ratio of clinopyroxene to olivine progressively decreased to the top of the unit. This original clinopyroxene-rich unit, in which clinopyroxene and plagioclase joined olivine and chromite as cumulus phases, is similar to the clinopyroxene-rich unit at the base of the olivine cumulate layer of MZ



THIS SKETCH IS AN ENHANCEMENT OF THAT PORTION OF PLATE THAT IS ABOVE AND SLIGHTLY TO THE LEFT OF THE HAMMER HEAD. THE SCALE OF THE LAYERING IS THAT OF MODALLY GRADED LAYERS ASSOCIATED WITH THE PLAGIOCLASE CUMULATE PART OF MEGARHYTHMIC LAYERS OF THE BANDED LAYER IN 722 E SECTION. DARK AREAS ARE PYROXENE-RICH, LIGHT AREAS ARE PLAGIOCLASE-RICH

Figure 7: Rhythmic layering, cyclic unit 3 plagioclase cumulate layer, MZ, Great Falls outcrop area.

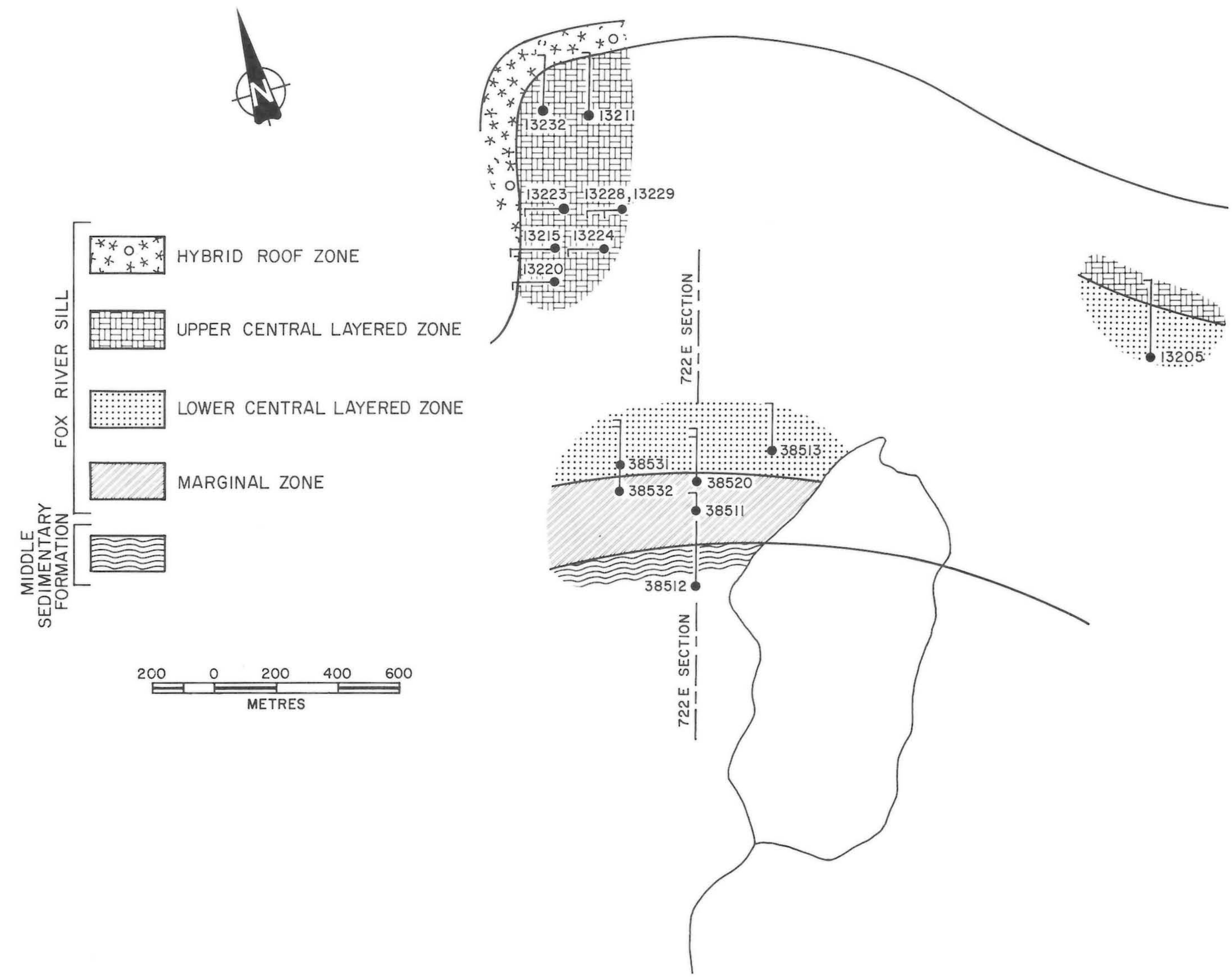


Figure 8: Distribution of drill holes, 722E section.

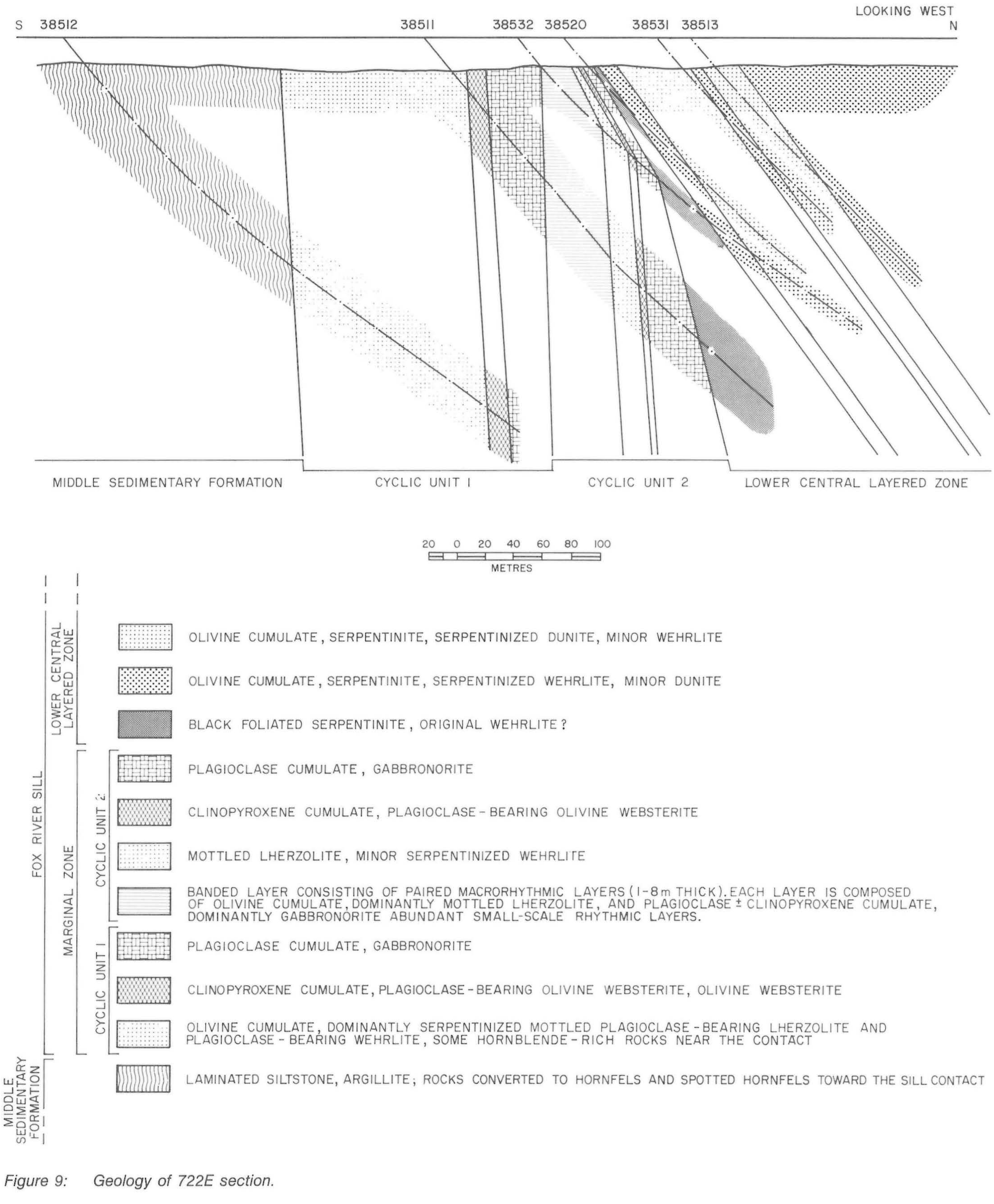


Figure 9: Geology of 722E section.

cyclic unit 1 exposed in the Great Falls area on the Fox River, 14 km to the west.

MAIN UNIT

The olivine cumulate layer, above the hornblende-rich unit, is distinguished by well preserved relict textures and a relatively homogeneous character. The greenish-black rocks are characterized by a patch-like mottling due to the distribution of large (about 1 cm) postcumulus crystals, and by a well developed lamination. Olivine and chromite are cumulus phases; clinopyroxene, orthopyroxene, plagioclase and hornblende are postcumulus phases.

The olivine content ranges from 65 to 90 percent and averages 75 percent throughout the layer (Table 2; Fig. 10). (Modal analyses were performed because of the relatively well preserved textures and homogeneous nature of the rocks that form this olivine cumulate layer). From 770 to 820 (core length footage interval) the olivine content shows little variation and averages 70 percent. From 830 to 1110 the olivine content averages slightly more than 80 percent. Within that interval, two step-like progressions can be interpreted, each displaying a gradually increasing olivine content with height. From 1130 to the top of the layer, the olivine content is more variable and averages 72 percent.

The trend toward more variable and slightly lower olivine abundance near the top of the layer is illustrated in drill hole 38511 (Fig. 11). The olivine content is greater and displays less variation in this olivine cumulate layer than in the possibly equivalent layer in the Great Falls area.[1]

Olivine occurs as polyhedral to subhedral elongate crystals that range from 0.1 mm in long axis dimension, to crystals 5 x 2 mm in size. The average grain size is estimated to be 1 x 0.5 mm. Olivine crystals that occur as inclusions in orthopyroxene tend to be smaller in size and more equidimensional in shape.

Olivine ranges from $Fo_{81.2}$ to $Fo_{86.7}$ and averages Fo_{85} in composition, based on an average of 19 determinations (Fig. 12). Eighteen of the determinations range from Fo_{84} to $Fo_{86.7}$, so that the compositional variation within the layer is small. There is a suggestion of slight decrease in Fo-content near the top of the layer, otherwise there is little compositional variation throughout the layer (Fig. 12). The abundance of olivine has no affect on its Fo-content (Fig. 13), and thus the variations notedin olivine abundance are not accompanied by variation in Fo-content. This suggests that the apparent cycles illustrated by the variations in olivine abundance are not due to influxes of fresh magma, but rather are caused by changing conditions in the chamber that did not affect magma composition during crystallization of olivine.

Small circular inclusions (less than 0.1 to 0.2 mm), consisting originally of red-brown to colourless hornblende, red-brown phlogopite and euhedral chromite crystals occur in the cores of some olivine crystals (Plates 7 and 8). In highly altered rocks, these circular areas contain colourless, fibrous, fine grained tremolite and nonfibrous, plate-like serpentine with grey-blue birefringence. Some inclusions have been completely recrystallized to serpentine $\pm$ chlorite $\pm$ tremolite $\pm$ magnetite. These features were initially thought to be recrystallization phenomena; subsequently inclusions were found wholly enclosed in nonserpentinized olivine.

The composition of these inclusions is commonly different from the mineral or minerals interstitial to and surrounding olivine crystals containing these inclusions. The circular habit of these features, and their presence at or near the core of the host crystals is considered noteworthy. The common occurrence of chromite suggests it may have provided sites for olivine nucleation. However, their spherical shape suggests that they were bubble-like inclusions. They are similar to inclusions in chromite crystals in the Stillwater complex (Jackson, 1961). The original nature of these features is not known.

Olivine has been altered most commonly to bipartite serpentinite and associated magnetite that form parallel veins within individual olivine pseudomorphs similar to banded or curtain-growth serpentine (Francis, 1956; Wicks *et al.,* 1977). Mesh-texture serpentine is rare. Serpentine pseudomorphs after olivine display yellow-green, nonpleochroic serpophitic cores in some rocks and several examples of coloured serpophitic serpentine altered directly from olivine have been observed. Most coloured serpentine possesses anomalous birefringence in green, greenish yellow, yellowish red and blue. Fine grained, secondary fibre-like clinopyroxene occupies the cores of some serpentine pseudomorphs where it defines bundles of subradially disposed crystals locally coexisting with serpentine and relict olivine (Plate 9). The assemblage serpentine + diopside is characteristic of ultramafic rocks that have suffered a low grade of metamorphism (Evans and Trommsdorf, 1970) and is compatible with the development of prehnite and pumpellyite in associated mafic volcanic rocks (Scoates, 1981).

Olivine has been replaced by nonpseudomorphous serpentine in some rocks, where the primary texture has been preserved by intercumulus minerals.

The lamination noted in the layer is caused by parallelism of the long axes of elongate olivine crystals with the layering plane. Measurement of olivine c-axes yield a well defined girdle (Fig. 14). This pattern, caused by elongate olivine crystals lying in a position of least potential energy, is interpreted as an apposition fabric (Jackson, 1961). The lamination is enhanced by a foliation caused by parallel, bipartite banded or curtain-growth serpentine, parallel to the long axes of olivine crystals. However, toward the top of the layer curtain-growth serpentine is oriented perpendicular to the long axes of olivine and, consequently, to the attitude of the lamination (Plate 10). This feature is more readily seen in thin section than in drill core.

Wicks *et al.* (1977) suggested that a rectangular olivine model would develop more convincing banded growth than a cubic model and that banded growth and curtain-like textures may reflect the fracture pattern of the olivine and thus the structural environment of the olivine before, rather than during or after serpentinization. In the cycle 1 olivine cumulate layer (722 section), the orientation of the olivine prior to serpentinization appears to play an important role in controlling the direction of curtain-growth serpentine.

Clinopyroxene is a postcumulus phase characterized by numerous inclusions of serpentine pseudomorphs after olivine. The dense packing of original olivine crystals leads to clinopyroxene oikocrysts that consist of widely separated, optically continuous parts of individual crystals that appear to be physically separated. Clinopyroxene, as oikocryst that range from 3 mm to 1.5 cm in size, is the primary silicate phase most resistant to recrystallization. Inclusions of euhedral chromite crystals are common. Clinopyroxene appears to have crystallized from intercumulus liquid with limited reaction with olivine. Some crystals possess a fine wavy pattern on their surface that may reflect fine-scale exsolution and many crystals display a well developed closely spaced parting.

Clinopyroxene, which is the best preserved of the primary assemblage minerals, has been altered to a variety of secondary minerals, including fine grained, fibrous, brownish amphibole, fine grained, plate-like, nonfibrous serpentine $\pm$ magnetite, and fine grained, greenish, nearly isotropic mixtures of chlorite and serpentine.

[1] These layers may not belong to the same cyclic unit and therefore may not be equivalent (see discussion in Summary).

Table 2: Modal Analyses, Cyclic Unit 1 Olivine Cumulate Layer, 722E Section

	512-770-1	512-780-1	512-790-1	512-800-1	512-810-1	512-820-1	512-830-1	512-840-1	512-860-1	512-880-1	512-900-1	512-930-1
Olivine	0.2	–	–	–	1.1	0.4	0.9	–	–	0.2	–	3.7
Serpentine	65.3	61.2	65.4	62.5	64.0	62.9	70.3	74.4	70.7	79.2	82.1	74.5
Magnetite	2.2	5.4	4.5	2.9	4.2	2.7	6.9	2.4	5.4	3.4	2.6	5.7
Orthopyroxene (+ alteration products)	2.9	3.6	–	–	–	–	–	–	1.9	–	3.0	3.8
Clinopyroxene (+ alteration products)	15.6	10.7	16.0	18.9	16.6	17.5	15.2	14.6	13.8	9.5	0.1	2.9
Plagioclase (+ alteration products)	10.2	15.2	10.4	9.5	8.8	11.0	1.2	6.7	3.0	5.7	5.6	5.4
Hornblende + phlogosite	3.0	2.4	2.5	3.5	3.6	4.5	2.5	1.3	2.5	1.8	–	3.2
Chromite + ilmenite + sulphide (undivided)	6.0	1.5	1.2	2.7	1.7	1.2	3.0	0.6	2.7	0.2	–	0.8
Carbonate	–	–	–	–	–	–	–	–	–	–	–	–

	512-950-1	512-1000-1	512-1010-1	512-1020-1	512-1060-1	512-1090-1	512-1110-1	512-1130-1	512-1140-1	512-1150-1	512-1160-1	512-1170-1
Olivine	0.9	0.4	0.3	1.3	0.3	0.9	0.9	0.9	–	–	7.2	–
Serpentine	70.5	72.0	70.9	72.0	77.8	73.8	75.4	69.5	68.1	72.8	58.8	74.3
Magnetite	4.0	2.9	3.6	2.7	4.6	4.1	2.3	4.3	3.0	2.9	3.0	3.9
Orthopyroxene (+ alteration products)	3.8	–	1.3	11.5	–	2.6	3.7	–	–	15.9	18.3	13.1
Clinopyroxene (+ alteration products)	8.8	20.4	6.6	9.4	11.2	5.9	–	23.5	24.7	–	8.0	0.7
Plagioclase (+ alteration products)	8.0	0.9	7.2	–	0.5	6.1	7.4	0.5	1.2	4.3	3.4	5.8
Hornblende + phlogosite	2.3	1.5	8.3	1.8	3.3	5.1	7.5	1.2	1.8	3.9	1.2	1.3
Chromite + ilmenite + sulphide (undivided)	1.7	1.9	1.9	1.5	2.2	1.5	2.8	0.8	0.7	0.3	0.1	0.9
Carbonate	–	–	–	–	–	–	–	–	–	–	–	-

	512-1190-1	512-1200-1	512-1220-1	512-1230-1	512-1240-1	511-100-1	511-110-1	511-120-1	511-130-1	511-140-1	511-150-1
Olivine	2.8	–	7.7	–	–	–	–	–	–	–	0.3
Serpentine	60.4	66.4	63.0	72.2	67.7	73.5	75.8	87.7	63.7	71.1	71.2
Magnetite	3.6	1.2	4.0	2.3	4.1	5.4	–	–	–	–	–
Orthopyroxene (+ alteration products)	5.4	14.8	–	5.2	13.0	3.5	0.3	1.7	10.2	0.6	4.0
Clinopyroxene (+ alteration products)	17.7	3.1	9.6	9.2	3.6	3.3	10.2	7.9	8.5	10.6	5.9
Plagioclase (+ alteration products)	8.7	14.3	13.6	9.0	9.4	8.7	12.8	8.7	8.7	9.6	11.0
Hornblende + phlogosite	0.9	0.3	2.3	1.4	0.9	1.2	0.9	1.0	1.5	2.4	1.4
Chromite + ilmenite + sulphide (undivided)	0.5	–	–	0.8	1.3	4.4	–	0.9	7.4	6.7	6.2
Carbonate	–	–	–	–	–	–	–	2.1	–	–	-

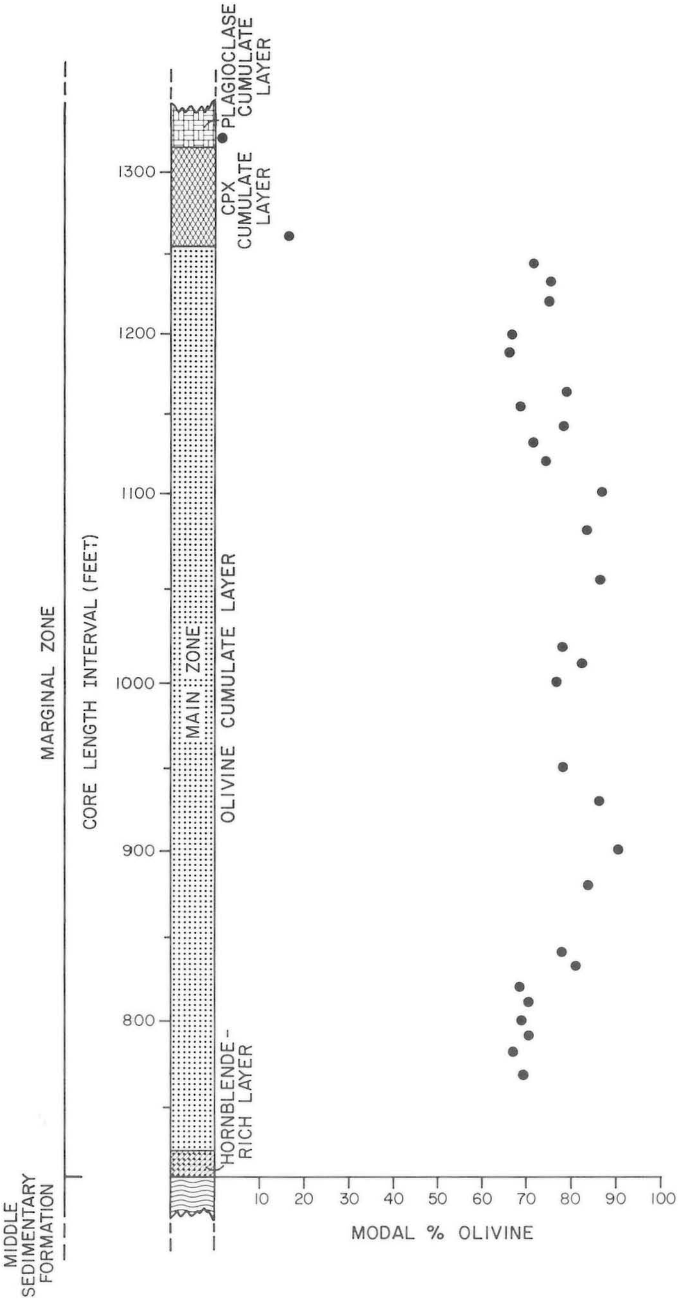


Figure 10: *Modal variation of olivine, cyclic unit 1 olivine cumulate layer, drill hole 38512, 722E section.*

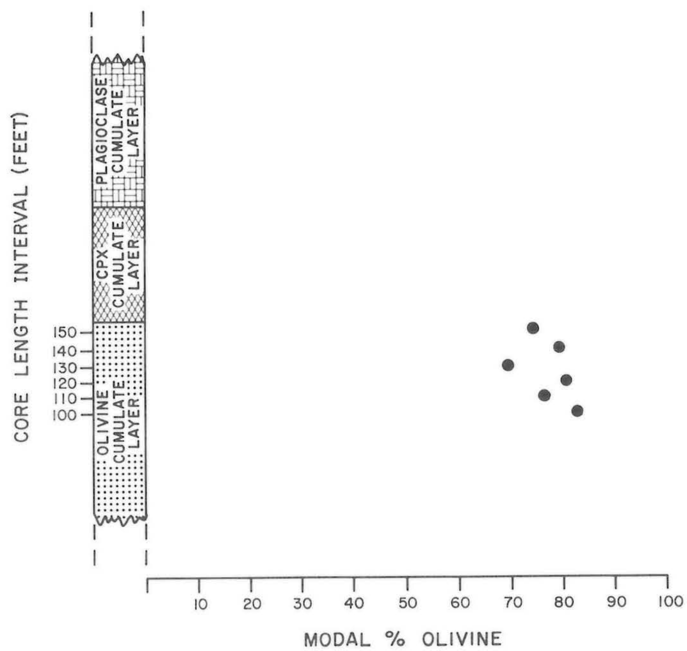


Figure 11: *Modal varation of olivine, cyclic unit 1 olivine cumulate layer, drill hole 38511, 722E section.*

The ratio of chlorite to serpentine is variable and some clinopyroxene has been replaced entirely by chlorite.

Orthopyroxene, a postcumulus phase, occurs as large irregular, plate-like poikilitic crystals (up to 1.5 cm) that contain numerous olivine inclusions. Olivine crystals as inclusions in orthopyroxene are fine grained and smoothly anhedral, suggesting that considerable reaction between olivine and liquid took place to form orthopyroxene. Inclusions of chromite are common, whereas inclusions of plagioclase are rare. Fine "ruled line" exsolution lamellae are a common feature of some crystals. Orthopyroxene is partly to completely recrystallized to serpentine ± talc ± tremolite ± chlorite ± magnetite that form bastite-like pseudomorphs.

Plagioclase, a postcumulus mineral, has a similar distribution to, and bears the same relationship with, cumulus olivine and chromite as clinopyroxene. Relict plagioclase is preserved in a few areas (An_{78}, An_{82}); however, it is mostly altered to a very fine grained mat of nearly isotropic chlorite. In some rocks, a brown to yellow-brown isotropic mineral with high relief, intergrown with chlorite has been identified as grossular garnet.[1] Other alteration products include muscovite and tremolite. In some areas, pale green, weakly pleochroic chlorite is associated with the alteration assemblage.

Red-brown hornblende is a postcumulus phase like clinopyroxene and plagioclase. Some crystals display a progressive zoning from red-brown cores to colourless or pale green margins. Hornblende is partly to completely altered to fine grained, nonfibrous, plate-like serpentine ± magnetite. Secondary magnetite is relatively abundant in hornblende as veins along cleavage traces and as spongy masses.

Red-brown phlogopite is a common, though not abundant, mineral. It occupies intercumulus areas and has a distribution similar to that of other postcumulus minerals. Phlogopite is considered to be a primary phase although recrystallization may have affected its distribution. It has been replaced by pale green chlorite, and by fine grained serpentine + magnetite. Secondary magnetite is an abundant phase in phlogopite, occupying cleavage traces.

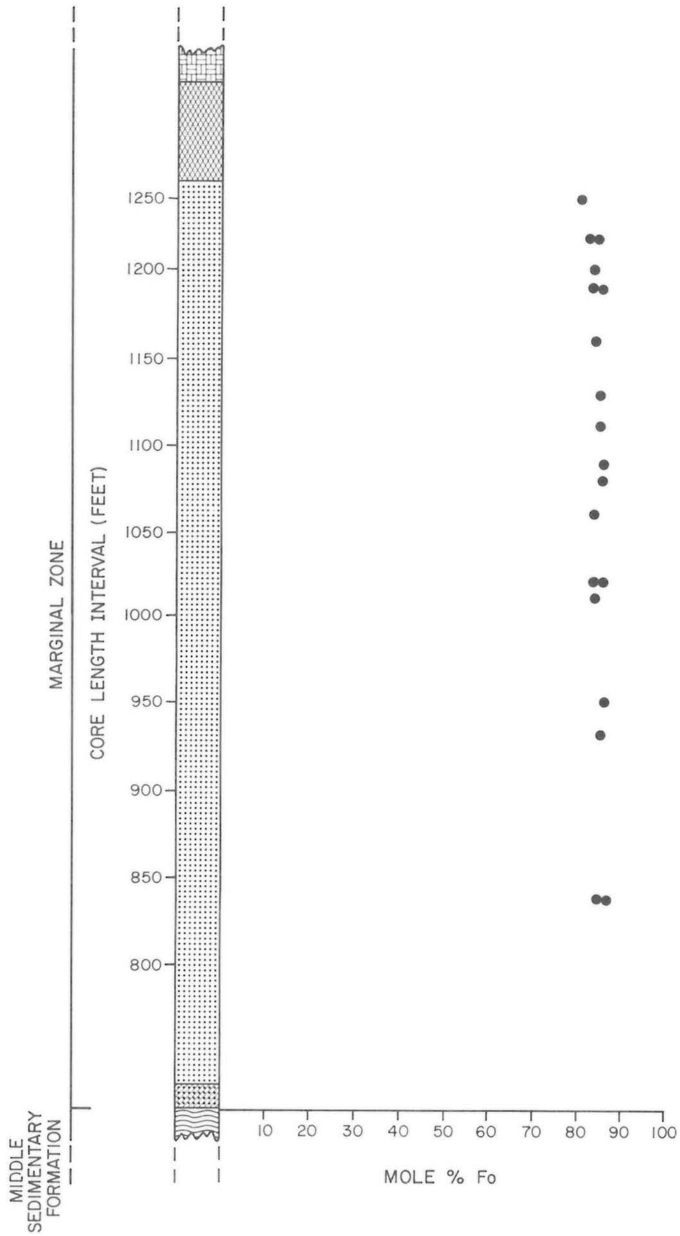


Figure 12: Olivine compositions, cyclic unit 1 olivine cumulate layer, drill hole 38512, 722E section.

[1] The presence of garnet (hydrogrossular, grossular, andradite) replacing plagioclase in Fox River Sill rocks appears to represent a rodingite-like assemblage. Rodingites are lime-rich assemblages of grossular garnet, clinopyroxene ± prehnite that are found in ultramafic rocks of ophiolitic association. Ca-rich garnets are common constituents of rodingites, pseudomorphously replacing plagioclase in some rocks. In ophiolites, rodingite is the product of alteration of pre-existing gabbro and there appears to be a consistent relationship between degree of serpentinization of ultramafic host rocks and the degree of metasomatic alteration of gabbro dykes. In addition to the alteration of gabbro to rodingite-like assemblages in the Sill, original postcumulus plagioclase oikocrysts of olivine cumulates have been partly to completely converted to Ca-rich garnet plus other fine grained secondary products. The formation of Ca-rich garnets must have been accomplished under conditions of low grade- to very low grade- metamorphism as indicated by the metamorphic assemblages of the surrounding volcanic rocks (Scoates, 1981). This concurs with the suggestion that rodingites represent low temperature reaction zones (Coleman, 1977).

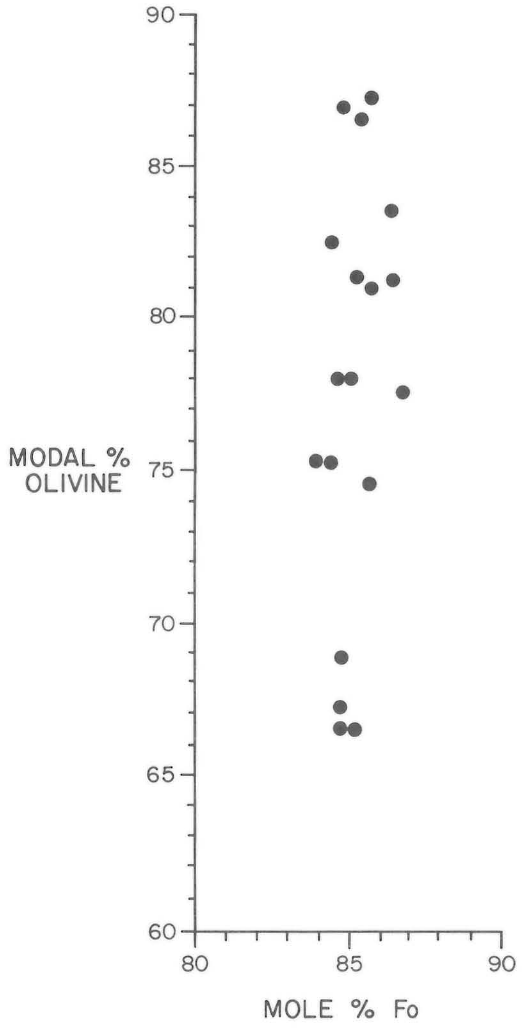


Figure 13: Mole percent Fo vs. modal percent olivine, cyclic unit 1 olivine cumulate layer, drill hole 38512, 722E section.

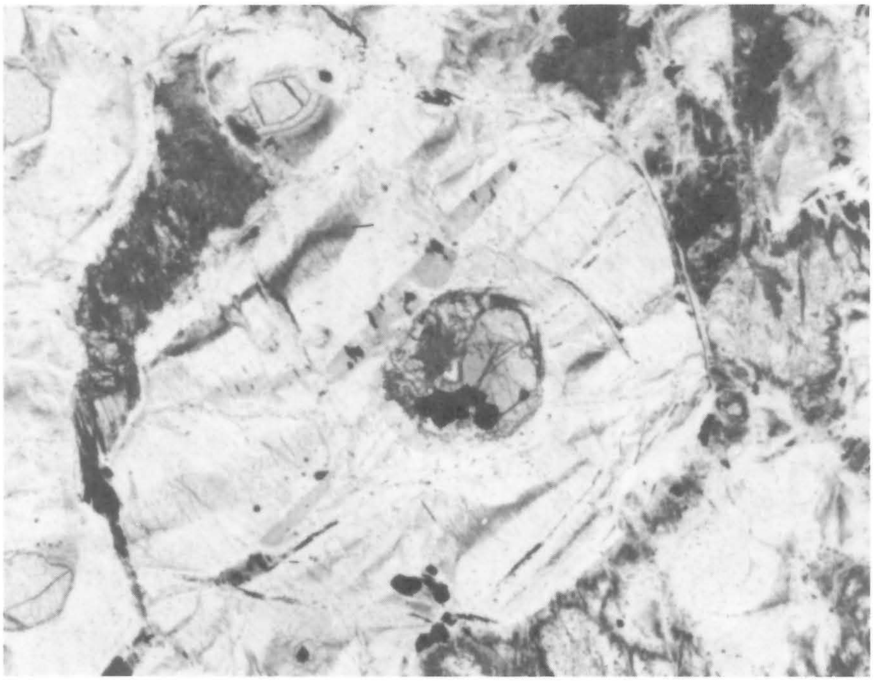


Plate 7: Near circular inclusion in serpentine pseudomorph after olivine. The inclusion consists of a cluster of subhedral, transluscent, brown chromite crystals, zoned hornblende with a pale red-brown core and colourless margin and unidentified, fine grained alteration products. Cycle 1, olivine cumulate layer, 722E section, DDH 38512-1130-1. PL.

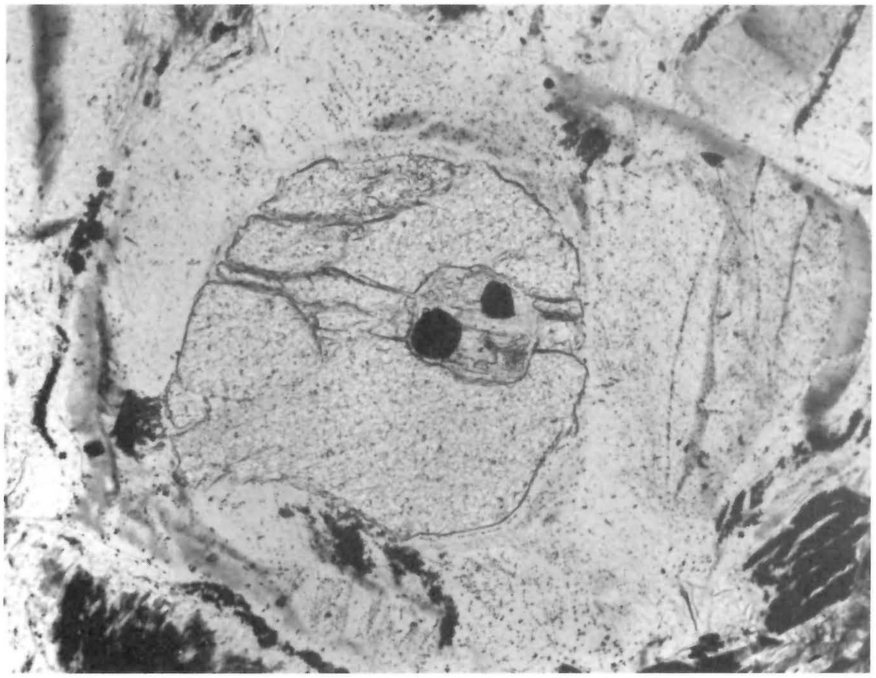


Plate 8: Small, near circular inclusion in core of relict olivine crystal. The inclusion is occupied by two chromite crystals and pale red brown phlogopite. Cycle 1, olivine cumulate layer, 722E section, DDH 38512-1130-1. PL.

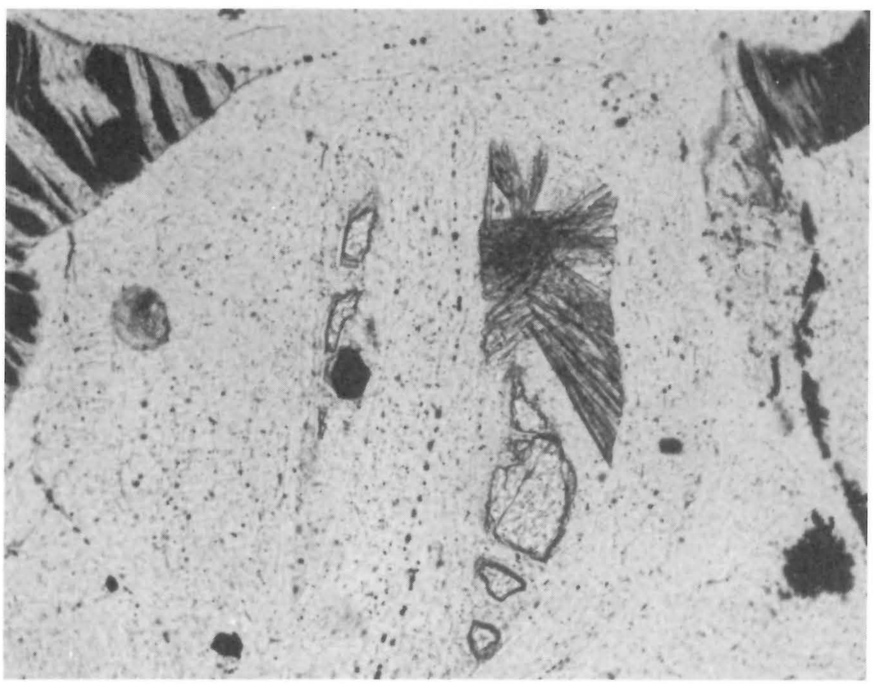


Plate 9: Co-existing relict olivine, secondary fibrous diopside and banded serpentine in serpentine pseudomorph after original cumulus olivine crystal. Cycle 1, olivine cumulate layer, 722E section, DDH 38512-1220-1. PL.

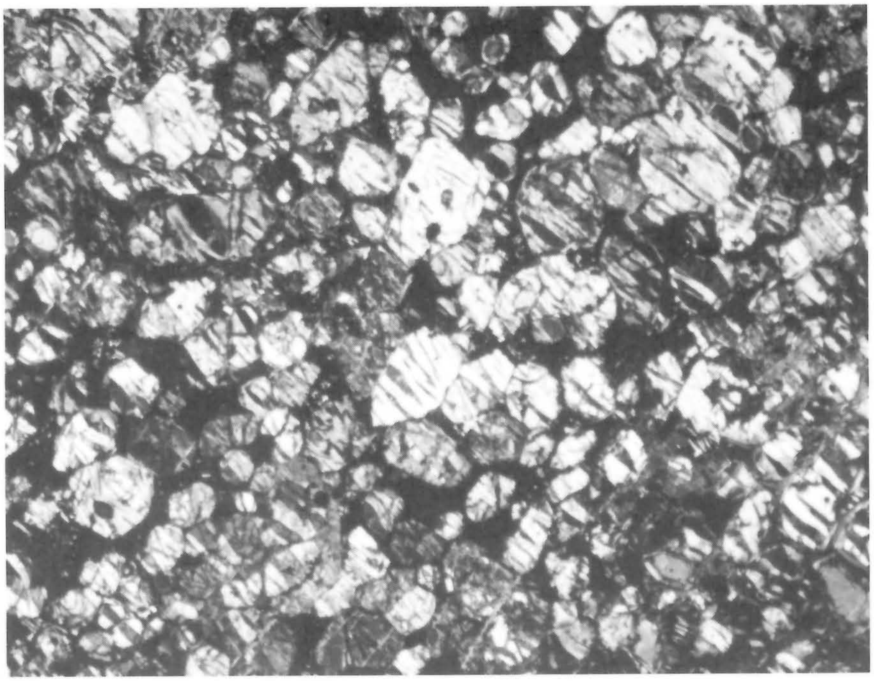


Plate 10: *Cumulus polyhedral olivine crystals showing preferred orientation (from lower left to upper right). Curtain-growth serpentine is oriented at right angles to the direction of elongation of olivine crystals. Clinopyroxene and plagioclase (partly altered) are postcumulus phases. Cycle 1, olivine cumulate layer, 722E section, DDH 38512-1220-1. XN.*

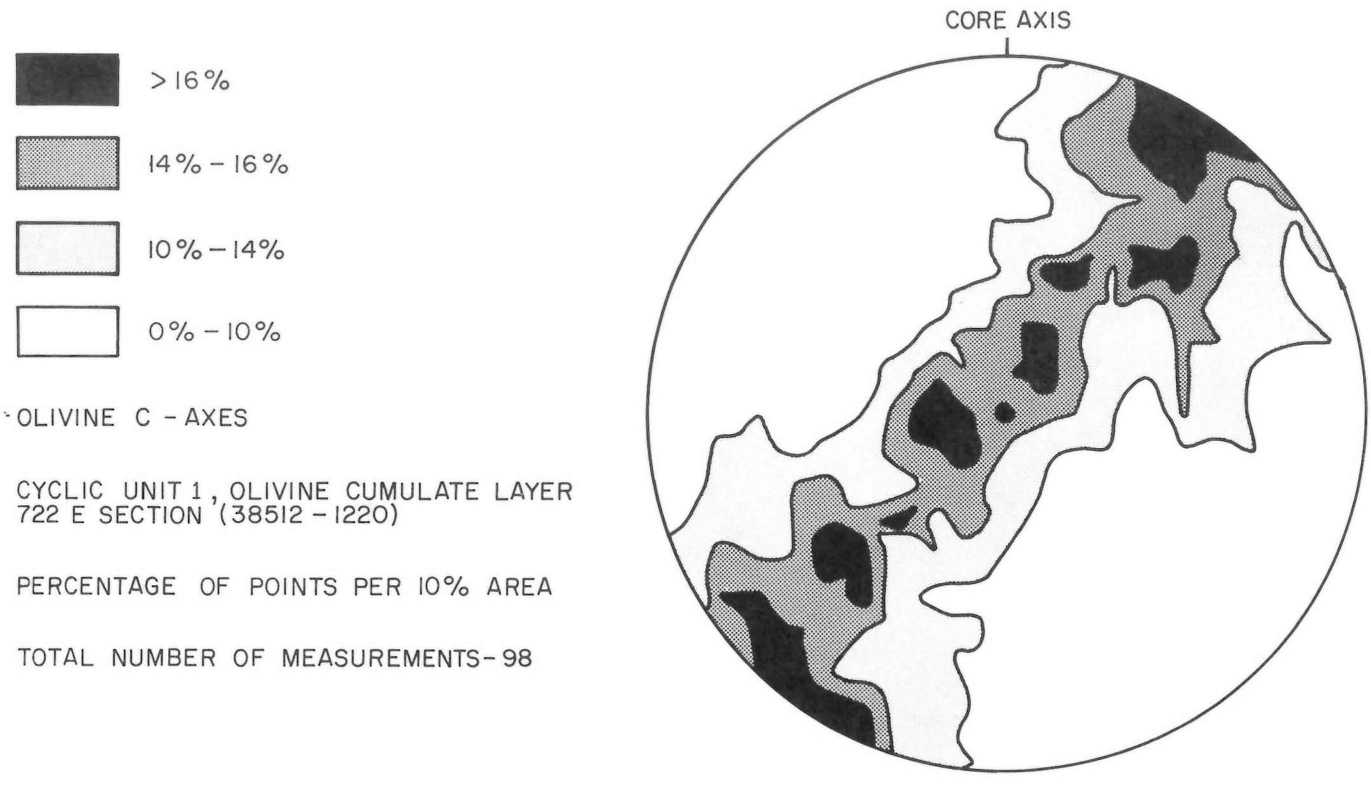


Figure 14: *Fabric diagram, olivine c-axes, cyclic unit 1, olivine cumulate layer, 722E section.*

Disseminated, euhedral chromite crystals occupy intercumulus areas and constitute approximately 1 percent of the olivine cumulate layer (Plate 11).

Intercumulus sulphide is common toward the top of the layer, particularly in drill hole 38511 where the sulphide content is estimated to average 5 percent. Pyrrhotite is the dominant sulphide mineral, although pentlandite and small amounts of chalcopyrite have been observed. In more highly serpentinized rocks intercumulus sulphide minerals display redistribution at their margins giving rise to discontinuous spongy mixtures of sulphide ± magnetite ± serpentine. Magnetite + pyrrhotite mixtures form veins and discontinuous spongy masses in more highly serpentinized rocks.

There is a substantial range in the degree to which the rocks have been recrystallized (Table 3). In terms of serpentinization of olivine the range is from 50 to 100 percent.

Table 3:
Range of recrystallization of primary assemblage minerals, drill hole 38512

Footage	
1150	no primary silicate minerals preserved
1160	olivine, orthopyroxene and clinopyroxene partly preserved, plagioclase relicts preserved
1170	no primary silicate minerals preserved
1180	clinopyroxene partly preserved
1190	olivine, orthopyroxene and clinopyroxene partly preserved
1200	olivine and clinopyroxene partly preserved
1210	no primary minerals preserved

Clinopyroxene cumulate layer

The clinopyroxene cumulate layer, intersected by drill holes 38512 and 38511, is 15 m thick. The rocks are medium grained, grey-green and possess a granular appearance. Some samples are delicately mottled by a sporadic distribution of orthopyroxene. The rocks were logged as websterite and petrographic examination shows that the compositional range is from plagioclase-bearing olivine websterite to olivine websterite (Table 4).

Table 4:
Modal analyses[1], cycle 1 clinopyroxene cumulate layer, 722E Section

	512-1320-1	511-230
serpentine (vein)	1.8%	-
magnetite (vein)	0.1	-
plagioclase (+ alteration products)	45.8	52.7%
orthopyroxene (+ alteration products)	10.4	10.7
clinopyroxene (+ alteration products)	40.8	36.6
phlogopite	0.3	-
opaque minerals	-	0.8

[1] Modal analyses based on 1000 counts per section.

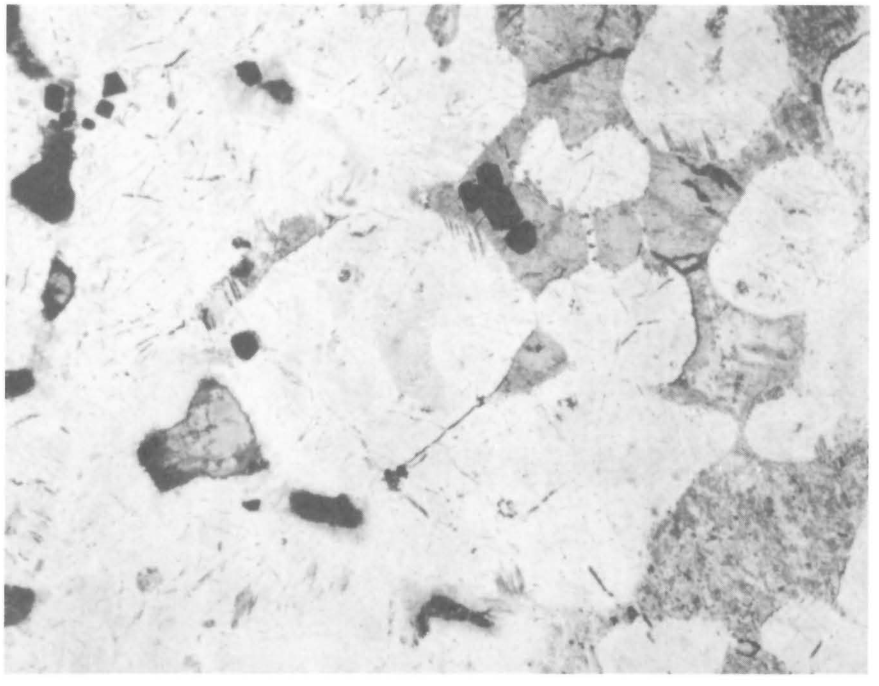


Plate 11: Clusters of disseminated chromite crystals occupying intercumulus areas. They occur as inclusions in postcumulus clinopyroxene and plagioclase. Cycle 1, olivine cumulate layer, 722E section, DDH 38512-1140-1. PL.

Clinopyroxene, the dominant cumulus mineral, occurs as discrete cumulus crystals that form interlocking crystal mosaics. Many individual crystals display irregular shapes suggesting that their shapes were modified through postcumulus crystallization (Plate 12). Much of the clinopyroxene is characterized by very closely spaced parting and many crystals are twinned. Near the base of the layer, clinopyroxene polycrystalline aggregates display highly complex mutual contacts with strongly developed interdigitation. Some individual crystals in these complex aggregates display blebby, vermicular, myrmekite-like exsolution. These aggregates are similar to those from cycle 1 MZ rocks of the Great Falls area. The crystal growth responsible for the complex grain relationships appears to have taken place after accumulation and is therefore adcumulus. Progressing upward in the layer, clinopyroxene forms a continuous interlocking mosaic with increasingly less complicated crystal boundary relationships.

Large, poikilitic orthopyroxene crystals (up to 1 x 0.5 cm), contain numerous clinopyroxene inclusions, as well as inclusions of olivine, plagioclase, chromite and sulphide (Plate 13). The clinopyroxene inclusions are much finer grained than cumulus clinopyroxene and possess smoothly rounded shapes implying substantial reaction between clinopyroxene and liquid to form orthopyroxene. Inclusions of plagioclase occur near orthopyroxene grain boundaries suggesting that the crystallization of orthopyroxene overlapped the crystallization of plagioclase. Orthopyroxene has been partly altered to talc + tremolite or completely altered to fibrous chlorite + tremolite that forms bastite-like pseudomorphs.

Olivine, a cumulus phase throughout, decreases in abundance toward the top of the layer. It is partly to completely altered to bipartite serpentinite $\pm$ fibrous diopside; some crystals have been altered to microcrystalline nonfibrous serpentine aggregates. Toward the top of the layer olivine has been altered to chlorite $\pm$ tremolite.

A single determination of olivine composition (Fo75.6) was made on a crystal from the base of the layer. This is lower than the olivine compositions of the underlying olivine cumulate layer, but is in keeping with the slight decrease in Fo-content observed toward the top of that layer.

Plagioclase forms isolated, intercumulus crystals distributed among cumulus clinopyroxene crystals. Near the top of the layer it occurs both as cumulus lath-like crystals and as intercumulus crystals in the same rock. It has been extensively altered to nearly isotropic mixtures of chlorite $\pm$ grossular $\pm$ muscovite.

Some relict intercumulus plagioclase possesses normal zoning (calcic core to less calcic rim); zoned crystals from two different samples gave An_{80-57}, and An_{92-73}. Determinations made on individual relict intercumulus crystals ranged from An_{72} to An_{90}. There are insufficient determinations to establish the presence of a trend. The original plagioclase was dominantly bytownite, close to anorthite in composition.

Secondary plagioclase forms clear to incipiently altered overgrowths on a few altered primary plagioclase crystals. Secondary plagioclase compositions range from An_{13} to An_{21}, and the preserved part of one highly altered crystal was determined to have a composition of An_{30}.

Chromite as euhedral crystals is the dominant oxide phase; however, toward the top of the layer highly altered ilmenite crystals make their first appearance.

Sporadic distribution of intercumulus sulphide is common toward the base of the layer where it locally achieves one percent of the rock.

Microfaults are sporadically distributed and are marked by narrow zones (0.1 to 0.2 mm) of microcrystalline, nearly isotropic chlorite $\pm$ fine grained tremolite. Some are curved, but others display an *en echelon* development and the amount of dislocation they represent is not known. Strain features in crystals adjacent to microfaults include deformation lamellae, continuous sweeping extinction, patchy extinction and anomalous extinction in clinopyroxene and kinked fibrous tremolite. Recrystallization of primary assemblage minerals has been promoted along these zones.

The progressive change in abundance of primary minerals is reflected in a decrease in olivine and an increase in plagioclase from the base to the top of the layer (Table 5). Clinopyroxene increases in abundance toward the top of the layer and several pseudomorphs after original cumulus olivine were observed at the top of the layer.

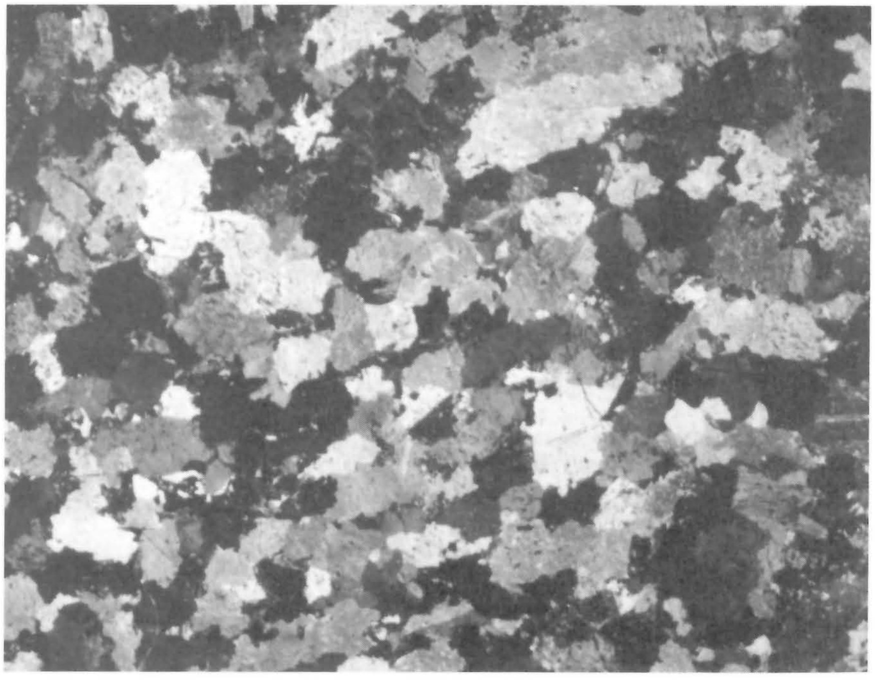


Plate 12: Dense cluster of irregularly shaped clinopyroxene crystals. Irregular crystal shapes are interpreted to be due to post-cumulus crystal growth. Cycle 1, clinopyroxene cumulate layer, 722E section, DDH 38511-1310-1. XN.

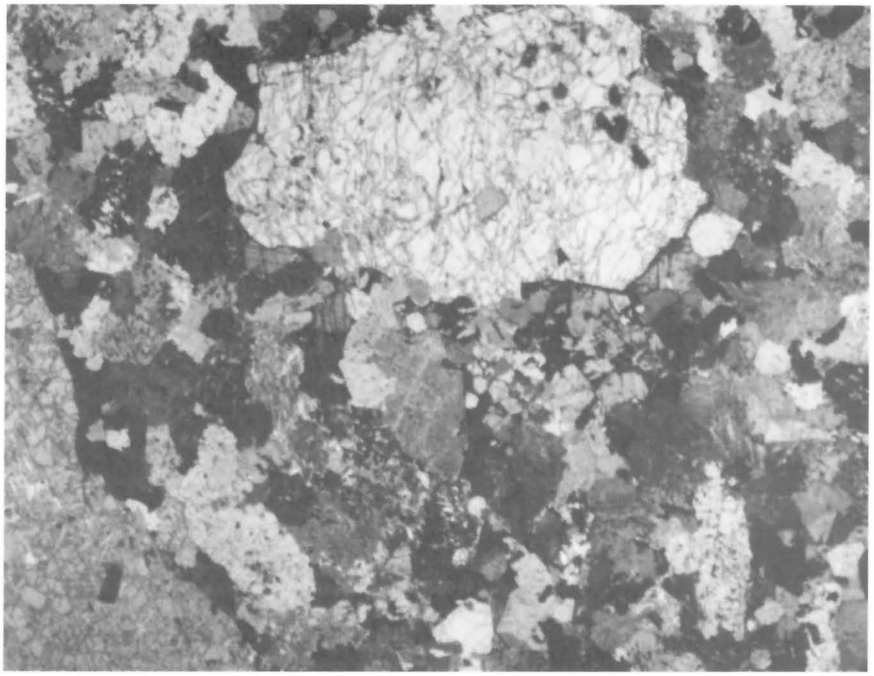


Plate 13: Clinopyroxene cumulate composed of polycrystalline clinopyroxene aggregates with complex mutual boundaries and large poikilitic orthopyroxene crystals with numerous clinopyroxene inclusions. Partly altered plagioclase is an intercumulus phase. Cycle 1, clinopyroxene cumulate layer, 722E section, DDH 38512-1290-1. XN.

Table 5:
Modal analyses[1], cycle 1 clinopyroxene cumulate layer, 722E Section

	512-1260-2	511-190-1
olivine	0.7%	-
serpentine (after olivine)	16.3	-
magnetite (after olivine)	0.5	-
orthopyroxene (+ alteration products)	20.4	12.5%
clinopyroxene (+ alteration products)	53.8	76.0
plagioclase (+ alteration products)	6.5	11.0
phlogopite	0.9	-
opaque minerals	0.9	0.5

[1] Based on 1000 counts per thin section

The changing abundance of olivine and plagioclase reflects the position of this layer between olivine and plagioclase cumulate layers. Olivine, the major cumulus mineral of the underlying layer, remains a cumulus phase throughout this layer, although decreasing significantly in abundance. Plagioclase, an intercumulus phase in the underlying layer, remains an intercumulus phase, except near the top of this layer, where cumulus plagioclase crystals begin to appear. This is evidence that plagioclase has reached the liquidus in the main magma and has joined clinopyroxene and olivine as a cumulus phase.

Plagioclase cumulate layer

Rocks of the plagioclase cumulate layer are light greenish grey to grey, medium grained, granular and mottled. A delicate, rhythmic-like, centimetre-scale layering is developed in the upper part of the layer due to changes in ratio of plagioclase to mafic minerals. Some rocks display a lamination caused by the dimensional orientation of plagioclase crystals, in places enhanced by dimensional orientation of elongate clinopyroxene crystals. The layer, which is approximately 30 m wide, appears to thicken slightly with depth. This reflects the gradual decrease of dip of layers inward, toward LCLZ rocks (Fig. 9). The contact between the plagioclase cumulate layer and the underlying clinopyroxene cumulate layer is not exposed in the telescoped core; however, the upper contact with the overlying olivine cumulate layer (cycle 2) is sharp.

Cumulus plagioclase originally formed discrete crystals and clusters of crystals (Plate 14), some displaying preferred orientation. Primary plagioclase (An_{87} to An_{95}, Table 6) is preserved sporadically through the layer, although it is commonly extensively to completely altered to secondary plagioclase (An_{35} to An_{56}) $\pm$ epidote $\pm$ chlorite $\pm$ muscovite. Prehnite pseudomorphously replaces plagioclase in one sample. Throughout the layer it is common to find primary and secondary plagioclase in the same thin section.

Table 6:
Plagioclase compositions[1], cycle 1 plagioclase cumulate layer, 722E Section

Drill Hole	Secondary Plagioclase	Primary Plagioclase	Normally zoned Primary Plagioclase
38511	An_{35}	An_{89-92}	-
38512	An_{36}-An_{56}	An_{87}-An_{95}	An_{87}-An_{60}
38532	An_{35}	An_{87}-An_{92}	-

[1] Plagioclase compositions were determined using the universal stage and Nakamura plate, and the Becke-Becker or Fedorov methods were followed, depending on the orientation of the plagioclase being measured. Some compositions were determined by 2V because of the highly altered nature and consequent poor quality of some grains.

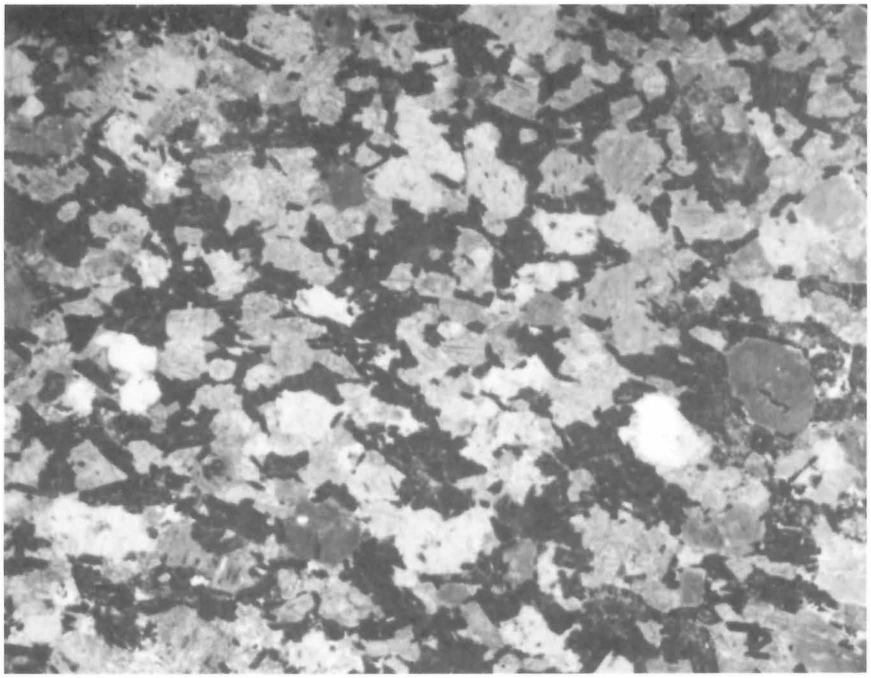


Plate 14: Altered plagioclase as individual lath-like crystals and clusters of crystals. Irregularly shaped clinopyroxene grains are interpreted to represent original cumulus crystals that have been modified by postcumulus crystal growth. Equidimensional orthopyroxene crystals and olivine (not seen here) are cumulus phases. Cycle 1, plagioclase cumulate layer, 722E section, DDH 38511-410-1. XN.

Clinopyroxene forms crystals and aggregates of crystals whose shapes are controlled by the surrounding cumulus plagioclase crystals. The general lack of inclusions suggests that the clinopyroxene was originally a cumulus phase that had its shape substantially modified through extensive postcumulus crystallization. The clinopyroxenes are distinguished by closely spaced parting and by many twinned crystals. Some crystal aggregates possess complex mutual boundaries. Toward the top of the layer clinopyroxene displays an imperfect dimensional orientation similar to that displayed by plagioclase. Clinopyroxene is well preserved and displays incipient alteration to colourless tremolite, although in one sample it is extensively altered to tremolite ± chlorite ± magnetite.

Orthopyroxene originally formed large (up to 1.5 cm), highly irregular, poikilitic crystals that contain numerous inclusions of clinopyroxene and lesser amounts of plagioclase and sulphide (Plate 15). It is rarely preserved and has been extensively altered to fibrous intergrowths of tremolite ± chlorite ± talc ± magnetite that form bastite-like pseudomorphs. Toward the top of the layer, finer grained (3 to 4 mm) equidimensional to rectangular inclusion-free crystals are interpreted as representing a cumulus phase (Plate 16).

Olivine originally occurred as sporadically distributed crystals and clusters of cumulus crystals. It has been extensively altered to ± chlorite ± tremolite ± magnetite and nonfibrous serpentine ± magnetite. Quartz and epidote are rare secondary products. Toward the top of the layer olivine becomes a postcumulus phase with inclusions of lath plagioclase and rounded clinopyroxene grains. The composition of one such olivine was determined to be $Fo_{76.8}$.

Phlogopite is a widely distributed, but not abundant, mineral that occupies intercumulus areas. It appears to be a late stage primary phase formed by crystallization of volatile-rich intercumulus liquid. Apatite crystals occur as inclusions in phlogopite in one sample.

Sulphide crystals are widely distributed throughout the layer. In the lower part of the layer, mixtures of sulphide and magnetite form discontinuous, wispy and spongy masses associated with altered olivine and orthopyroxene crystals. Original intercumulus sulphide grains are prominent in the upper part of the layer and locally form 2 percent of the rock. Some of the centimetre-scale layers near the top of the plagioclase cumulate layer are enhanced by concentrations of intercumulus sulphides and spongy sulphide associated with altered cumulus orthopyroxene crystals.

Microfaults have a sporadic distribution throughout the layer. Some are marked by the development of chlorite ± quartz ± tremolite and all show displacement.

Plagioclase, clinopyroxene and olivine formed cumulus phases throughout most of the layer. Orthopyroxene and phlogopite were postcumulus phases. In the upper part of the layer orthopyroxene joined plagioclase, clinopyroxene and olivine as a cumulus phase. Olivine became a postcumulus phase near the top of the layer. Throughout the layer clinopyroxene displays substantial postcumulus crystallization.

CYCLIC UNIT 2

Cyclic unit 2 is composed of an olivine cumulate layer, in turn overlain by clinopyroxene cumulate and plagioclase cumulate layers. The olivine cumulate layer is composed of two distinct parts, a lower heterogeneous suite distinguished by numerous layers, and an upper homogeneous part (Fig. 15). The lower heterogeneous part is composed of numerous olivine cumulate and plagioclase cumulate layer and it has been separated into 12 paired layers or macrorhythmic units (Fig. 15). The olivine cumulate layer is termed the Banded Layer and it reflects its appearance in drill core. The lower heterogeneous part of the Banded Layer is considered to be part of the olivine cumulate layer on the basis that 75 percent of it is composed of olivine cumulate rocks. However, it is possible that the lower heterogeneous part of the layer may represent a trough band-like feature that separates Cyclic units 1 and 2.

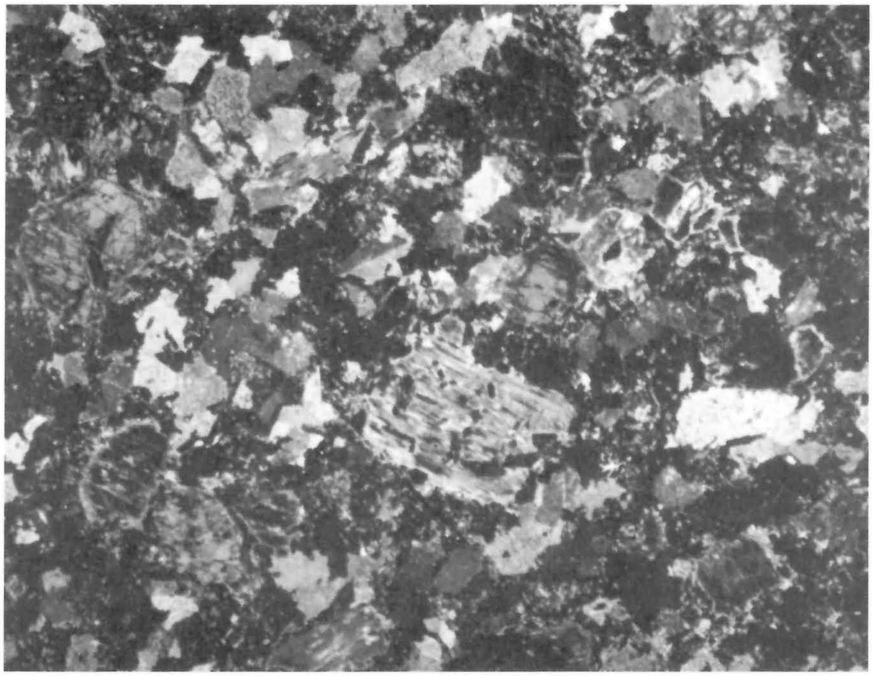
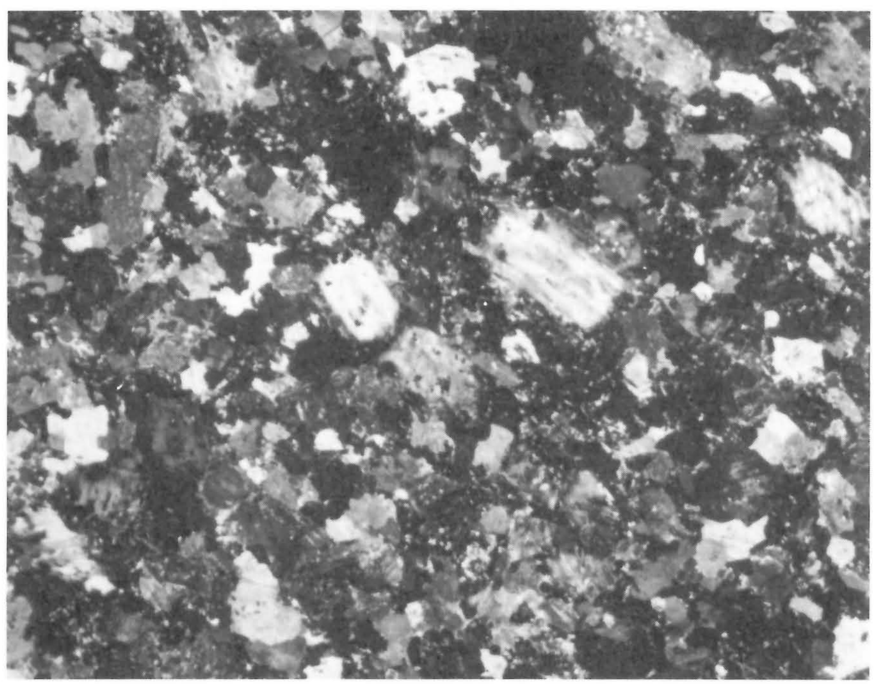


Plate 15: Pseudomorphously replaced poikilitic orthopyroxene crystal with numerous inclusions of altered plagioclase. Remainder of rock is composed of cumulus plagioclase and clinopyroxene. Cycle 1, plagioclase cumulate layer, 722E section, DDH 38511-280-1. XN.

Plate 16: Possible cumulus orthopyroxene as rectangular-shaped crystals associated with cumulus plagioclase, clinopyroxene and olivine. The orthopyroxene has been replaced by an interwoven intergrowth of tremolite and chlorite. Cycle 1, plagioclase cumulate layer, 722E section, DDH 38511-340-1. XN



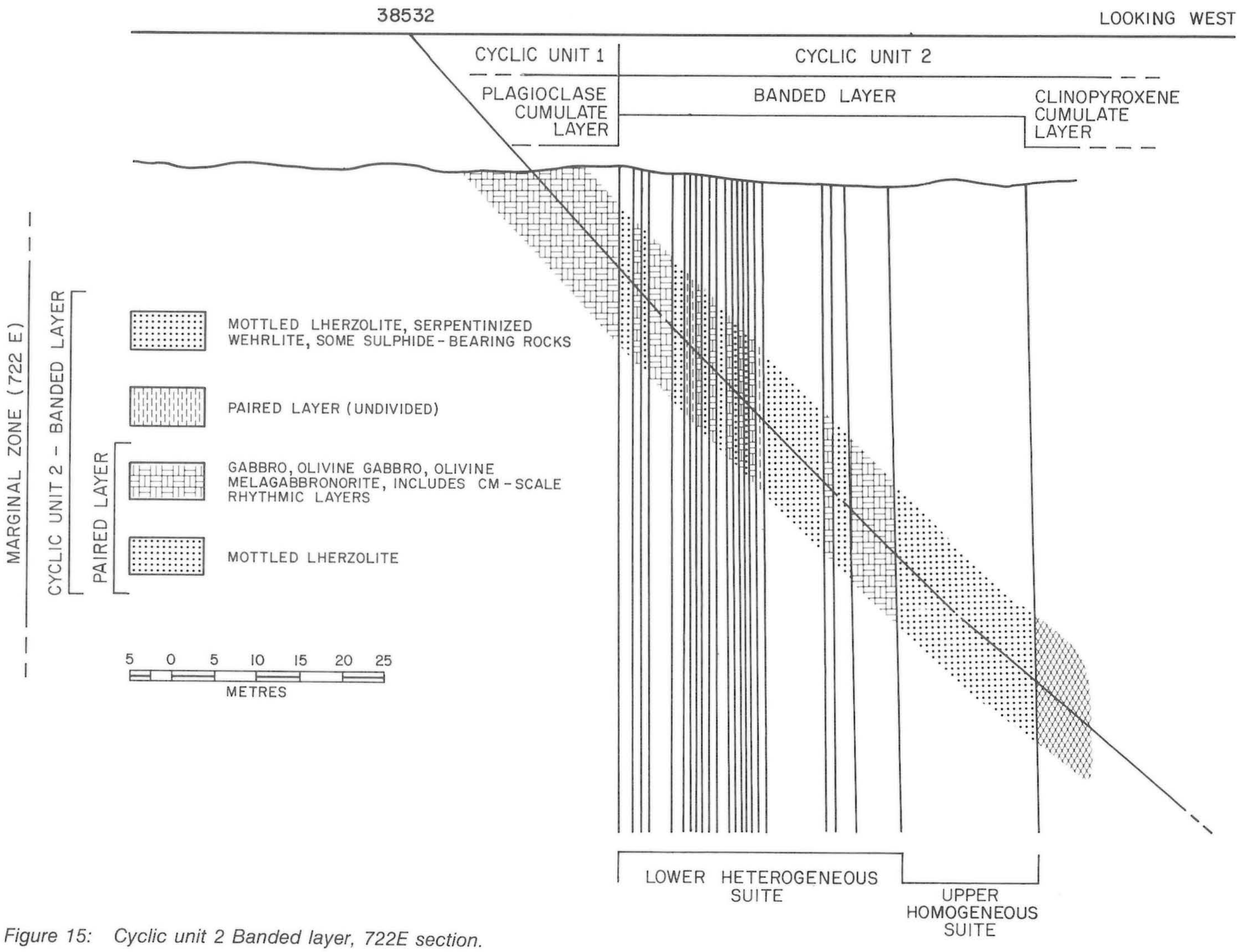


Figure 15: Cyclic unit 2 Banded layer, 722E section.

Banded Layer

LOWER HETEROGENEOUS PART

The olivine cumulate layer of cyclic unit 2 is distinguished by numerous small-scale layers; it was penetrated by drill holes 38511 and 38532, spaced approximately 240 m apart (Fig. 8). Drill hole 38532 consists of continuous split core and more than 50 layers were logged over the 70 m of core intersection. The estimated true layer thickness ranges from 42 to 45 m (Fig. 9); the slight increase in thickness of the layer between drill holes 38532 and 38511 is considered a result of the progressive decrease in dip of layers stratigraphically upward. The dramatic change in dip of the layer between drill holes 38532 and 38520 (Fig. 9) may be caused by a change in strike of the layered sequence between the two drill holes, the holes being on section lines that are approximately 240 m apart.

Individual layer thickness ranges from less than a centimetre to 74 m. Numerous mm-scale, microscopic layers have been discovered during petrographic examination and the total number of layers is probably several times the number logged megascopically. More than 75 percent of the units composing the layer are olivine cumulates; the remainder are plagioclase and clinopyroxene cumulates. The contacts with the underlying cyclic unit 1 plagioclase cumulate layer and overlying cyclic unit 2 clinopyroxene cumulate layer are sharp.

The lower two-thirds of the Banded Layer has been separated into 12 paired layers, each of which consists of a lower, olivine-rich, olivine cumulate part and an upper, plagioclase-rich, plagioclase cumulate layer (Fig. 15). The lower, olivine-rich portion of most paired layers displays a progressive upward increase in plagioclase:olivine ratio. Plagioclase occurs as cumulus and postcumulus phases in olivine-rich olivine cumulate rocks. In six paired layers, plagioclase is observed to be a cumulus phase with olivine in the olivine-rich part of the layer. In each of these layers a progressive increase in the plagioclase:olivine ratio toward the top of the layer has been observed. Thus, the lower part of some paired layers is modally graded. In three of these layers the contact between the olivine-rich and plagioclase-rich parts is gradational. These three layers, which display a continuous modal grading and are truly rhythmic in character, are termed macrorhythmic layers following the usage of Irvine (1980). The ratio of ultramafic to gabbroic rocks within individual macrorhythmic layers is variable; it ranges from less than 1:1 to greater than 90:1, although most range from 1:1 to 4:1. Two of the six layers display sharp contacts between the olivine-rich and plagioclase-rich parts.

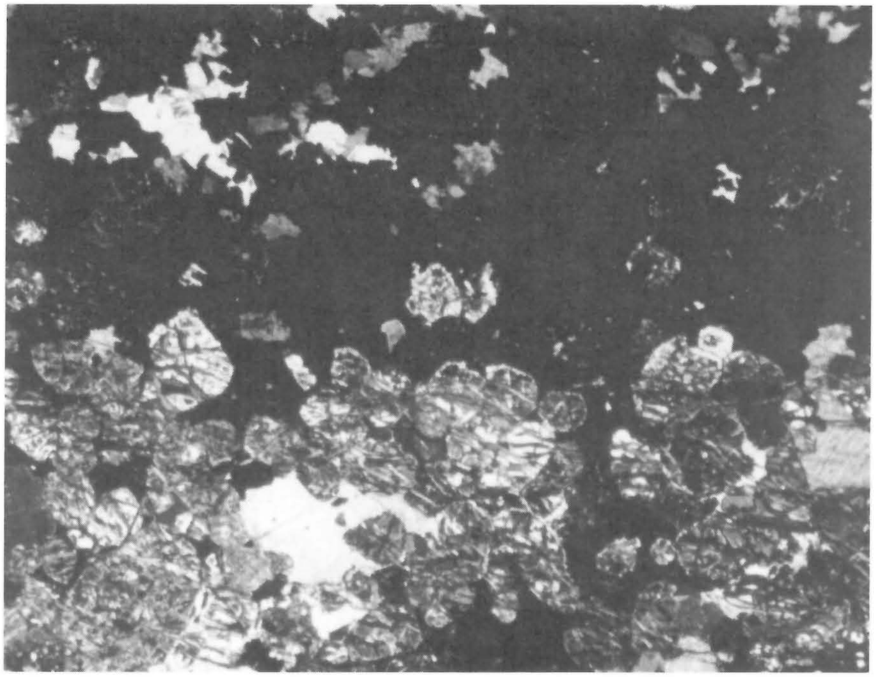


Plate 17: Contact between olivine + plagioclase cumulate (below) and plagioclase + clinopyroxene + olivine cumulate (above). The contact is a ratio contact (Jackson, 1967) as cumulus plagioclase occurs in the olivine cumulate and cumulus olivine occurs in the plagioclase cumulate. Plagioclase has been converted to hydrogrossular garnet. MZ, cycle 2, Banded layer, 722E section, DDH 38532-245.2. XN.

Thus, although the lower part of these layers displays a continuous increase in the plagioclase:olivine ratio, this progressively continuous change is interrupted by an abrupt contact. Where contacts between the lower olivine-rich part and the upper plagioclase-rich part are sharp (Plate 17), they resemble phase contacts (marked by the appearance or disappearance of a mineral phase). However, the contacts are ratio contacts, where there is an abrupt change in the ratio of the accumulating primary phases. The contact between olivine-rich and plagioclase-rich parts of the other paired layer was not observed because of missing core.

Progressive changes in the plagioclase:olivine ratio have not been observed in the lower parts of the other layers and their internal contacts are variously sharp or gradational. In one case, the contact between the olivine-rich and plagioclase-rich parts of a layer is a zone of chlorite schist.

Olivine cumulate layers

The olivine cumulate rocks are dominantly laminated, medium grained, mottled greenish black to greyish black, and heterogeneous (Plates 18 and 19). The lamination is caused by a rough segregation of the rock into olivine-rich and olivine-poor (plagioclase ± clinopyroxene ± orthopyroxene-rich) mm-scale bands. The lamination is enhanced by a planar fabric due to parallel serpentine veinlets. Orthopyroxene occurs as large (up to 2 cm), sporadically distributed, equidimensional to slightly elongate or elliptical crystals, that impart a heterogeneous, mottled character to the rock (Plates 20 and 21). Many orthopyroxene crystals display a preferred orientation that is parallel to the lamination and layering direction (Plate 22). Two modal analyses of olivine cumulate rocks, one from the base and one from the top of the layer (Table 7) are similar and suggest that the layer may be uniform in composition throughout. However, the heterogeneous character of the rocks, even at thin section scale, precludes systematic modal analyses; modal proportions, other than those in Table 7, have been based on visual estimates.

Table 7:
Modal analyses[1], cycle 2, Banded Layer, olivine-rich, olivine cumulate rocks, 722E Section

	511-420-1	511-640-1
olivine	-	23.3%
serpentine	58.9%	35.0
magnetite	-	-
orthopyroxene (+ alteration products)	8.8	12.7
clinopyroxene (+ alteration products)	13.1	9.5
plagioclase (+ alteration products)	11.2	12.5
hornblende + phlogopite	8.2	5.7
chromite + ilmenite + sulphide (not divided)	-	1.3

[1] Modal analyses based on 1000 counts per section.

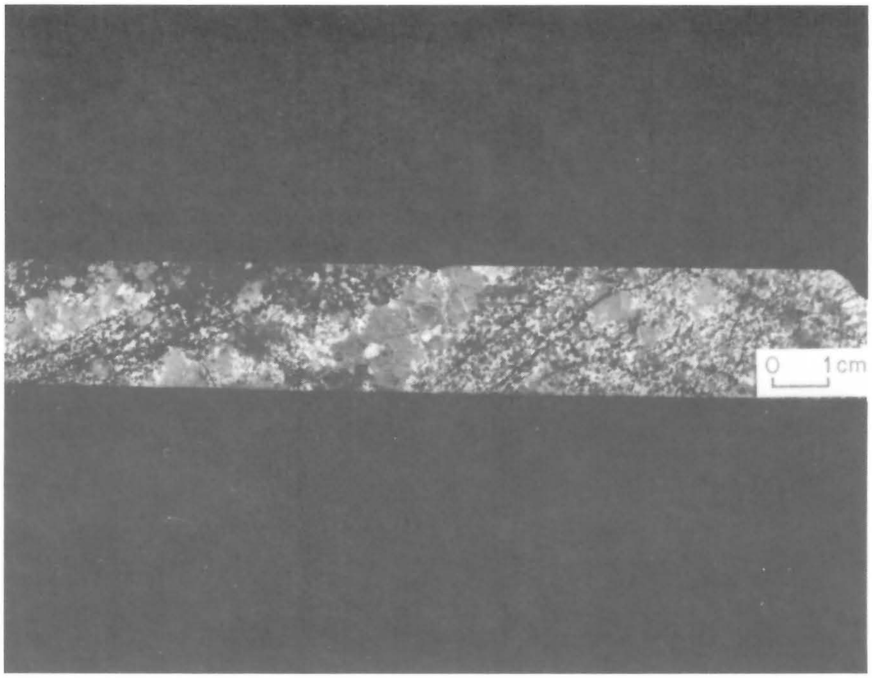


Plate 18: *Heterogeneous character of Banded layer olivine cumulate rocks. Mid-grey patches are large irregular pokilitic orthopyroxene crystals. Whitish areas in matrix are altered plagioclase oikocrysts, dark areas are serpentinized olivine. Lamination is caused by segregation of the rock into orthopyroxene-rich and olivine + plagioclase-rich laminae. MZ, Banded layer, 722E section, DDH 38532-166.5.*

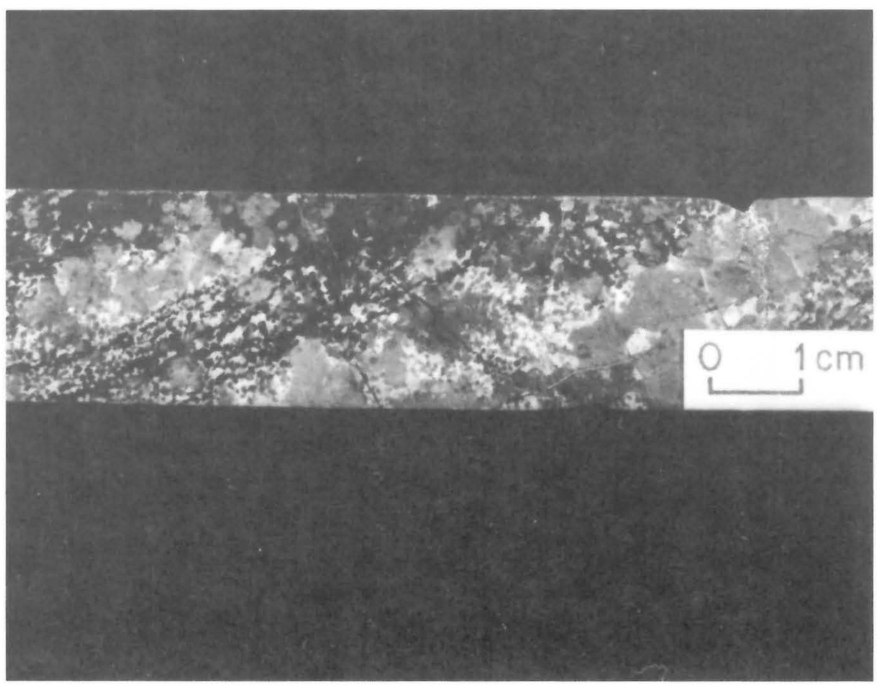


Plate 19: *Detail of heterogeneous Banded layer olivine cumulate rocks seen in Plate 18.*

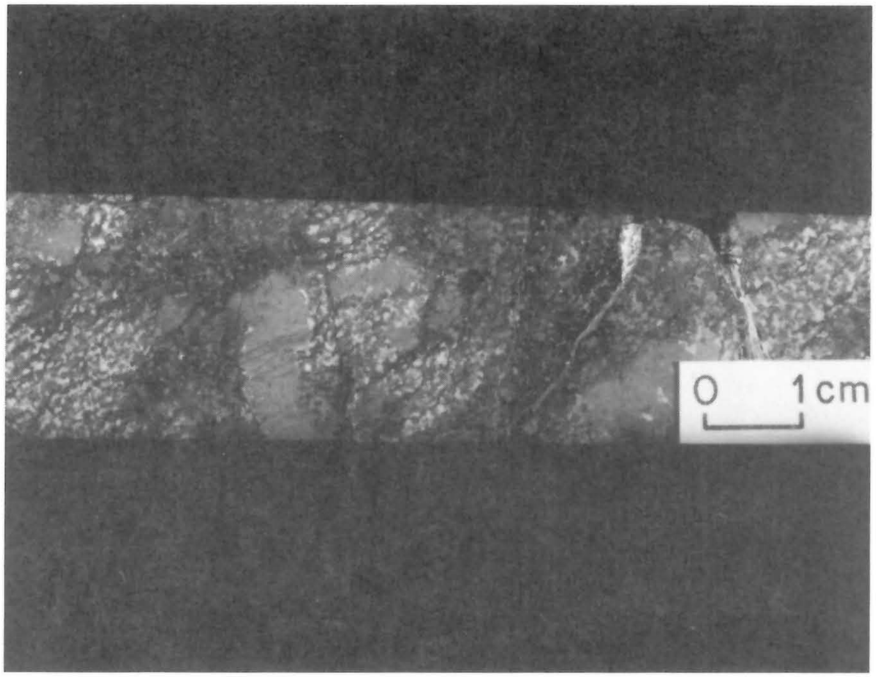


Plate 20: *Heterogeneous olivine cumulate. Large mid-grey patches are poikilitic orthopyroxene crystals; finer grained, mid-grey intercumulus material is clinopyroxene. Whitish material is alteration after original postcumulus plagioclase. Mid to dark grey kernel-like crystals are serpentinized olivine. MZ, Banded layer, 722E section, DDH 38532-216.6.*

Plate 21: *Banded layer olivine cumulate with large pokilitic orthopyroxene crystal, characterized by numerous rounded olivine inclusions. The dark (isotropic) areas surrounding cumulus olivine crystals are alteration products after intercumulus plagioclase. MZ, Cycle 2, Banded layer (olivine cumulate), 722E section, DDH 38532-216.6.2a. XN.*

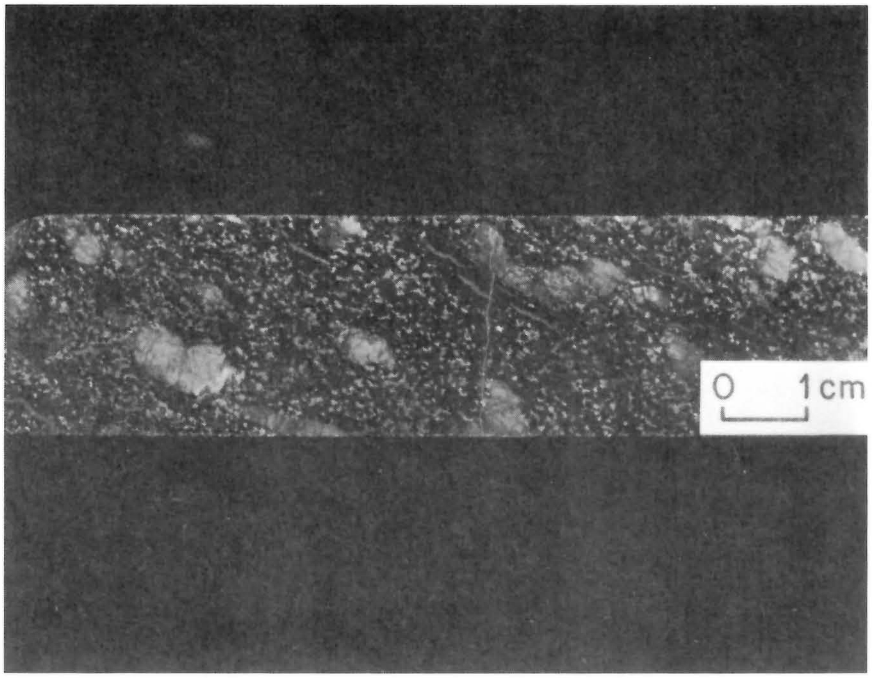


Plate 22: Strongly laminated, Banded layer olivine cumulate. Light grey elongate patches are poikilitic orthopyroxene crystals. Fine grained, whitish to light grey material is alteration after postcumulus plagioclase. Fine grained mid-grey material is postcumulus clinopyroxene. Dark grey to black is serpentinized olivine. Orientation of elongate, poikilitic orthopyroxene contributes to the overall lamination of the rock. Olivine cumulate, MZ, Banded layer, 722E section, DDH 38532-172.7.

Plagioclase cumulate layers

The plagioclase ($\pm$ clinopyroxene) cumulate rocks that form the upper part of the paired or macrorhythmic layers are fine grained, greenish- to brownish-grey, and considerably more homogeneous in appearance than the olivine cumulates. A large variation in the ratio of pyroxene $\pm$ olivine to plagioclase has been observed and plagioclase cumulate rocks range from leucocratic to melanocratic varieties. The plagioclase cumulates contain intervals of fine-scale rhythmic layers where individual layers of one cm or less are common (Fig. 16 and Plate 23). Centimetre-scale layers display well developed continuous modal grading, from olivine-rich at the base to plagioclase-rich at the top. The centimetre-scale layers occur predominantly in the upper, plagioclase-rich parts of paired layers. This small-scale layering corresponds closely in thickness with rhythmic layering as defined by Wager and Deer (1939), Wager and Brown (1968) and Irvine (1965).

Some layers are distinguished by a decrease in grain size of one or more constituent minerals from base to top. One 3.5 cm thick layer consists of coarse grained poikilitic orthopyroxene crystals (5 mm) at the base and medium- to fine-grained cumulus olivine and plagioclase (1 mm) at the top. Some layer contacts are marked by an abrupt change in grain size of constituent minerals and, at one plagioclase cumulate-olivine cumulate contact, the olivine crystals immediately above the contact have their long axes oriented at right angles to the contact (Plate 24). In some rocks, certain minerals, like orthopyroxene, tend to be several times (up to 5x) larger than the other constituent minerals.

UPPER HOMOGENEOUS PART

The inner or upper third of the Banded Layer is composed of lherzolite and wehrlite (Fig. 15). The lherzolite is mottled and plagioclase-bearing, and both units are sulphide-bearing in places. The contact between the plagioclase-rich upper part of the innermost (uppermost) paired layer and the olivine-rich rocks of the upper third of the layer is sharp.

OLIVINE COMPOSITIONS

Olivine compositions determined from Banded Layer rocks range from $Fo_{75.6}$ to $Fo_{80.7}$ and average $Fo_{80.2}$ (38 determinations, Fig. 17 and 18). The olivine displays a greater variation in composition than cyclic unit 1, and has a significantly lower average Fo-content ($Fo_{80.2}$ vs. $Fo_{85.0}$). These features can be clearly seen in Figure 19 where trends for cyclic unit 1 and cyclic unit 2 olivine have been superimposed. It is interesting to note that cyclic unit 1 rocks, which are relatively homogeneous, possess limited variations (less than 3 percent Fo) in Fo-content of their contained olivine. In contrast, olivine of the heterogeneous cyclic unit 2 Banded Layer rocks displays a substantial range (9 percent Fo) in Fo-content. There is no apparent correlation between modal abundance of olivine and mole percent Fo in cyclic unit 2 Banded Layer rocks (Fig. 20). A similar lack of correlation was previously noted in cycle 1, olivine cumulate rocks. The large range in compositions of Banded Layer olivines suggests a mixing of olivines that crystallized in different places and/or at different times. Thus, some of these olivines might be considered as having been redeposited or "reworked" through the action of magmatic currents.

PLAGIOCLASE COMPOSITIONS

The anorthite content of partly preserved cumulus plagioclase ranges from An_{87} to An_{95} (6 determinations). Several highly altered crystals possess lower anorthite compositions (An_{67}, An_{75}). Reliable determinations are insufficient to define a trend.

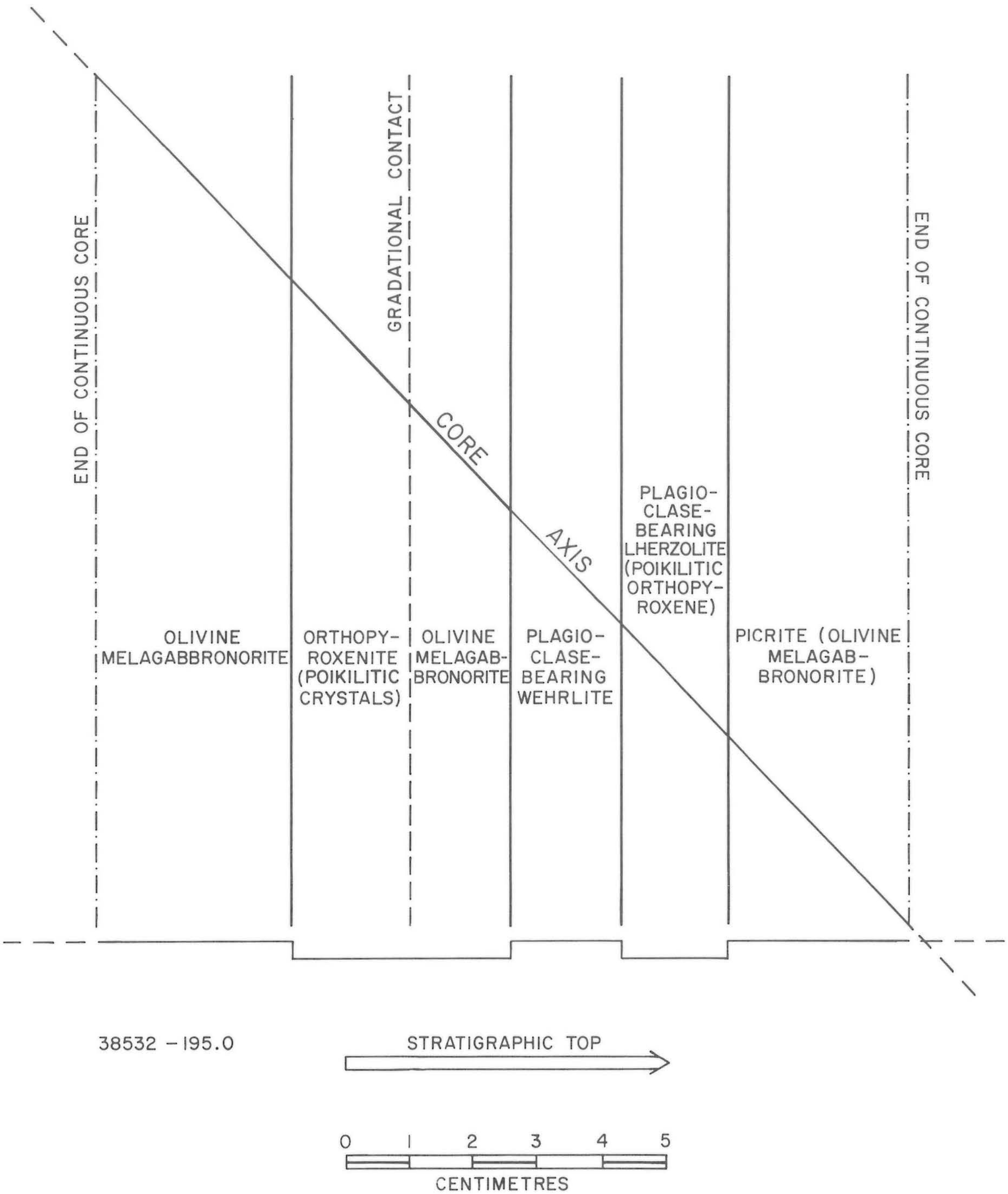


Figure 16: *Organization of centimetre-scale layering, upper part of paired macrorhythmic layer 8, Banded layer, 722E section.*

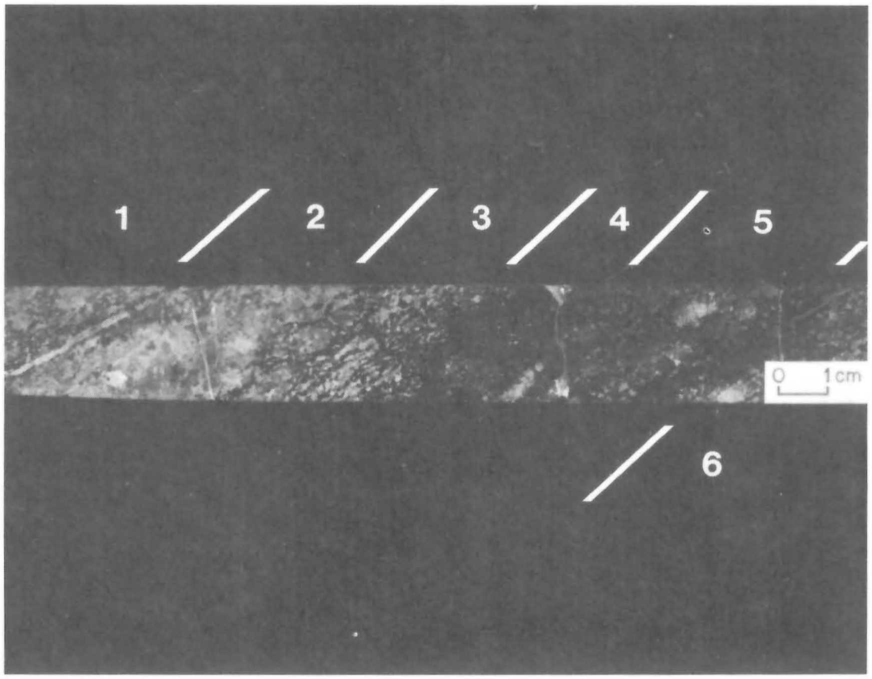


Plate 23: *Heterogeneous character, Banded layer. Progressing from left to right, the rock changes from a dense aggregation of poikilitic orthopyroxene ± plagioclase to an olivine cumulate with abundant orthopyroxene and plagioclase to an olivine cumulate with abundant clinopyroxene. The light grey patches toward the right hand side are poikilitic orthopyroxene crystals. Darkest areas are concentrations of serpentinized olivine. The contacts and numbers refer to Fig. 16 which shows the rock types in greater detail. Note secondary amphibole veinlet that separates olivine melagabbronorite (1) from orthopyroxenite (2). MZ, Banded layer, 722E section, DDH 38532-195.0.*

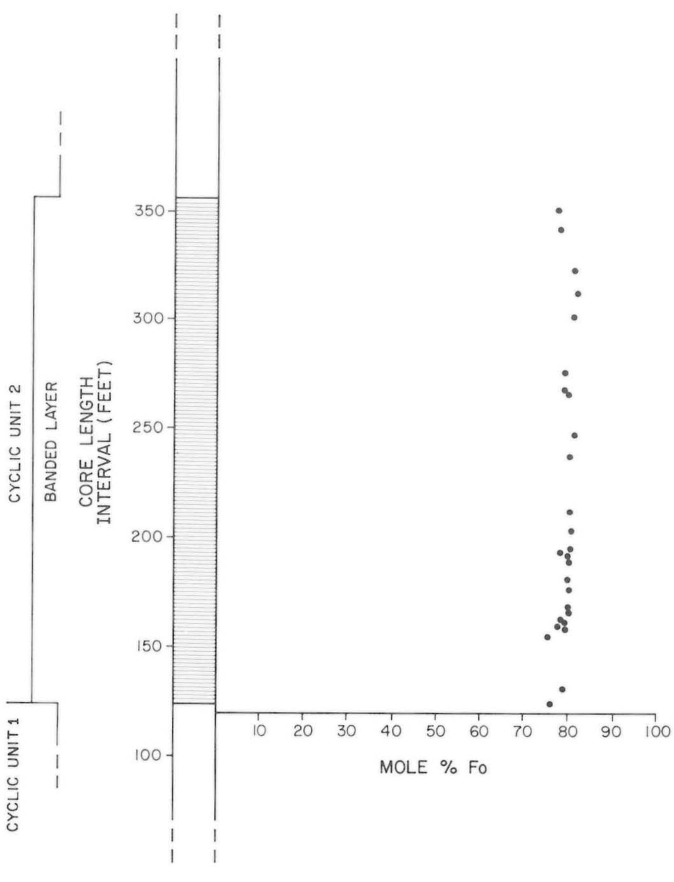


Figure 17: *Olivine compositions cyclic unit 2, Banded layer, drill hole 38511, 722E section.*

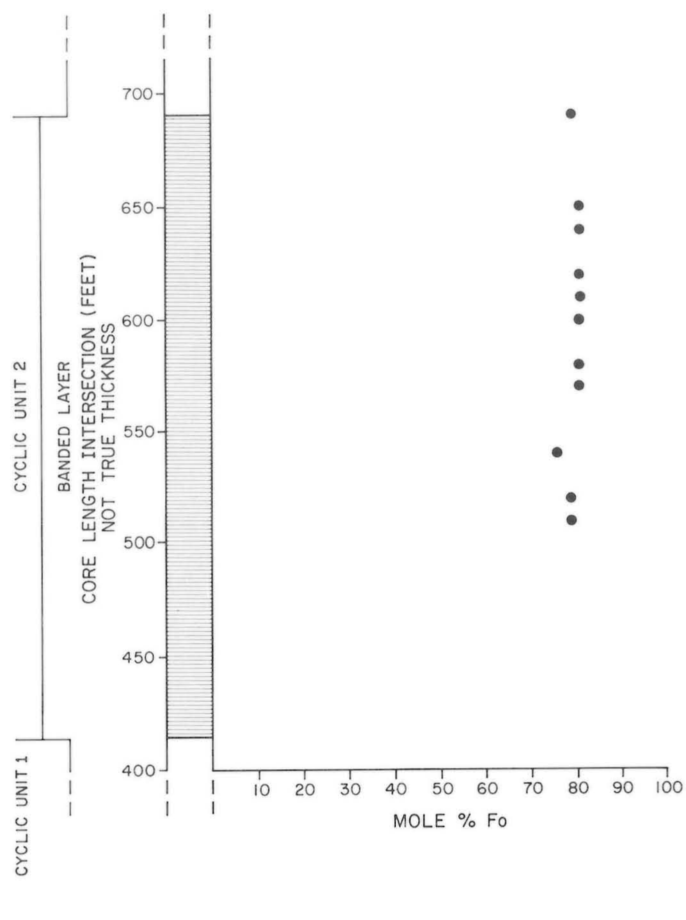


Figure 18: *Olivine composition, cyclic unit 2, Banded layer, drill hole 38511, 722E section.*

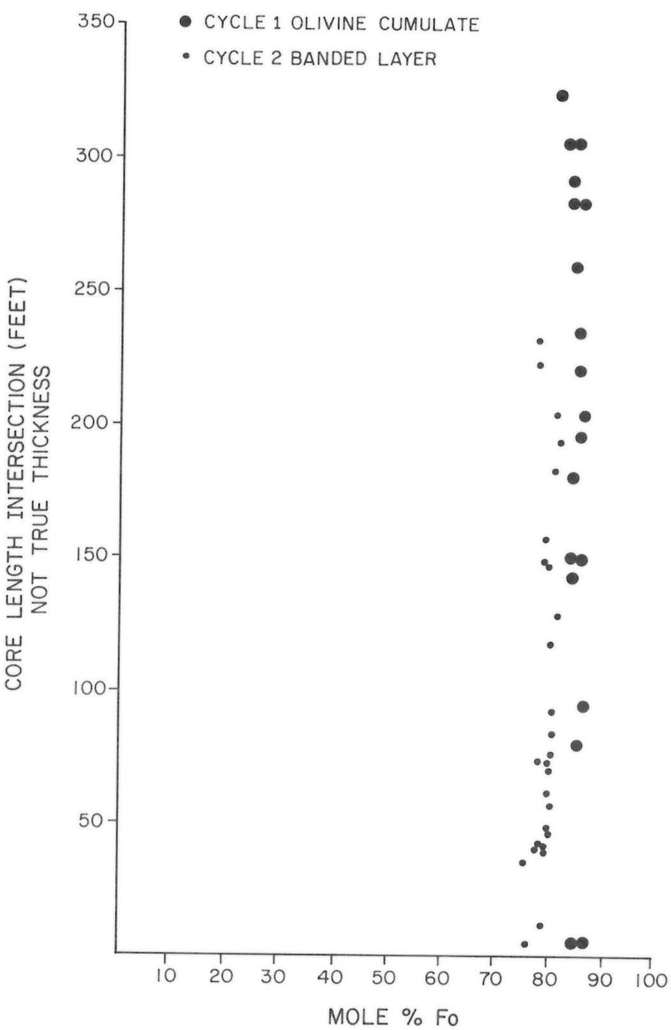


Figure 19: Superimposed olivine compositions, cyclic unit 1, olivine cumulate layer.

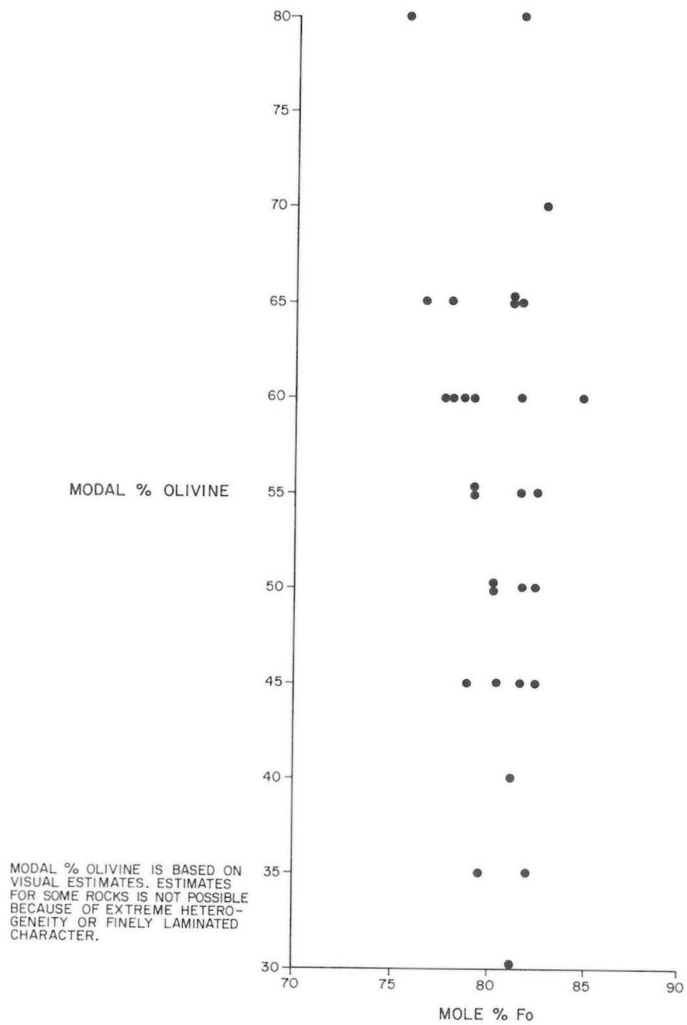


Figure 20: Mole percent Fo vs. modal percent olivine, cyclic unit 2, Banded layer.

ROCK FABRIC

Many olivine cumulate rocks display a fabric caused by parallel arrangement of serpentine veinlets. The fabric is parallel to layering and lamination in most rocks. Two mutually perpendicular directions of serpentine fabric have been observed in some rocks. The one that is parallel to layering and lamination is best developed, the other consists of more widely spaced serpentine $\pm$ magnetite veinlets.

The serpentine fabric is caused by banded or curtain-growth serpentine (Wicks *et al.*, 1977), developed either parallel or at right angles to the preferred orientation of elongate olivine crystals. The lack of other angular relationships suggests that the direction of curtain-growth serpentine may be controlled by crystallographic elements of the replaced olivine crystals. Since serpentine develops along fractures within olivine crystals (Wicks *et al.*, 1977), the implication is that the fracture directions are controlled by the orientation of olivine crystallographic elements in the rock. The well developed curtain-growth in some rocks suggests that some olivine crystals in the rock were oriented with respect to crystallographic axes a, b and c prior to serpentinization.

Preferred orientation of olivine with respect to c-axes in Banded Layer rocks is clearly demonstrated in Figure 21 where an elongate, bull's-eye pattern is associated with a continuous girdle. The girdle represents the original layering plane of the rock and the bull's-eye pattern indicates the maxima of c-axes orientation. Thus, the olivine crystals have a strong lineate lamination in the layering plane. Rocks possessing lineate lamination of cumulus phases are interpreted to have formed during magma flow by current movement of crystal-charged magma in the chamber. The overall orientation of olivine crystals in the rocks has not been investigated, that is, whether the a and b directions also display parallel orientation. However, the presence of curtain-growth serpentine suggests the possibility that some cumulus olivine was perfectly oriented with respect to a, b and c prior to serpentinization.

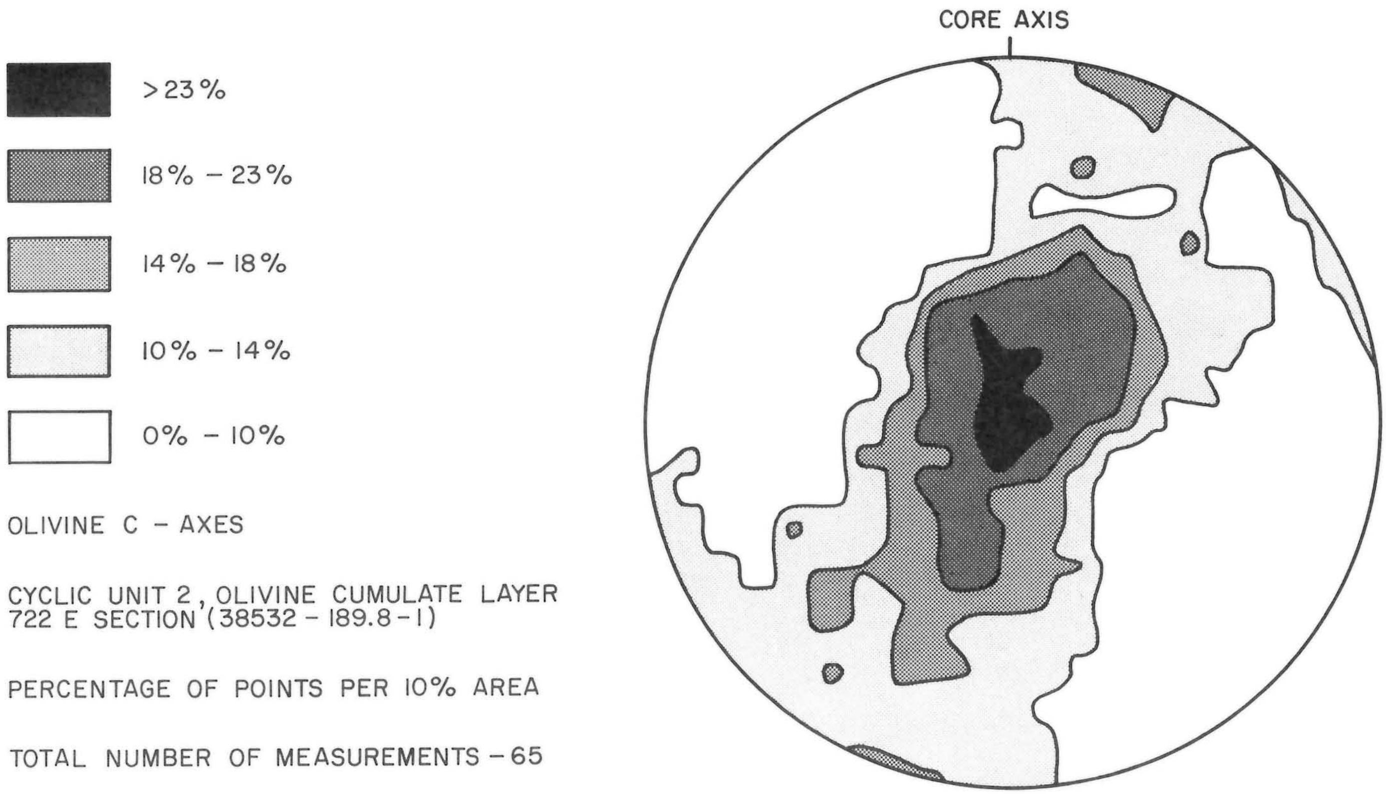


Figure 21: Fabric diagram, olivine c-axes, cyclic unit 2, Banded layer.

CUMULUS AND POSTCUMULUS CRYSTALS

Olivine is a cumulus phase throughout the Banded Layer and plagioclase is a cumulus phase in the plagioclase-rich parts of the layer. However, in many plagioclase-bearing olivine-rich rocks within the layer, it is extremely difficult to determine whether plagioclase was originally a cumulus or intercumulus phase. In the example illustrated in Figure 22 olivine is an obvious cumulus mineral. Altered plagioclase appears to have originally formed large oikocrysts enclosing numerous olivine crystals. However, in the upper right part of the figure, the boundary relations between altered plagioclase and clinopyroxene suggest that plagioclase originally formed lath-like crystals. Thus the large contiguous areas of altered plagioclase may originally have been composed of aggregates of cumulus lath plagioclase. The uncertainty of determining the original character of the plagioclase is caused by the complete replacement of plagioclase by fine grained alteration products and the consequent destruction of original plagioclase grain boundaries. This is not to imply that all large contiguous areas of altered plagioclase represent original aggregates of lath-like crystals, nor that it is possible that cumulus and intercumulus plagioclase might not co-exist in some rocks.

It seems likely that many combinations of cumulus and intercumulus phases occur in the Banded Layer and that no single combination holds for the entire zone. Clinopyroxene is clearly postcumulus in rocks where it originally formed large oikocrysts, yet in other areas it forms discrete crystals and aggregates of crystals that lack inclusions and, therefore, are likely of cumulus origin.

In rocks where olivine and plagioclase were cumulus crystals, large elongate poikilitic orthopyroxene crystals display preferred orientation. The parallel orientation of the orthopyroxene crystals suggests that they were deposited from magmatic currents, yet the crystals poikilitically enclose numerous olivine ± clinopyroxene crystals that imply crystallization in situ. In many of these rocks olivine ± clinopyroxene are the only phases that occur as inclusions in orthopyroxene. In some rocks, rare plagioclase inclusions are concentrated at or near orthopyroxene grain boundaries. If such orthopyroxene crystallized *in situ,* it is difficult to explain its lack of plagioclase inclusions. A possible explanation is that these orthopyroxenes crystallized through reaction in a part of the magma chamber that was free of cumulus plagioclase. The orthopyroxene crystals were subsequently transported and deposited at a site where cumulus plagioclase was present. Subsequent additional postcumulus crystallization on orthopyroxene at the new depositional site would be responsible for plagioclase inclusions at or near grain boundaries. Thus it is possible that some poikilitic orthopyroxene crystals may represent a "reworked" cumulus phase, accumulated at the time of formation of the rock.

Concentration of poikilitic orthopyroxene crystals in centimetre-scale layers has been observed. The orthopyroxene of one such layer that was examined in detail (Fig. 16, layer 2) contains numerous olivine and plagioclase inclusions. The rocks immediately above and below the layer contain cumulus olivine and plagioclase. The crystals are roughly equidimensional and do not display a preferred orientation. The presence of plagioclase inclusions and apparent lack of preferred orientation suggest that the orthopyroxene crystals that constitute the orthopyroxenite layer crystallized *in situ.* The orthopyroxene of the mottled lherzolite, 3 cm stratigraphically above the orthopyroxenite layer, contains elongate, poikilitic orthopyroxene crystals that display a preferred orientation parallel to the layering direction. This orthopyroxene may have crystallized elsewhere and subsequently transported and deposited at this site by magmatic currents. Thus orthopyroxenes, possibly originating in a very different manner, may be closely related in centimetre-scale layering of the Banded Layer.

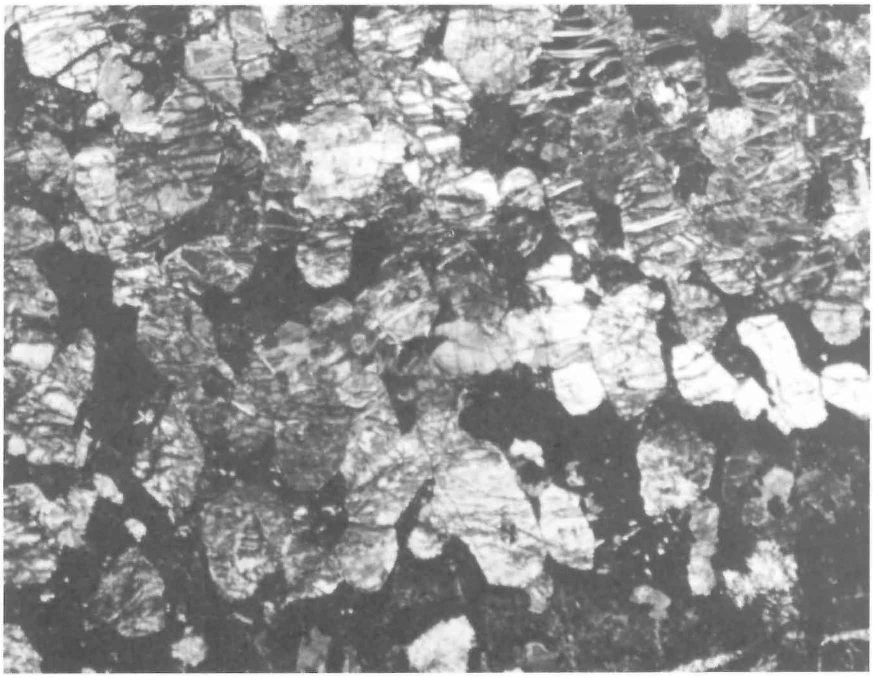


Plate 24: *Contact between plagioclase + clinopyroxene cumulate (below) and olivine cumulate (above). The long axes of the olivine crystals are oriented at right angles to the layer contact. The contact is gradational over several mm. MZ, Cycle 2, Banded layer, 722E section, DDH 38532-275.3-1. XN.*

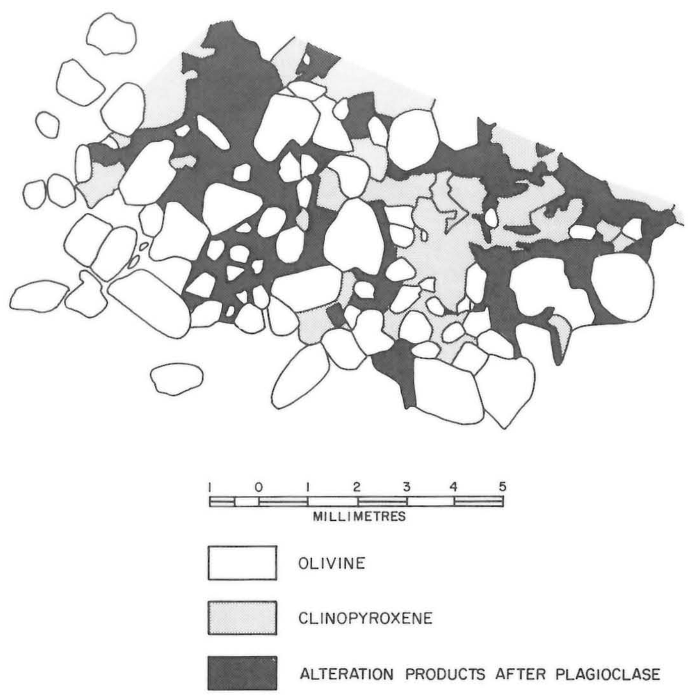


Figure 22: *Crystal boundary relationships between clinopyroxene and totally altered plagioclase.*

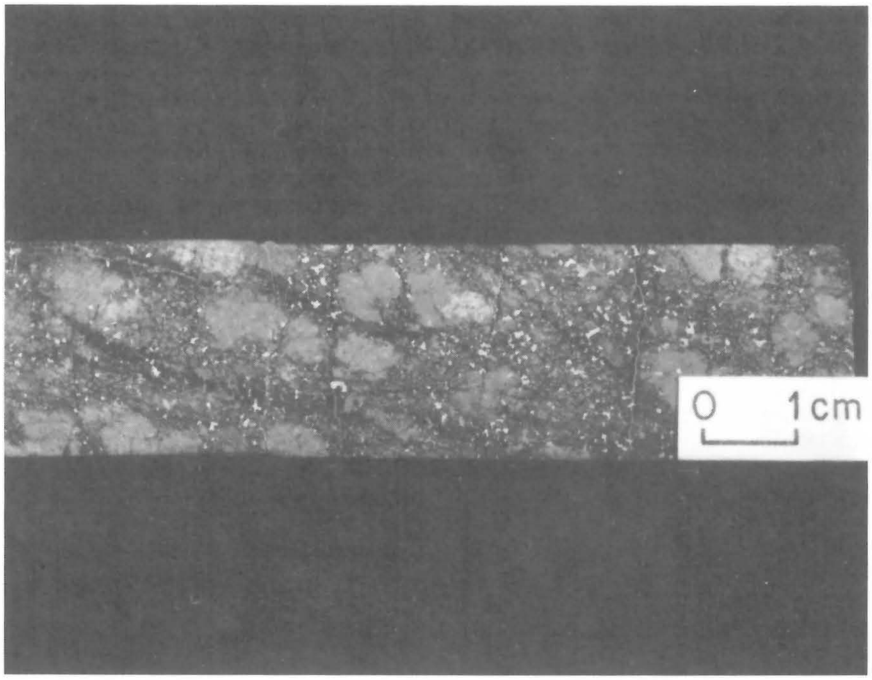


Plate 25: Sulphide-bearing heterogeneous olivine cumulate. The highly irregular shape of the sulphides (whitish grey) is due to their intercumulus nature, their shape being controlled by the shape and packing density of the surrounding silicate phases. Sulphide inclusion in poikilitic orthopyroxene is circular in outline (NW corner of scale marker). Large irregular mid-grey patches are poikilitic orthopyroxene crystals. Fine grained kernel-like crystals are serpentinized olivine. MZ, Banded layer, 722E section, DDH 38532-290.4.

OPAQUE MINERALS

Chromite forms fine grained (less than 0.1 mm) euhedral crystals and clusters of euhedral crystals that occur as inclusions in olivine and all postcumulus mineral phases. It displays a small variation in abundance and grain size and rarely composes more than one percent of the rock.

Sulphide minerals, predominantly pyrrhotite, are sporadically distributed throughout the layer and occur as rounded bleb-like masses in intercumulus areas (Plate 25). They rarely compose up to 5 percent of the rock and average less than one percent throughout the lower two-thirds of the layer. The lherzolite and wehrlite of the homogeneous upper third of the Banded Layer is more sulphide-rich than the underlying layers, and in places sulphide minerals, predominantly pyrrhotite, constitute up to 5 percent of the rock. The sulphide minerals occupy intercumulus areas and occur as irregularly shaped, bleb-like masses, many with cusp-like outlines. Sulphide minerals average 1 to 2 percent in the olivine-rich upper third of the layer, but in the rest of the layer average less than one percent.

SIGNIFICANCE OF THE BANDED LAYER

The heterogeneous nature of the Banded Layer, the range in scale of the layering, the presence of modal grading, and the widespread mineral lamination, imply deposition from moving magma or current deposition of crystals. The lateral extent of the Banded Layer is not known, because these heterogeneous rocks have been observed only in drill holes 38511 and 38532. The range in core axis angles[1] suggests a variation in layer attitudes. The apparent restricted character of these features could reflect some kind of local structure, possibly a trough band, similar to those described from the Skaergaard Intrusion (Irvine and Stoeser, 1978). There, trough bands occur as synformal structures, distinguished by chute-like axial zones of modally differentiated layers. In the Skaergaard Intrusion most trough bands occur in a relatively small stratigraphic interval in the upper part of the intrusion where a single trough band was traced for about 300 m along strike. If the Banded Layer represents a trough band-like structure, and if the scale of the structure is similar to those described from the Skaergaard Intrusion, the drill holes may have intersected parts of the same trough or two different trough bands. Trough bands are interpreted to have formed through successive density currents, each of which deposited a layer in the trough.

Clinopyroxene cumulate layer

The rocks of the clinopyroxene cumulate layer are medium grained, grey-green and plagioclase- and sulphide-bearing. Some are mottled due to the sporadic distribution of large (up to 6 mm) poikilitic orthopyroxene crystals.

The texture is dominated by a continuous to partly continuous mosaic of interlocking, irregularly shaped clinopyroxene crystals. The crystals are well preserved throughout the layer commonly twinned and many possess well developed parting. Their irregular shape is interpreted as being caused by postcumulus crystallization.

Orthopyroxene forms sporadically distributed, large, rectangular to elliptical poikilitic crystals characterized by numerous rounded and embayed clinopyroxene inclusions. Orthopyroxene crystals are partly to completely replaced by tremolite $\pm$ talc $\pm$ chlorite $\pm$ magnetite that form bastite-like pseudomorphs.

Plagioclase has been extensively altered to chlorite + garnet + epidote and consequently its original character is difficult to determine. Inclusions in clinopyroxene of lath-like pseudomorphs after original plagioclase imply that some plagioclase was a cumulus phase, whereas it is clearly a postcumulus phase in other rocks.

Original polyhedral olivine crystals that have been completely replaced by chlorite $\pm$ tremolite $\pm$ magnetite display a sporadic

[1] The term 'core axis angles' is used in reference to the angles between primary structures or foliation and the core axis.

distribution and indicate that a small amount of olivine was a cumulus phase throughout the layer.

Intercumulus, bleb-like sulphide constitutes up to 3 percent of the rock. The original sharp outlines of the sulphide minerals have become diffuse by recrystallization of the primary silicate minerals.

The middle and upper parts of the layer contain numerous microfaults, some with offsets up to 4 mm. They range from hairline to 0.7 mm wide, the wider ones containing finely comminuted clinopyroxene ± orthopyroxene. Chlorite ± magnetite ± sulphide are commonly associated with microfaults and crystals adjacent to microfaults are moderately to highly strained.

Plagioclase cumulate layer

Plagioclase cumulate rocks range from greenish grey to grey, are medium- to fine-grained and many are mottled or spotted (Plate 26). The greenish grey variety contains abundant clinopyroxene, the grey variety is plagioclase-rich, the mottled variety contains large poikilitic orthopyroxene crystals and the spotted variety originally contained olivine. The contact between the plagioclase cumulate layer and the underlying clinopyroxene cumulate layer is gradational over 6 m.

Plagioclase originally formed lath-like crystals (up to 1.5 mm long) that accumulated to form crystal aggregates. Many individual crystals display a dimensional orientation and contribute to a moderately well developed rock fabric. They are commonly recrystallized to albite ± muscovite ± epidote ± chlorite ± calcite assemblages. In the highly recrystallized rocks at the top of the layer, plagioclase has been completely converted to garnet.

Compositions were determined optically on six samples (Table 8). The number is insufficient to define trends, and little deviation is present from an average composition of An_{90}.

Clinopyroxene forms irregularly shaped discrete grains and aggregates of crystals. The crystals appear to have been cumulus and owe their shape to postcumulus crystallization. The presence of plagioclase laths in some crystals is also considered to be due to postcumulus crystallization. Many elongate crystals (up to 4 x 0.75 mm) display a dimensional orientation and, like plagioclase laths, contribute to the rock fabric. The clinopyroxene crystals are characterized by fine parting and many are twinned. In some rocks polycrystalline aggregates are characterized by strongly interdigitated contacts and some individual crystals possess a blebby, myrmekite-like exsolved phase. Clinopyroxene is most resistant to recrystallization and is preserved in rocks where all other primary minerals are recrystallized; however, it does display incipient recrystallization to colourless tremolite.

Table 8: Plagioclase compositions[1], cyclic unit 2, plagioclase cumulate layer

	Nonzoned crystals	Zoned crystals (rim to core)
38532 - 400.5	An_{90}	$An_{87r-93c}$
38532 - 413.8	An_{88}	$An_{92r-85c}$
38532 - 423	An_{89}	
38532 - 431.2	An_{92}	
38511 - 740	An_{90}	
38511 - 870	An_{89}	

[1] Plagioclase compositions were determined using the universal stage and Nakamura plate, and the Becke-Becker or Fedorov methods were followed depending on the orientation of the plagioclase being measured.

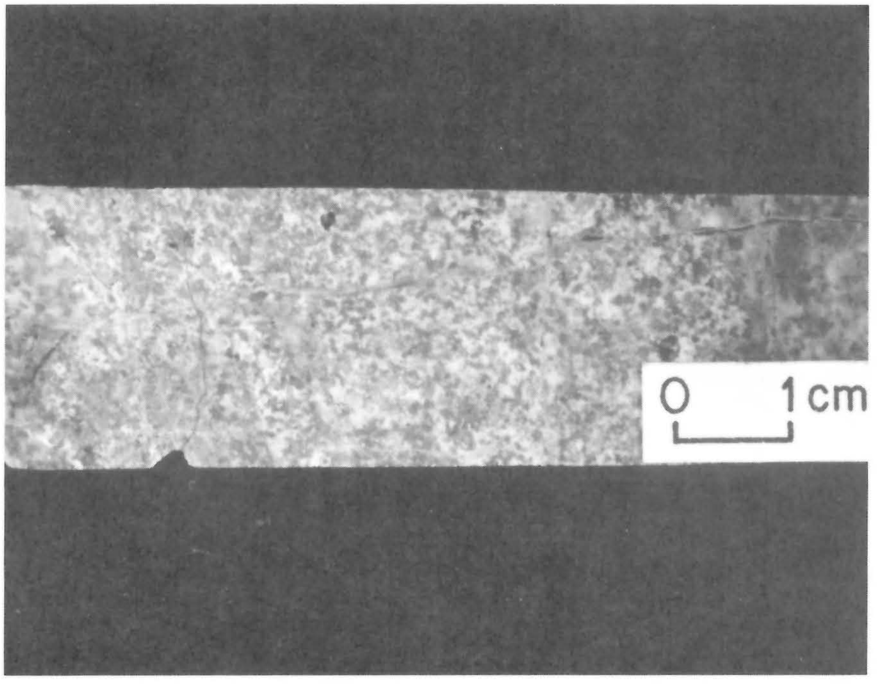


Plate 26: Plagioclase cumulate. Whitish areas are alteration products after original cumulus plagioclase. Light grey areas are clinopyroxene. Rare dark patches are serpentinized olivine. Note fractures which have been filled by prehnite + chlorite. MZ, Cycle 2 plagioclase cumulate layer, 722E section, DDH 38532-391.3.

Apart from a narrow (less than 1 m) orthopyroxenite layer, orthopyroxene is not abundant in these rocks (less than 3 percent). It occurs as poikilitic crystals (up to 5 mm) with numerous clinopyroxene and plagioclase inclusions and is clearly postcumulus. It has been completely recrystallized to aggregates of talc ± tremolite. The orthopyroxenite layer consists of a dense aggregate of cumulus orthopyroxene crystals (up to 2 x 1 mm) that have been completely converted to tremolite ± chlorite ± magnetite (Plate 27). The rock is sulphide-bearing and contains postcumulus clinopyroxene that possesses inclusions of orthopyroxene.

Olivine was a common phase throughout the layer where it formed polyhedral crystals, as well as anhedral, postcumulus crystals with inclusions of lath plagioclase. Some of the crystals are elongate and display a dimensional orientation that is parallel with the orientation of clinopyroxene and plagioclase crystals. Olivine is rarely preserved being extensively recrystallized to chlorite ± tremolite ± magnetite. In very highly recrystallized rocks, large irregular patches of prehnite ± chlorite appear to have replaced clusters of original olivine crystals.

Apart from 2 to 3 percent remobilized sulphide ± magnetite associated with the orthopyroxenite, opaque minerals are not abundant in the layer. Sulphide minerals (± magnetite), dominantly pyrrhotite, formed irregular masses with ragged outline within altered olivine crystals; intercumulus sulphide is rare.

The layer is characterized by numerous microfaults and fractures. Clinopyroxene crystals adjacent to microfaults display strain effects including deformation lamellae. Microfaults range from hairline to 1 mm wide, the wider ones being occupied by strongly foliated chlorite ± tremolite. Some microfractures are filled with quartz.

In highly altered rocks alteration to prehnite is pervasive, with prehnite forming stellate rosettes. A prehnite ± chlorite ± garnet veinlet was observed in one highly altered rock. The degree of recrystallization increases toward the top of the layer.

Apart from the thin (less than 1 m) cumulate orthopyroxenite, orthopyroxene is much less abundant in cyclic unit 2 plagioclase cumulate rocks than in cyclic unit 1 plagioclase cumulate rocks, whereas olivine is more abundant. Cyclic unit 2 plagioclase cumulate rocks display a better developed primary lamination caused by dimensional orientation of lath plagioclase, elongate clinopyroxene and to some extent elongate olivine crystals. This lamination becomes more distinct toward the top of the layer. Cyclic unit 2 plagioclase cumulate rocks differ from their cyclic unit 1 equivalents by possessing numerous microfaults and microfractures, and by displaying more intense recrystallization. The degree of recrystallization increases toward the top of the layer, where prehnite and hydrogrossular garnet are common recrystallization products.

The top of the layer is also the contact between MZ and LCLZ rocks in this area. The abundance of microfaults is likely related to movement along the MZ-LCLZ contact, and the more intense recrystallization to rodingite-like assemblages is likely due to the intense serpentinization of adjacent LCLZ rocks.

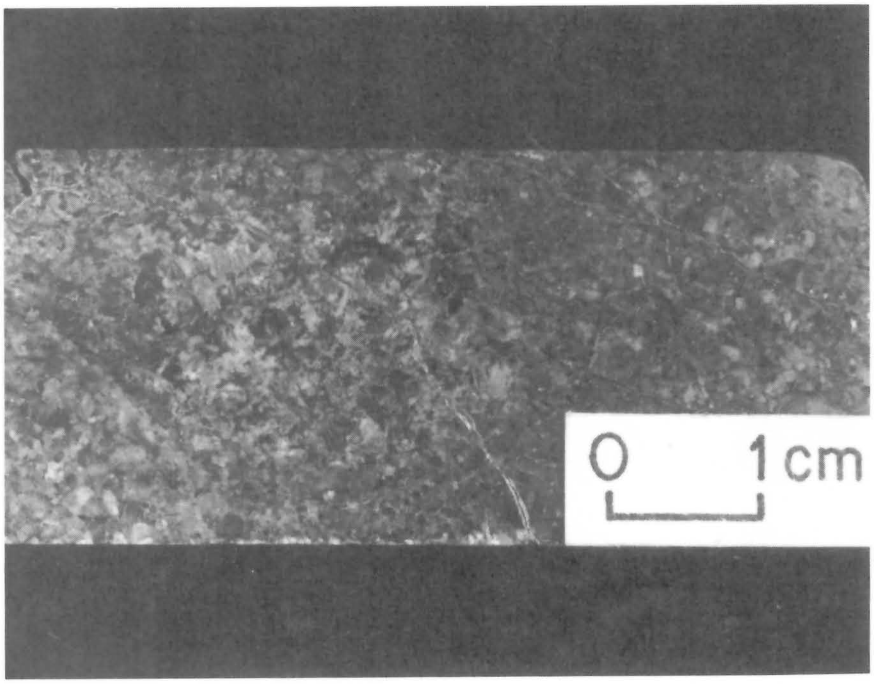


Plate 27: Orthopyroxenite. A dense aggregation of stubby, prismatic, cumulus orthopyroxene crystals that have been completely converted to talc ± tremolite. This sulphide-bearing rock forms a narrow (less than 1.0 m) layer in plagioclase cumulate. MZ, Cycle 2 plagioclase cumulate layer, 722E section, DDH 38532-383.7.

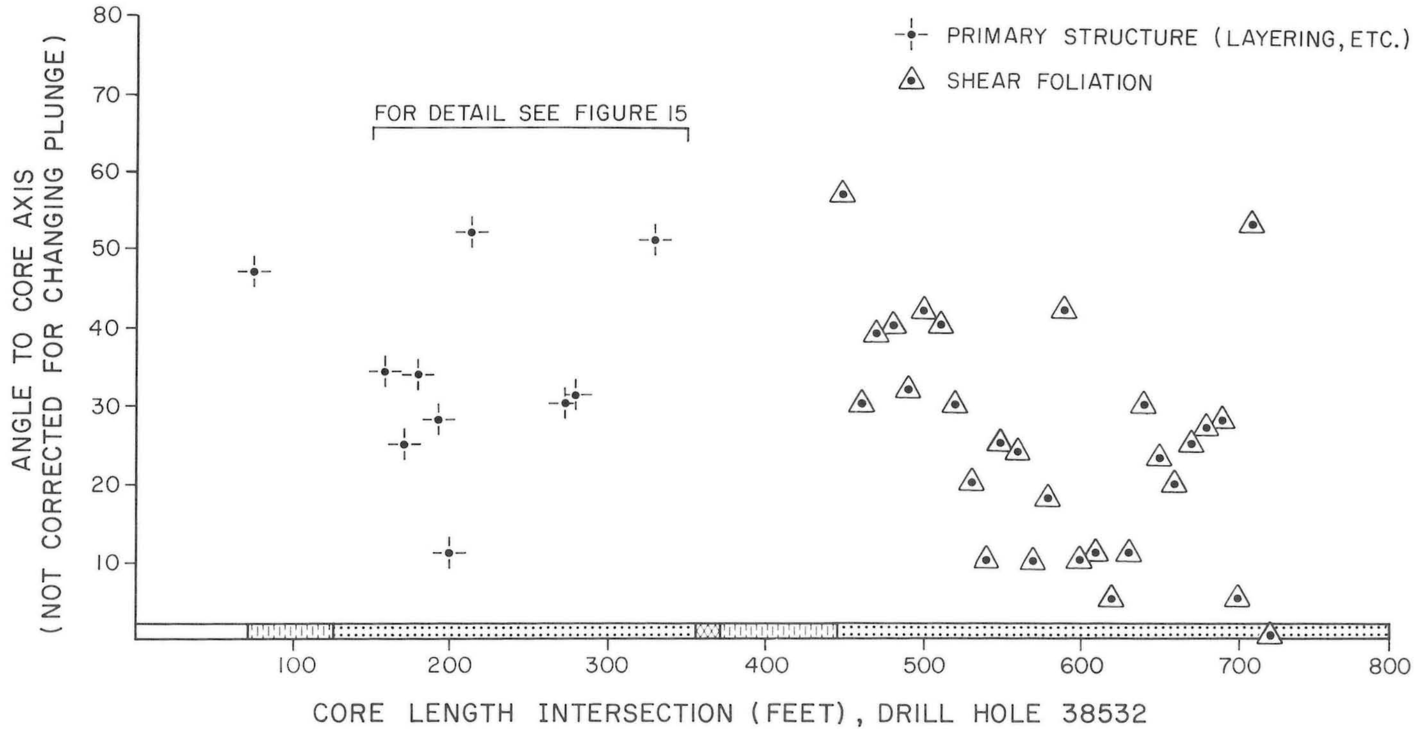


Figure 23: Structural synopsis, drill hole 38532.

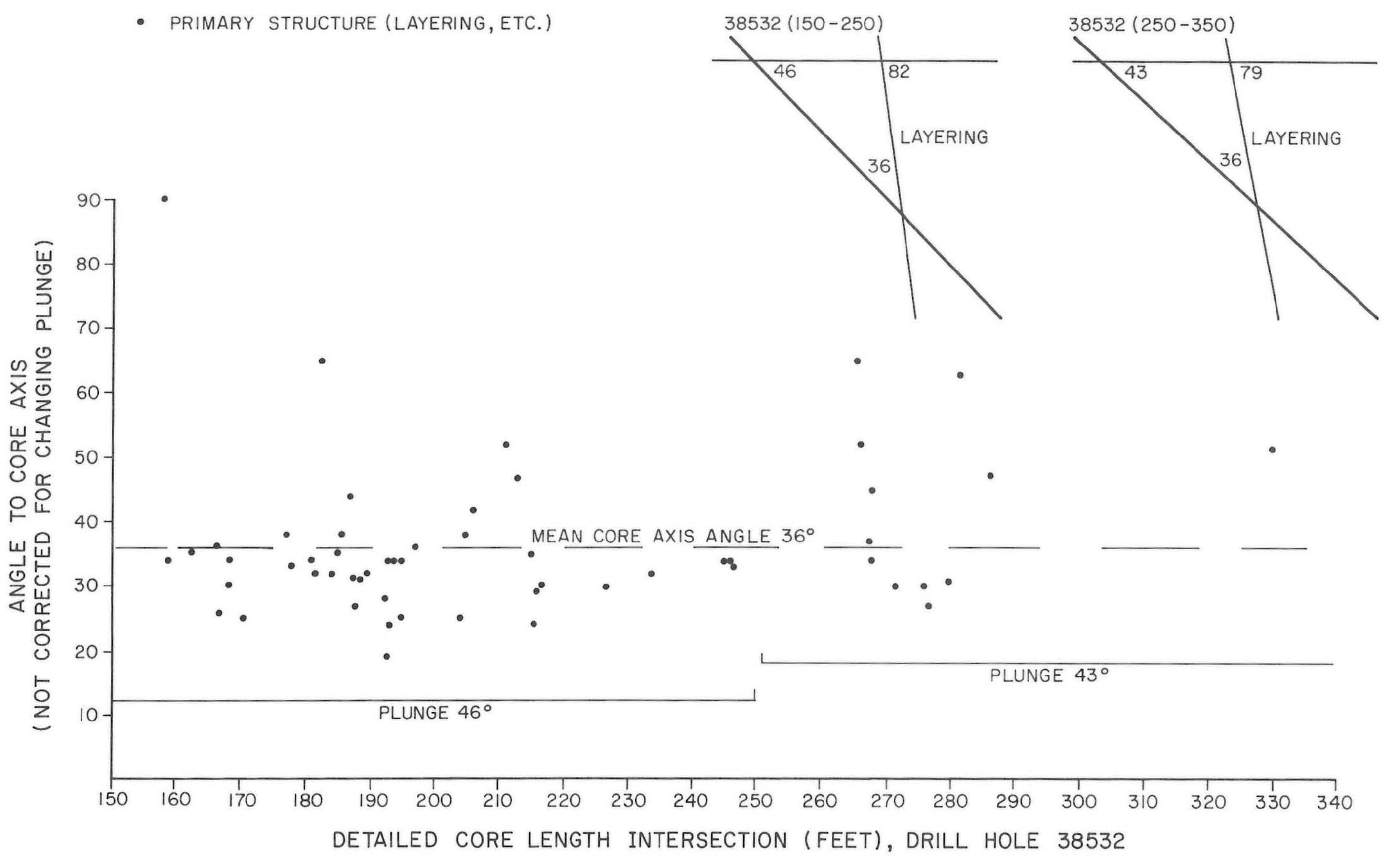
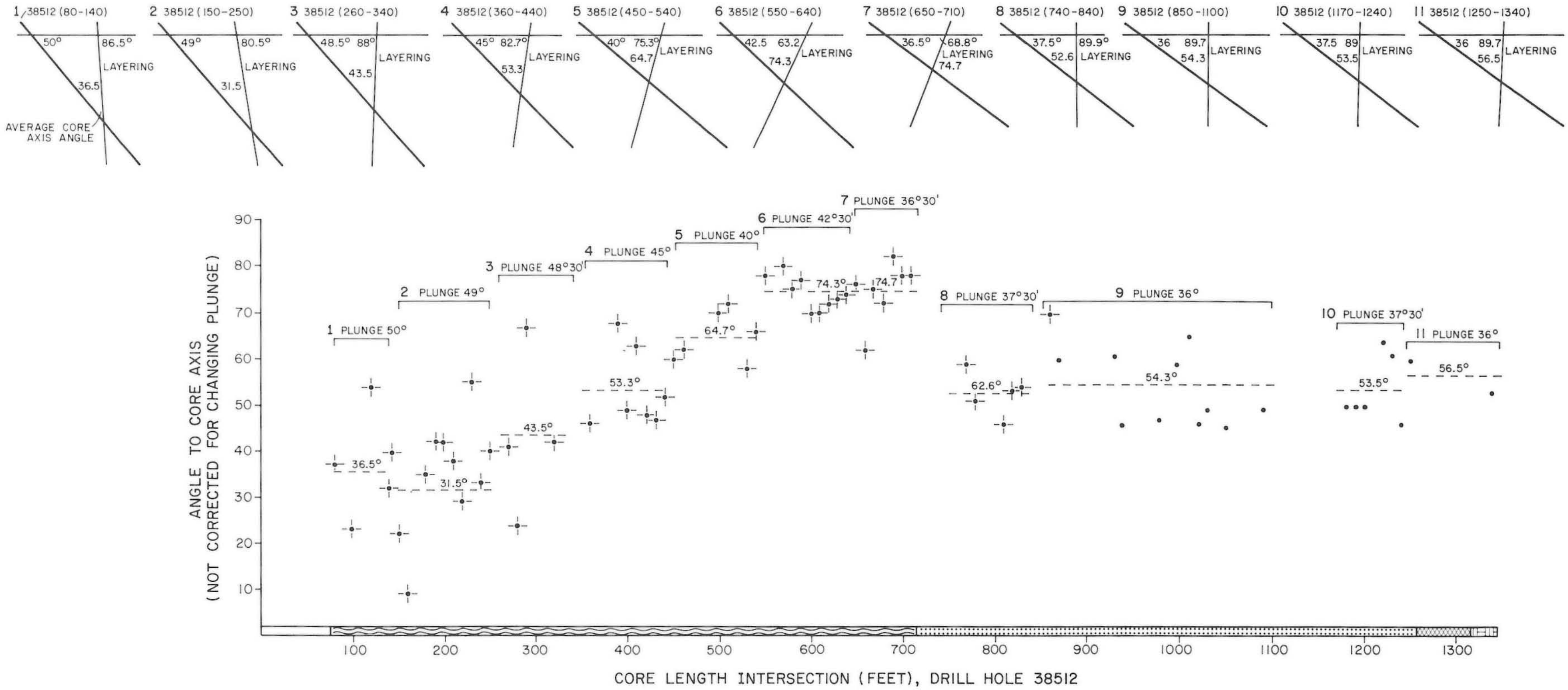


Figure 24: Detail, structural synopsis, drill hole 38532.



PRIMARY STRUCTURE (LAYERING, ETC.)

• FOLIATION - SERPENTINE FOLIATION IS APPROXIMATELY PARALLEL TO OLIVINE LAMINATION

- - - MEAN OF CORE AXIS ANGLES OVER A FIXED CORE LENGTH INTERVAL

Figure 25: Structural synopsis, drill hole 38512.

Layer attitudes

The core axis angles illustrated in Figures 23 and 24 indicate the attitudes of primary structures observed in drill hole 38532 and include layer contacts, mineral laminations and serpentine foliation. In these rocks serpentine fabric is parallel to primary structures and has been included in the plotted measurements.

Shear foliation, identified by slickensided surfaces and brittle (picrolitic) serpentine, commonly obliterates primary textural and structural features and has not been used in determining the dip of layering.

The dips of laminated Middle sedimentary formation rocks change by more than 35° (Fig. 25) and this suggests the presence of a large-scale fold. MZ rocks on the other hand display a constant, near vertical dip (8, 9, 10 and 11, Fig. 25). The dip of layering of sedimentary rocks and MZ rocks is discordant (compare 7 and 8, Fig. 25), implying that the contact between the Sill and sediments is discordant in this place. This contrasts with the observation of an apparent conformable contact between sedimentary rocks and MZ rocks in the Great Falls outcrop area. The constant, near vertical dip of Cyclic unit 1 MZ rocks can be demonstrated through correlation of the clinopyroxene cumulate layer between drill holes 38511 and 38512 (Fig. 15). Although the dip is not vertical, the difference between the dip determined through correlation between holes and the dip calculated from core axis angle measurements is very small (6°).

The variation in core axis angles reflects difficulties in measuring attitudes in split core although great care was taken to make accurate measurements. It also reflects the fact that only a small part of any layer is exposed in drill core so that small irregularities in the attitude of individual layers become significant. As a result of these factors the mean value of 30.6° for the detailed core axis angle measurements made between 150 and 300 feet (core length interval) represents a reasonable average angular relationship for primary structures to the core axis.

A large variation in core axis angles of primary structures for this same unit can be seen in Figure 26 where the angular relationships observed in drill hole 38511 are illustrated. The range in core axis angles is large and is considered to reflect variations in layer attitudes, as well as reflecting the difficulty of measuring attitudes in split core as noted above.

Despite the irregularities in core axis angles there is a trend toward decreasing core axis angles with hole depth, implying that dips of primary structures become shallower with depth or stratigraphically upward in the MZ succession.

Observation of changes in dip within MZ cyclic units indicates that dip change was taking place during accumulation of MZ rocks. This may reflect progressive downwarping of the central part of the intrusion caused by successive magmatic impulses along the intrusion axis.

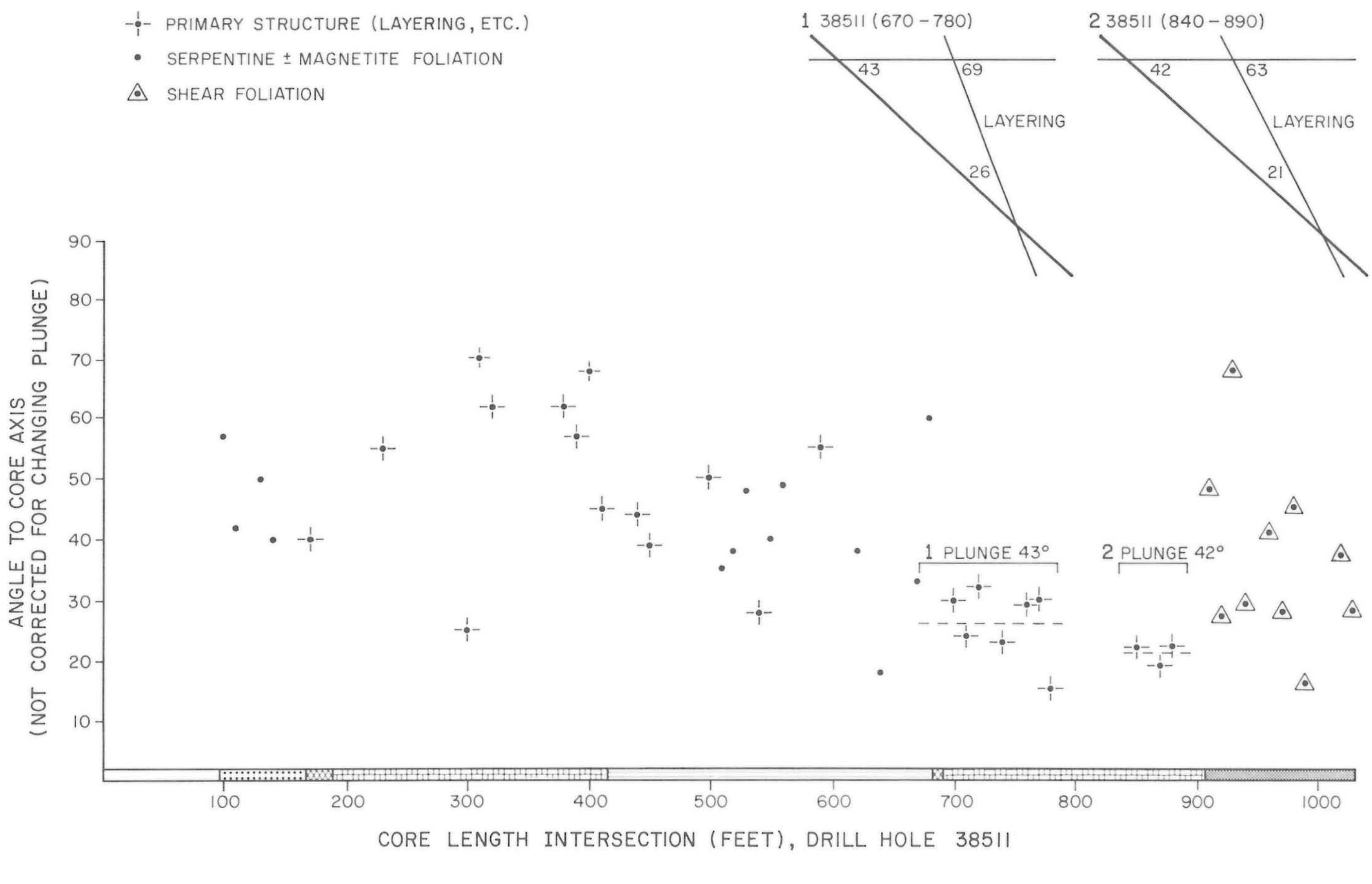


Figure 26: Structural synopsis, drill hole 38511.

380W SECTION

Drill hole 13206

Three drill holes (13202, 13206, and 13201) were sited along 380W section (Fig. 27). The section is at the extreme western end of the west lobe of the Fox River Sill, and the holes intersected a foreshortened sequence of the Sill that includes MZ, LCLZ and UCLZ rocks. Thus, although the roof contact was not penetrated, a highly telescoped but nearly complete Sill section has been intersected.

Drill hole 13206 intersects the south Sill contact and approximately 22 m of Middle sedimentary formation rocks. The rocks, which originally consisted of interlaminated quartz-rich siltstone and argillite, are predominantly hornfels.

NON-CYCLIC MZ ROCKS

MZ rocks intersected by drill hole 13206 (Fig. 27), consist of an altered pyroxene-rich olivine melagabbronorite (logged as pyroxene-rich picrite) that forms a 4 m thick zone at the contact and serpentinized, plagioclase-bearing lherzolite to olivine melagabbronorite. The pyroxene-rich zone grades into lherzolite, which in turn grades into serpentinized wehrlite and dunite that are interpreted to represent LCLZ rocks. Cyclic units composed of olivine, pyroxene and plagioclase cumulates that characterize MZ rocks in the Great Falls area and in 722E section are not present here. The MZ is estimated to be 59 m thick.

Olivine cumulate layer

PYROXENE-RICH UNIT

Near the contact, MZ rocks were originally composed of lath-like clinopyroxene crystals (up to 4 x 1 mm) that may represent original cumulus crystals. Clinopyroxene oikocrysts that contain rounded inclusions of olivine also occur. Extensive alteration in the form of colourless tremolite precludes determining with certainty whether orthopyroxene and plagioclase were original constituents. The rock appears to have been originally a clinopyroxene-rich, clinopyroxene and olivine cumulate.

Apatite and zircon are associated with patches of red-brown pleochroic phlogopite. Zircon crystals possess irregular shapes and have concentrically developed thin zones, and apatite crystals are rounded in character. The pyroxene-rich unit is approximately 4 m thick and is equivalent to the hornblende-rich unit observed at the base of cycle 1 olivine cumulate layer, 722E section.

MAIN UNIT

Olivine and chromite were originally cumulate phases and clinopyroxene and orthopyroxene were original postcumulus phases that formed oikocrysts, some of which are 1 cm in size (Plate 28). Plagioclase, red-brown hornblende, and phlogopite formed postcumulus oikocrysts. The original rock, a plagioclase-bearing lherzolite to olivine melagabbronorite, has been extensively altered to colourless tremolite. The ratio of olivine to other phases is estimated to have been 1:1 throughout much of the unit, increasing to approximately 2:1 near the unit top. A single olivine determination from the lherzolite is $Fo_{85.1}$. The contacts with the underlying pyroxene-rich rock and overlying olivine-rich rock are gradational.

Olivine has been recrystallized to mesh-texture and curtain-growth serpentine, and less commonly to a fine grained mat of apparently nonfibrous serpentine. Plagioclase has been replaced by a fine

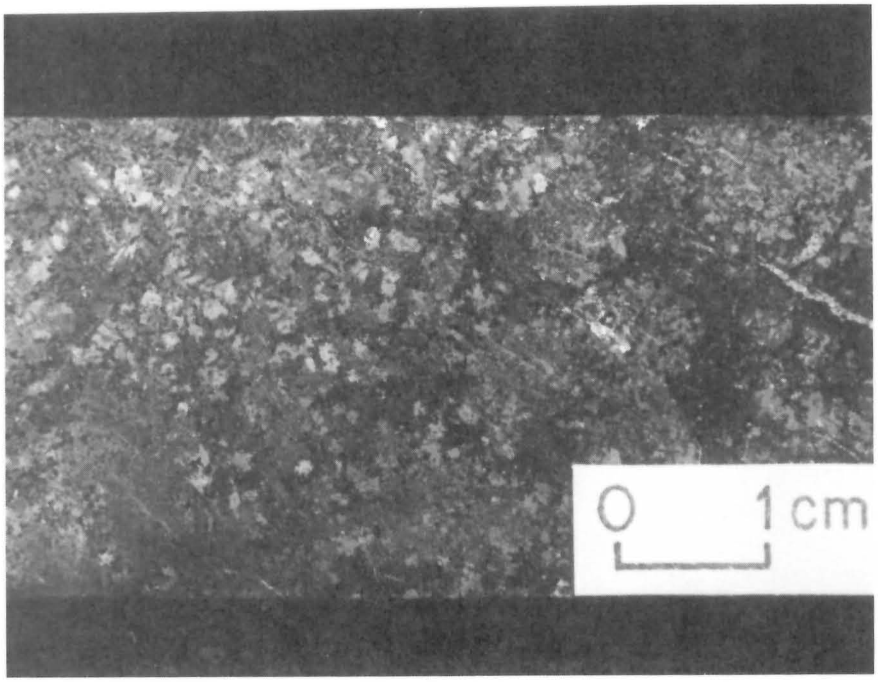


Plate 28: Mottled character of MZ olivine cumulate. Reflecting irregular patches are pyroxene, darker spots are serpentinized olivine. Lamination that is parallel with serpentine veinlet at left of photo is caused by parallel serpentine ± magnetite veinlets. MZ, olivine cumulate (serpentinized lherzolite), DDH 13206-480.

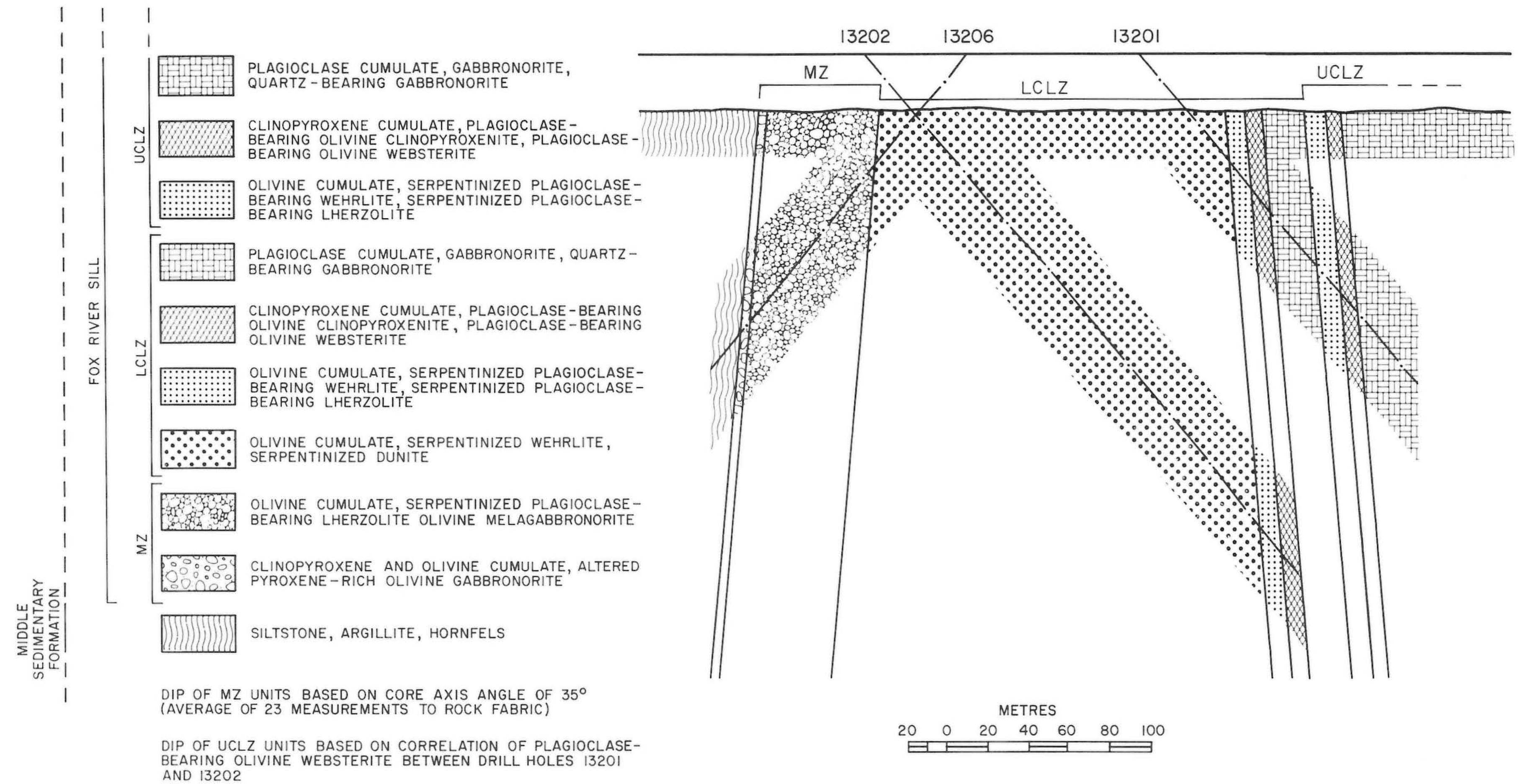


Figure 27: Geology of 380W section.

grained mat of nearly isotropic chlorite. The pyroxenes have been replaced by colourless tremolite and spears of colourless tremolite occupy the central areas of some serpentine pseudomorphs.

Olivine displays a preferred orientation in some rocks (Fig. 28) and in these examples curtain-growth serpentine is developed at right angles to the preferred orientation of the olivine crystals.

Postcumulus phlogopite is a common though not abundant phase. Irregularly shaped, zoned zircon crystals have been observed associated with phlogopite in some rocks.

Chromite and secondary magnetite are common opaque minerals; sulphide minerals are less common (less than 1 percent) and are associated with secondary magnetite.

MZ rocks of 380W section consist of an original pyroxene-rich, pyroxene + olivine cumulate at the contact that grades into a mottled serpentinized plagioclase-bearing lherzolite to olivine melagabbronorite. The latter unit is similar to cyclic unit 1 olivine cumulate layers of the Great Falls and 722E sections. However, the layer is not successively overlain by pyroxene and plagioclase cumulate layers, but grades into a wehrlite that is interpreted as representing the lowermost LCLZ olivine cumulate. Thus, noncyclic MZ rocks occur near the western termination of the west lobe of the Sill.

Rock fabric

In drill hole 13206, 23 rock fabric measurements (serpentine ± magnetite foliation, mineral lamination) average 35° to the core axis (Fig. 29). Three well developed mineral laminations (included in the above average) also average 35° to the core axis. These measurements are considered to represent an approximation of the layer dip in this part of the intrusion. The dip, 85°SW, is in the opposite sense to the dip of layering as measured in drill holes 13201 and 13202, but agrees with the sense of dip (based on 7 measurements) of sedimentary layering (average 25° to the core axis) in Middle sedimentary formation rocks. The difference of 10° in core axis angles between Middle sedimentary formation rocks and Sill rocks suggests that the contact is slightly discordant. The change in the sense of dip from steeply SW in MZ rocks to steeply NE in the central and upper part of the intrusion is similar to the change in attitude observed in the Great Falls outcrop area and in 722E section. As noted previously, it is these observations that have been interpreted as indicating that the intrusion has a lopolithic cross-section.

OTHER DRILL HOLES

Drill hole 13221

Drill hole 13221 intersects the contact between LCLZ and MZ rocks (Fig. 30). The hole terminates in MZ rocks and the contact between the intrusion and enclosing Middle sedimentary formation rocks was not intersected. The plagioclase cumulate layer of one cyclic unit and the entire uppermost MZ cyclic unit have been intersected by the drill hole. The thickness of the MZ as well as the number of cyclic units that constitute the zone in this area is not known. Approximately 83 m of core length interval was intersected, which is interpreted as representing 42 m of true thickness (Fig. 30).

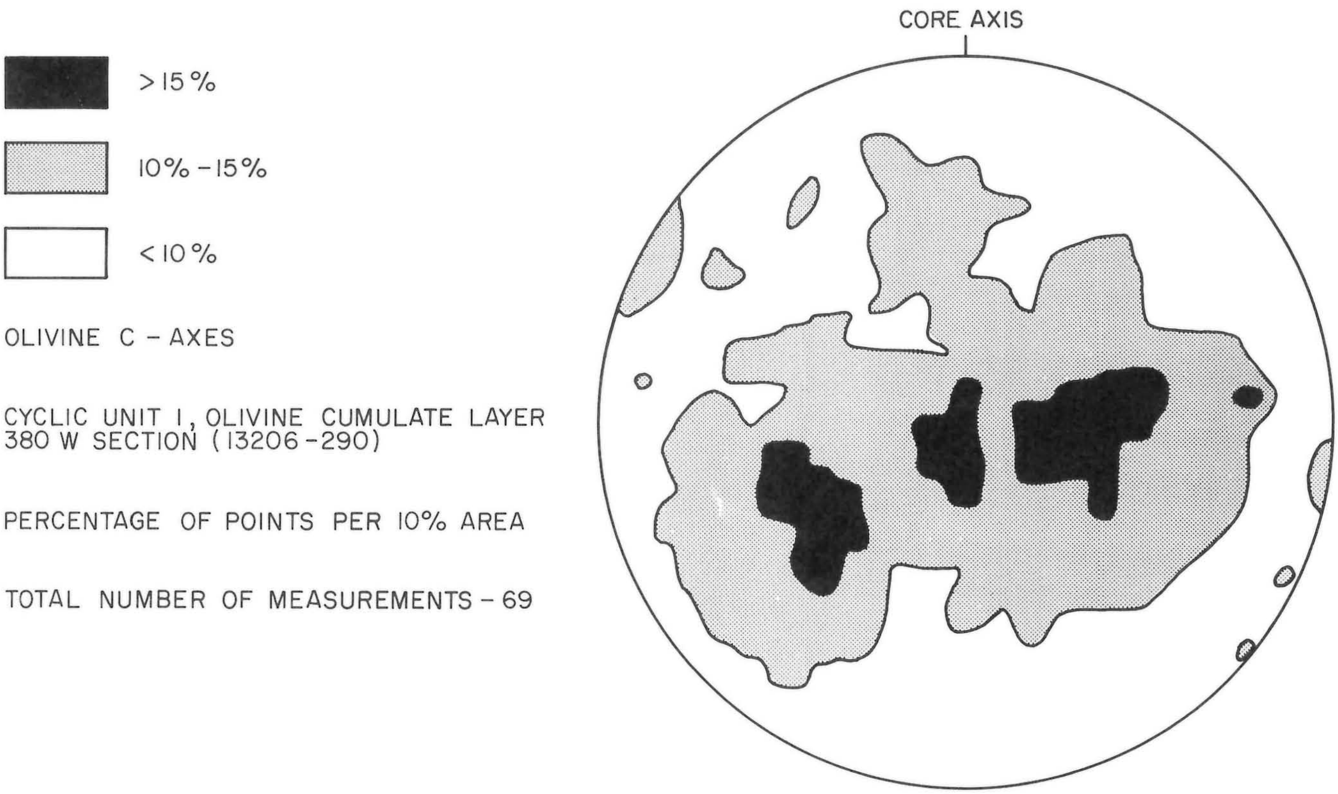


Figure 28: Fabric diagram, olivine c-axes, cyclic unit 1, olivine cumulate layer, 380W section.

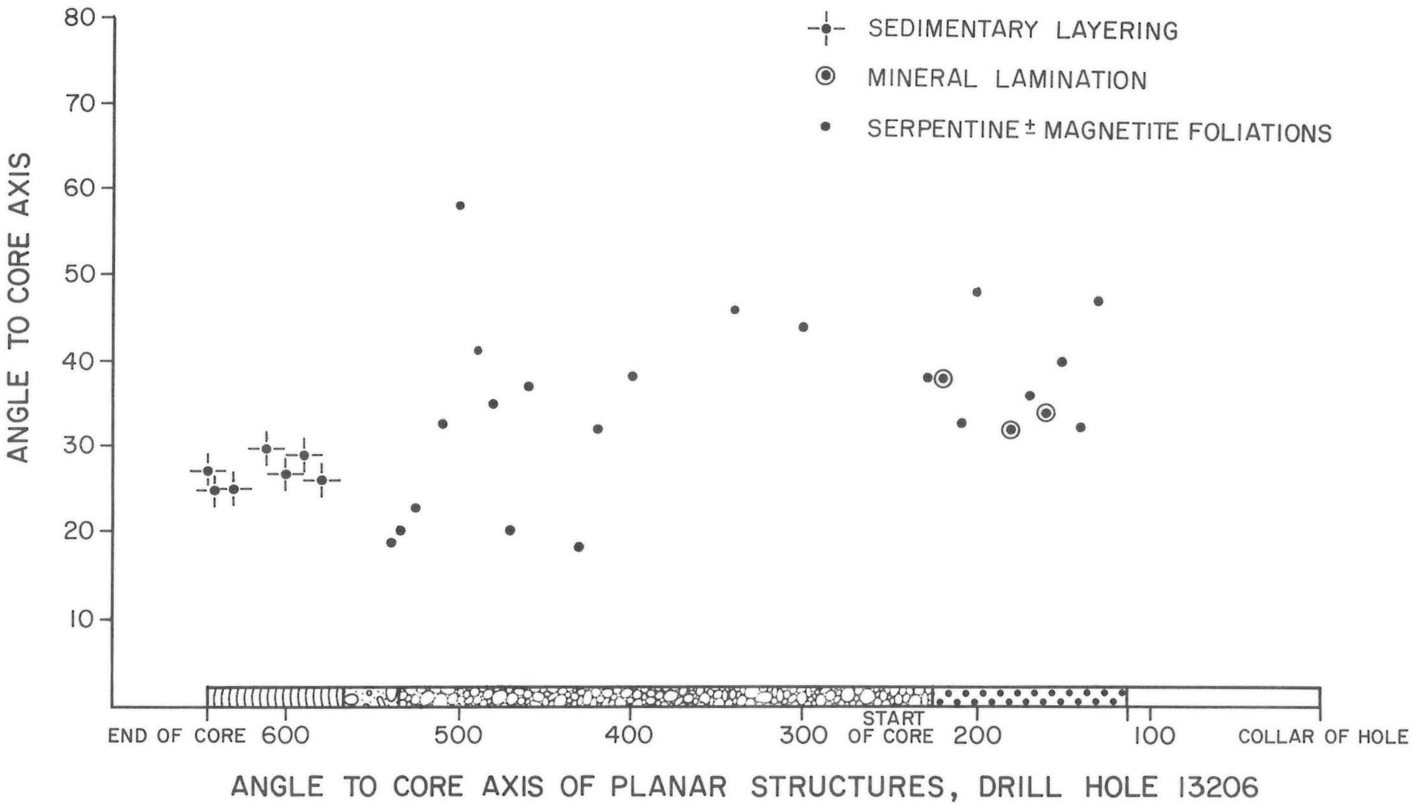


Figure 29: Core axis angles to planar structures, drill hole 13206.

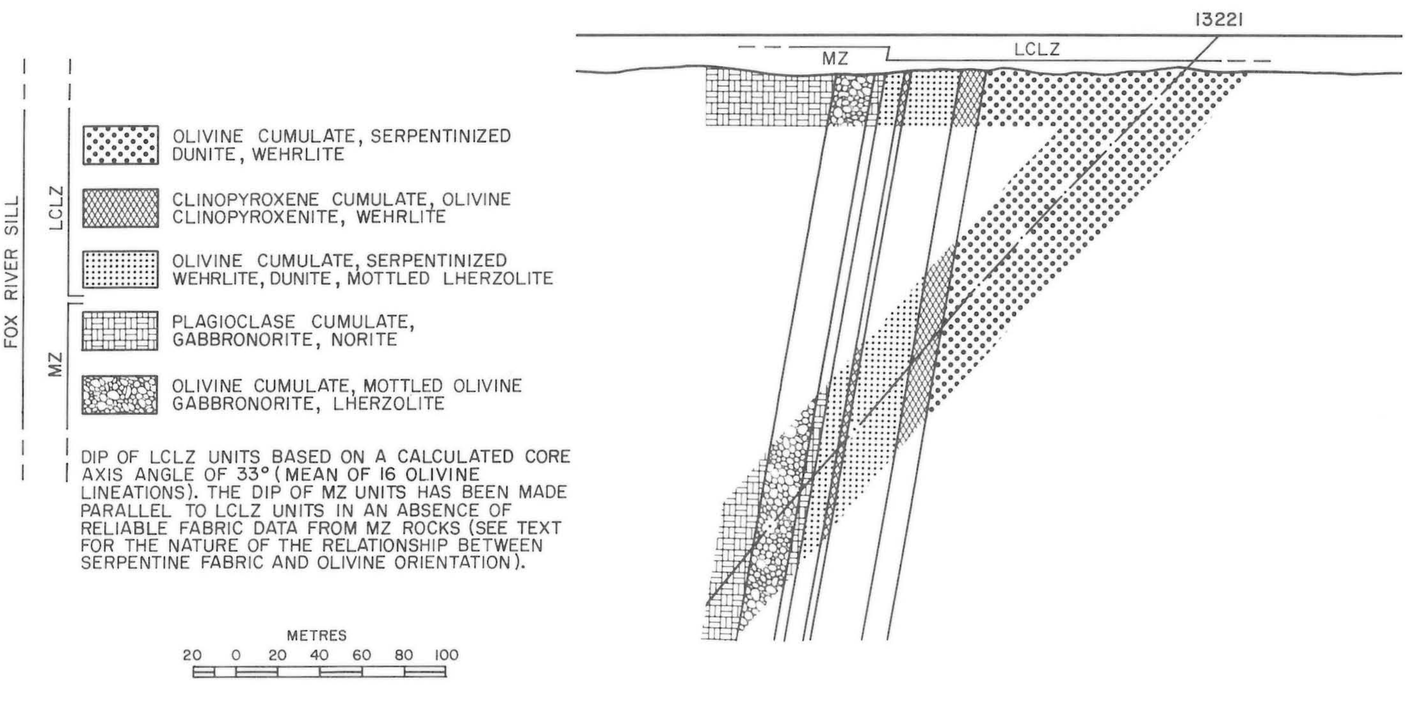


Figure 30: MZ geology, drill hole 13221.

CYCLIC UNIT 1

Plagioclase cumulate layer

A portion of the plagioclase cumulate layer of a cyclic unit has been intersected by the lower part of drill hole 13221. This cyclic unit is referred to as cyclic unit 1, although the presence or absence of cyclic units underlying it is not known.

The plagioclase cumulate intersected by the lowermost part of the drill hole is light grey to light greenish grey, finely spotted and medium- to fine-grained. Variation in grain size is slight, and some samples possess a definite fabric. The light colour of the rock is caused by whitish alteration products after plagioclase.

The rock originally consisted of aggregates of cumulus lath-like plagioclase crystals. Plagioclase laths display a well developed dimensional orientation in rocks where the original texture has not been completely obliterated. Clinopyroxene, interpreted as being an original cumulus phase near the base of the hole (toward the base of the layer), originally occurred as a postcumulus phase toward the top of the layer where it formed oikocrysts. Original poikilitic orthopyroxene occurred toward the base of the hole; however, moderately well preserved pseudomorphs after orthopyroxene reveal that it was a cumulus phase near the top of the layer. The highly recrystallized nature of the rocks makes it impossible to determine if olivine was an original constituent.

Extensive alteration has obliterated the primary texture in some rocks. Plagioclase has been replaced by epidote + muscovite + albite + chlorite + quartz + sphene, clinopyroxene has been extensively replaced by colourless tremolite, and orthopyroxene has been completely replaced by bastite-like intergrowths of tremolite $\pm$ chlorite. Rosettes of prehnite replace plagioclase in some rocks, and discontinuous prehnite veinlets occur in other altered rocks. Ilmenite $\pm$ magnetite are sporadically disseminated throughout the rock, and sulphide minerals are rare.

The rock, an original gabbronorite, becomes noritic toward the top of the layer, where it is clear that orthopyroxene joined plagioclase as a liquidus phase. Clinopyroxene, which appears to have been a cumulus phase throughout the rest of the exposed part of the layer, became a postcumulus phase toward the top of the layer.

CYCLIC UNIT 2

A MZ cyclic unit consisting of an olivine cumulate layer and an overlying plagioclase $\pm$ clinopyroxene cumulate layer, separates Cyclic unit 1 plagioclase cumulate layer from rocks of the LCLZ.

Olivine cumulate layer

Rocks of the olivine cumulate layer are grey green, medium- to coarse-grained, mottled and heterogeneous. They are structureless for the most part, although parallel serpentine veins impart a fabric to a few rocks.

Olivine, the only cumulus silicate phase, is dominantly granular to elliptical or slightly rounded, although some original polyhedral crystals occur. Olivine tends to be highly rounded where it is poikilitically enclosed in pyroxene crystals. It constitutes from 30 to 60 percent of the rock (based on visual estimates). Chromite, the other cumulus phase, has an erratic distribution and is estimated to reach 3 percent in one sample. Clinopyroxene, orthopyroxene, plagioclase and red-brown hornblende originally formed postcumulus phases and occurred as oikocrysts and/or poikilitic crystals. Clinopyroxene displays parting and twinning, orthopyroxene possesses fine, ruled-line exsolution lamellae, and red-brown hornblende is zoned, displaying less intensely coloured margins. There is a substantial range in grain size of the original constituent minerals, olivine crystals seldom exceed 1 mm, and the other minerals (clinopyroxene, orthopyroxene, plagioclase and hornblende) formed large oikocrysts and/or poikilitic crystals up to and exceeding 1 cm in size. The sporadic distribution of poikilitic crystals and the substantial range in grain size contributes to the heterogeneous character of the rocks.

The rocks range from being totally recrystallized at the base of the layer to being moderately well preserved at the top. At the base of the layer the rocks have been extensively altered to colourless tremolite. There, olivine has been completely replaced by tremolite $\pm$ chlorite. Throughout the layer, olivine has been altered to chlorite $\pm$ tremolite $\pm$ coarsely fibrous serpentine, and toward the top of the layer, pale yellow to pale yellow-green, nonfibrous and fibrous serpentine replaces olivine. In one sample spears and laths of tremolite cut across partly preserved olivine. Tremolite and chlorite cut across serpentine and clearly seem to be later. Clinopyroxene is extensively altered to tremolite at the base of the layer and displays incipient alteration to tremolite throughout the rest of the layer. Orthopyroxene has been completely to partly replaced by talc $\pm$ tremolite $\pm$ magnetite. Plagioclase has been extensively altered to a finely interwoven, nearly isotropic mat of chlorite. Red-brown hornblende displays incipient alteration to colourless tremolite.

OLIVINE COMPOSITIONS

Two olivine determinations from the uppermost part of the olivine cumulate layer gave $Fo_{78.8}$ and $Fo_{78.0}$, respectively. These compositions are 4.0 mole percent lower than the Fo-content of olivine from the lowermost olivine cumulate layer of the overlying LCLZ (Fig. 31). This result is in keeping with the sense of changing MgO/MgO + FeO ratios between MZ and LCLZ rocks observed in other areas.

Plagioclase cumulate layer

Plagioclase cumulate rocks are medium grey to brownish grey, medium grained and somewhat mottled. Plagioclase, an original cumulus phase, has been extensively recrystallized to epidote $\pm$ muscovite $\pm$ chlorite $\pm$ sphene. Orthopyroxene appears to have been an original cumulus phase that increased in abundance toward the top of the layer. It has been altered to talc $\pm$ tremolite $\pm$ chlorite; however, orthopyroxene is partly preserved toward the top of the layer. Original postcumulus clinopyroxene crystals have been partly altered to colourless tremolite. Prehnite, replacing plagioclase, has been observed. The rocks were logged as gabbronorite and the brownish-grey, orthopyroxene-rich rock at the top of the layer was logged as plagioclase-bearing orthopyroxenite. Neither the lower nor the upper contact of the layer is exposed in the telescoped core.

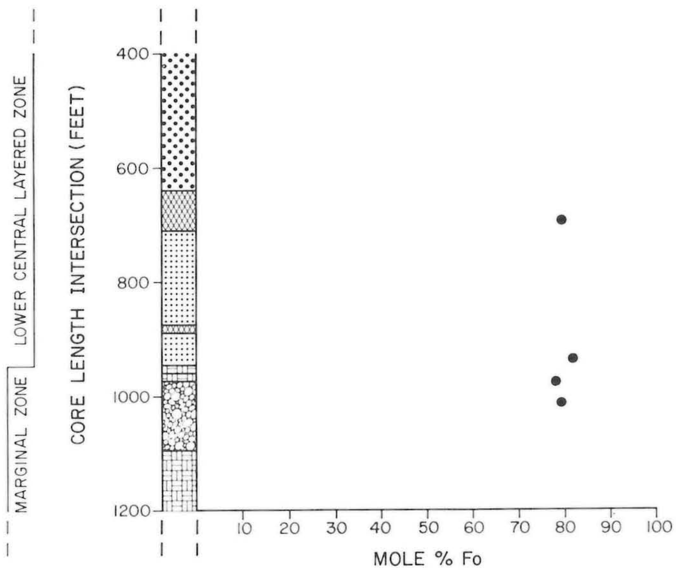


Figure 31: Olivine compositions, drill hole 13221.

Rock fabric

Examination of core reveals a moderately well developed serpentine foliation in the olivine cumulate layers of the LCLZ. The foliation averages 57 degrees to the core axis for 16 determinations (Fig. 32). It has been previously noted and has been observed here, that certain serpentine foliation is caused by curtain-growth serpentine that is developed at right angles to the preferred orientation of elongate olivine crystals. If the direction of elongation of olivine crystals represents the original layering plane, it follows that the original layering direction must lie at right angles to the orientation of serpentine foliation. Thus the original layering would have had an average angle to the core axis of 33 degrees (Fig. 33). This attitude fits reasonably well with two of the four measured attitudes of primary layered structures (Fig. 32).

There is a suggestion of a progressive change in core axis angle measurements to serpentine foliations over the upper 500 feet of the drill hole. This would be interpreted as indicating that the change in layering attitude between MZ and LCLZ rocks, as previously noted from other parts of the intrusion, takes place here in the lowermost part of the LCLZ.

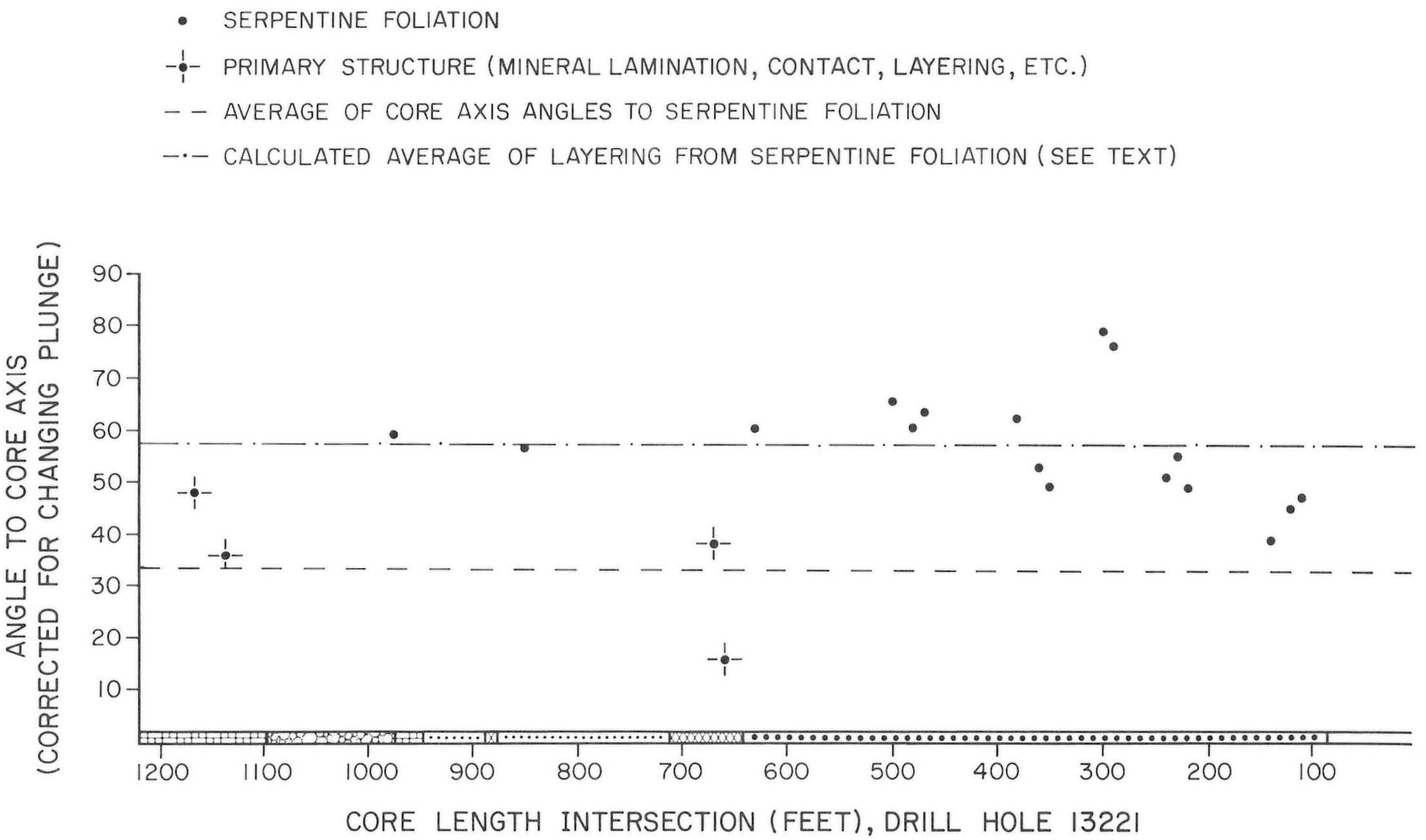


Figure 32: Core axis angles to planar structures, drill hole 13221

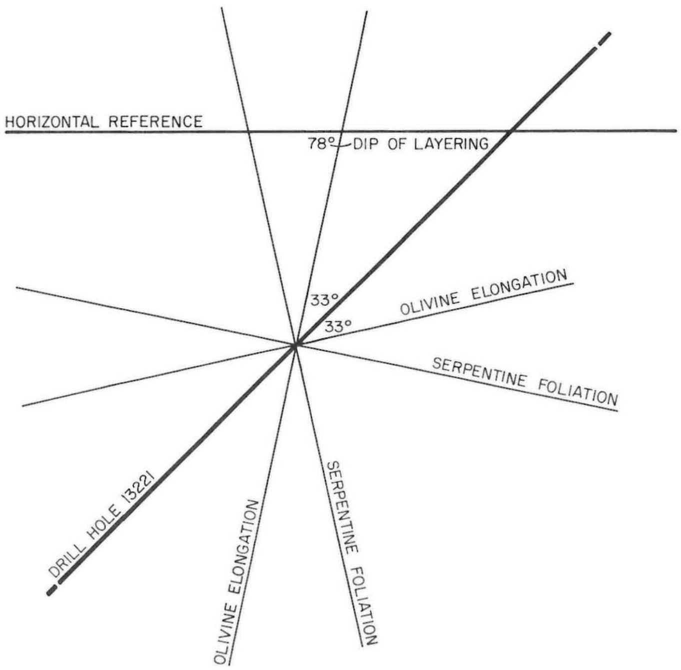


Figure 33: Simplified relationship between serpentine foliation, olivine fabric and layering direction.

Drill hole 13227

Drill hole 13227 intersects a substantial thickness of LCLZ rocks, the LCLZ-MZ contact and 24 m (core length interval) of the plagioclase cumulate layer of the uppermost MZ unit in this area (Fig. 34). Although the MZ-LCLZ contact is not exposed in the telescoped core, the character of the plagioclase cumulate near the contact indicates that the contact may be gradational.

UPPERMOST MZ UNIT

Plagioclase cumulate layer

The rocks are medium- to fine-grained, grey and even textured. Cumulus plagioclase that originally formed laths has been extensively altered to albite ± muscovite ± epidote ± chlorite. Clinopyroxene and orthopyroxene are interpreted to have been present throughout the exposed part of the layer, changing from postcumulus to cumulus phases toward the top of the layer. Clinopyroxene has been pseudomorphously converted to pale green tremolite, and orthopyroxene has been replaced by shredded and wispy colourless tremolite. Near the base of the hole original polyhedral to granular olivine has been replaced by quartz. At the top of the layer, the rock is distinguished by randomly oriented, slender plagioclase laths and relatively abundant red-brown hornblende that contains, as inclusions, fine grained pseudomorphs after granular olivine. This rock appears to represent a transition from MZ plagioclase cumulate to LCLZ olivine cumulate.

Ilmenite is sporadically distributed throughout the layer and near the base of the hole forms rounded, irregularly shaped grains.

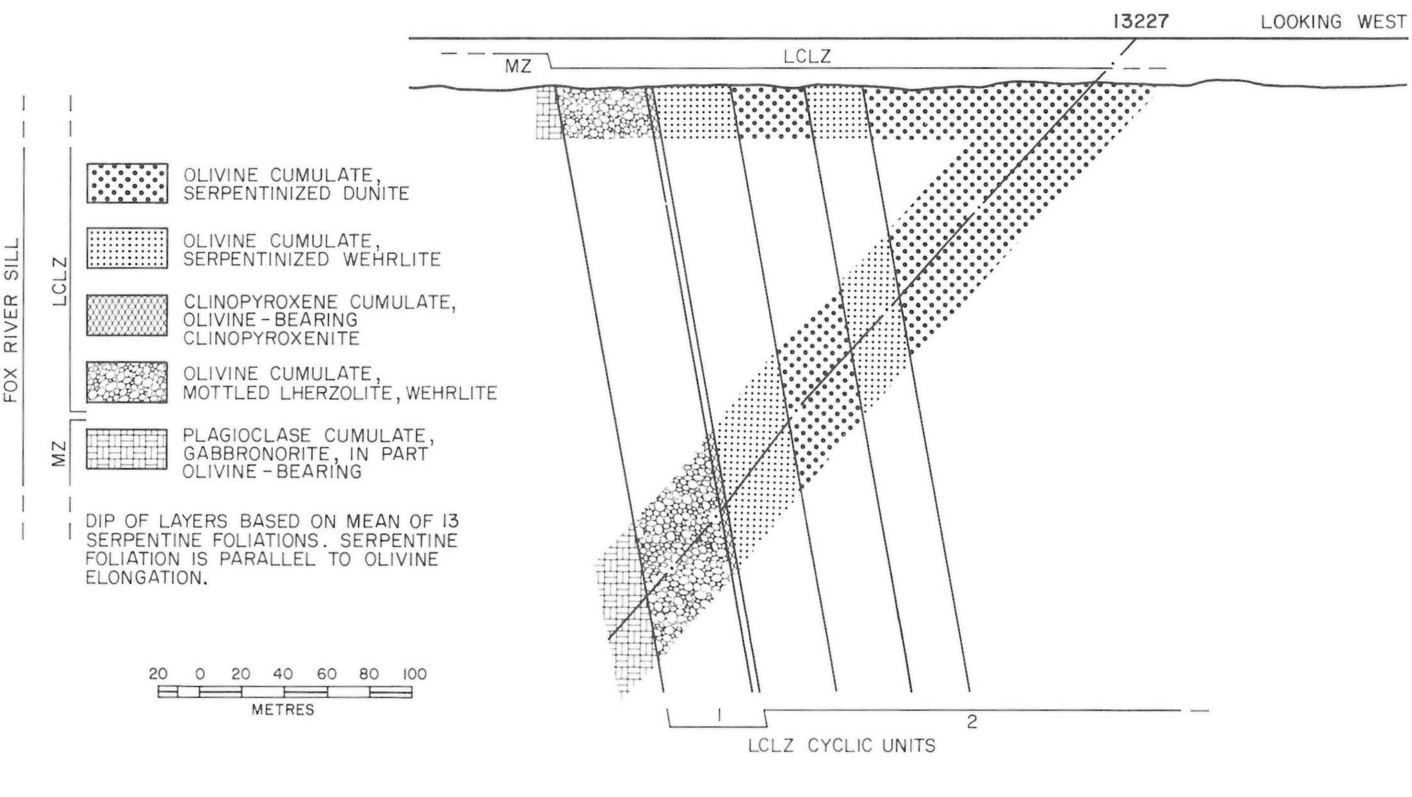


Figure 34: MZ geology, drill hole 13227.

Drill hole 11925

UPPERMOST MZ UNIT

Plagioclase cumulate layer

Plagioclase cumulate rocks of the outermost (uppermost) MZ unit were intersected by drill hole 11925 (Fig. 35). The rocks are green to slightly bluish grey, medium- to fine-grained, and some are slightly mottled. The rocks originally consisted of an accumulation of plagioclase laths, separated by orthopyroxene and clinopyroxene. Orthopyroxene was a cumulus phase throughout most of the exposed section, except near the top of the layer, where the crystals poikilitically enclose plagioclase laths. Clinopyroxene, a postcumulus phase, originally formed highly irregular crystals with inclusions of plagioclase. The rock becomes coarser grained near the contact with LCLZ rocks.

Plagioclase has been altered to a fine gained, nearly isotropic mat of epidote ± chlorite ± muscovite ± albite. Clinopyroxene has been partly recrystallized to colourless tremolite, and orthopyroxene has been converted to a felted mat of shredded, wispy tremolite ± talc. Irregularly shaped ilmenite crystals are sporadically distributed throughout the rock. Prehnite ± epidote veinlets are common near the contact.

Strongly deformed rocks near the contact between MZ and LCLZ rocks suggest that the contact may be a fault.

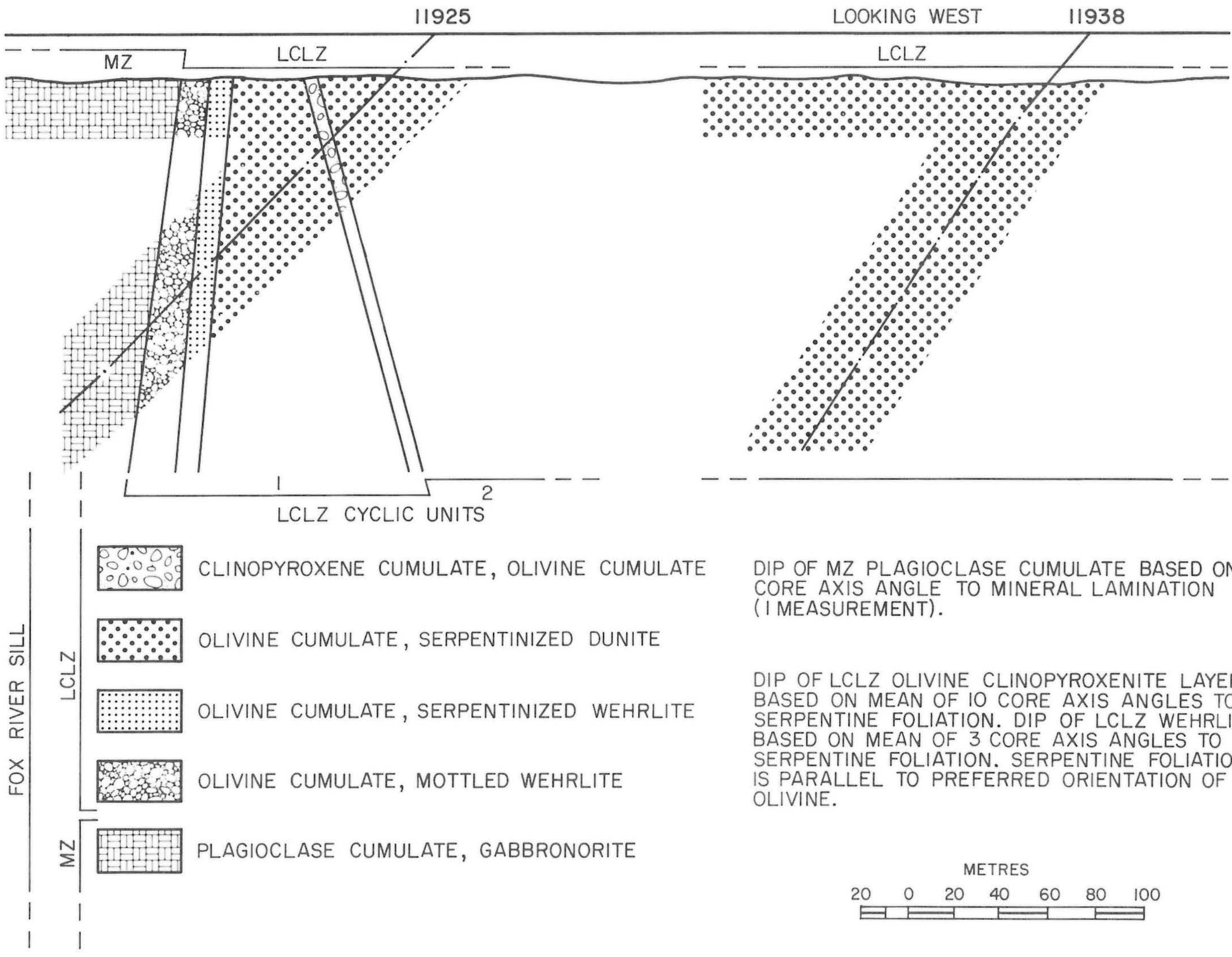


Figure 35: MZ geology, drill hole 11925.

Drill hole 38515

Two complete cyclic units, a portion of the plagioclase cumulate layer of a third cyclic unit and the MZ-LCLZ contact were intersected by drill hole 38515 (Fig. 36). The lowermost plagioclase cumulate layer is arbitrarily designated as being part of MZ cyclic unit 1, although there may be other underlying cyclic units. The two uppermost MZ cyclic units are distinguished by thin olivine cumulate and clinopyroxene cumulate layers, overlain by thicker plagioclase cumulate layers (Fig. 36). The extensive recrystallization of MZ rocks intersected in the hole is related to an olivine diabase dyke that cuts LCLZ serpentinite, close to the MZ-LCLZ contact (Fig. 36).

CYCLIC UNIT 1

Plagioclase cumulate layer

The rocks are medium- to fine-grained, granular, greenish- to bluish- grey and delicately mottled or spotted. They were originally composed of cumulus plagioclase as laths and equidimensional crystals. Clinopyroxene and orthopyroxene were original cumulus crystals near the start of the core intersection but both become postcumulus phases toward the top of the layer. Brown to red-brown hornblende formed a late stage, postcumulus phase in some rocks, and is best developed toward the top of the layer.

The rocks are highly recrystallized, plagioclase is replaced by andesine ± muscovite ± epidote ± chlorite near the start of the core intersection and replaced by a fine grained, nearly isotropic intergrowth of epidote ± chlorite ± muscovite toward the top of the layer. Clinopyroxene has been pseudomorphously replaced by pale green to colourless tremolite; orthopyroxene has been pseudomorphously replaced by colourless, shredded intergrowths of tremolite and chlorite. Veinlets filled with chlorite ± prehnite ± albite ± quartz are sporadically distributed throughout the unit, as are microfractures, some displaying movement and deformed crystals that indicate some post-consolidation movement.

Ilmenite, the only opaque phase identified, occurs as widely disseminated clusters of irregularly shaped crystals.

CYCLIC UNIT 2

Olivine and clinopyroxene cumulate layers

Olivine cumulate rocks are medium grained, mottled and dark greenish black to black, and become dark greyish green, well foliated, veined and brecciated toward the top of the layer. The rock originally consisted of granular to slightly polyhedral cumulus olivine, suspended and separated by postcumulus oikocrysts of clinopyroxene, plagioclase and hornblende. Orthopyroxene originally formed irregularly shaped poikilitic crystals. Fine grained, euhedral chromite crystals and an original cumulus phase are widely disseminated. The rock was originally an olivine melagabbronorite.

The rock has been extensively recrystallized with olivine completely replaced by fibrous serpentine that in places contains fibre-like tremolite needles. Orthopyroxene has been completely converted to talc ± tremolite. Clinopyroxene is partly replaced by colourless tremolite, and plagioclase has been converted to a nearly isotropic mat of finely intergrown epidote ± chlorite ± muscovite. As previously noted, the upper part of the layer is strongly foliated and veined, suggesting that the contact between the olivine cumulate and pyroxene cumulate layers is a fault.

The clinopyroxenite is medium grained, greenish- to brownish-grey and consists predominantly of clinopyroxene. Orthopyroxene and red-brown hornblende are rare constituents.

Plagioclase cumulate layer

Plagioclase cumulate rocks are medium grained, mottled, and grey green to bluish grey. Clinopyroxene and orthopyroxene were postcumulus phases at the base of the layer. Orthopyroxene originally formed poikilitic crystals up to 1 cm in size, and in places compose 15 to 20 percent of the rock. Midway through the layer clinopyroxene becomes a cumulus phase and orthopyroxene is interpreted to have been a cumulus phase at the top of the layer. Ilmenite occurs as clusters of irregularly shaped crystals, many displaying rounded outlines. Some larger ilmenite crystals are sieve-like, and some are partly to completely altered to leucoxene.

Plagioclase has been altered to andesine + epidote ± muscovite ± chlorite. Secondary albite forms sporadically distributed, discontinuous veinlets. Clinopyroxene has been partly altered to colourless to pale green tremolite, and orthopyroxene has been completely replaced by chlorite ± tremolite.

The rock is characterized by numerous fractures, some occupied by quartz ± chlorite ± carbonate. Prehnite veinlets are common. Rocks that possess numerous microfractures commonly display deformed crystals. A 1 mm wide galena ± chalcopyrite ± chlorite veinlet was observed in one sample (Plate 29).

CYCLIC UNIT 3

The uppermost MZ cyclic unit consists of a thin olivine cumulate and clinopyroxene cumulate layer (2.6 m and 1.5 m, estimated true thicknesses) and a somewhat thicker (7.3 m) plagioclase cumulate layer (Fig. 36). Extensive recrystallization makes placement of the contact between pyroxene and plagioclase cumulate rocks difficult and it is likely that this contact is gradational.

The lowermost layer represents an original olivine + chromite cumulate with abundant postcumulus poikilitic crystals and oikocrysts. The rock, which has been completely recrystallized to an assemblage of talc + chlorite, was originally olivine melagabbronorite in composition.

Overlying the olivine cumulate layer is a variable unit ranging from pyroxenite to gabbro. The rocks are grey to grey green and granular, and were originally composed of cumulus clinopyroxene, orthopyroxene and plagioclase. The rocks have been substantially recrystallized, plagioclase being replaced by garnet. The presence of microfractures in the rock and the well developed foliation in the overlying LCLZ serpentine suggests that the MZ-LCLZ contact is a fault.

Plagioclase compositions

Plagioclase compositions determined on altered plagioclase crystals average An_{37} in Cyclic unit 1 rocks and An_{31} in Cyclic unit 2 rocks. Several determinations on veins and overgrowths ranged from An_4 to An_{10}. All these values represent secondary, recrystallized plagioclase.

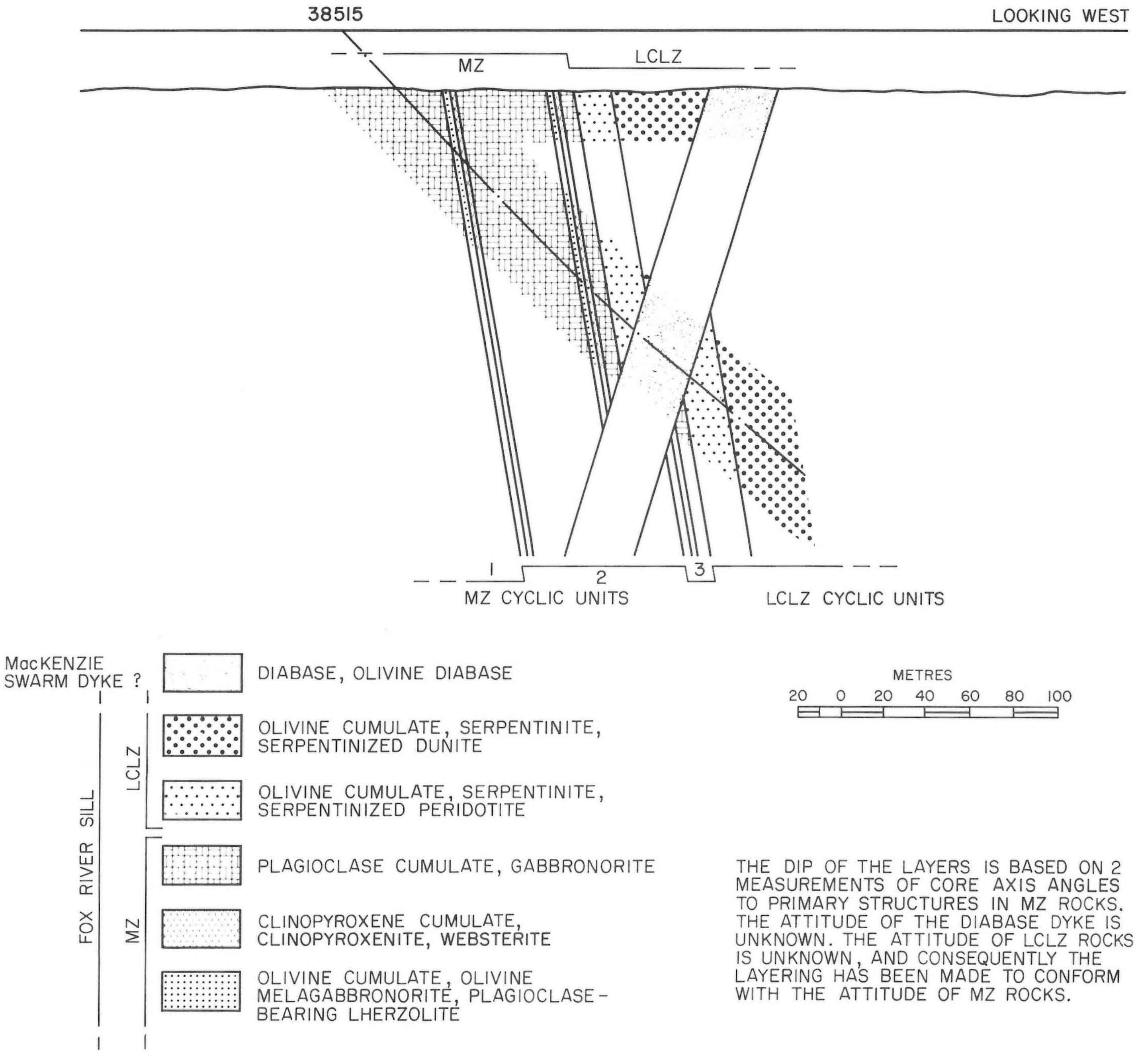


Figure 36: MZ geology, drill hole 38515.

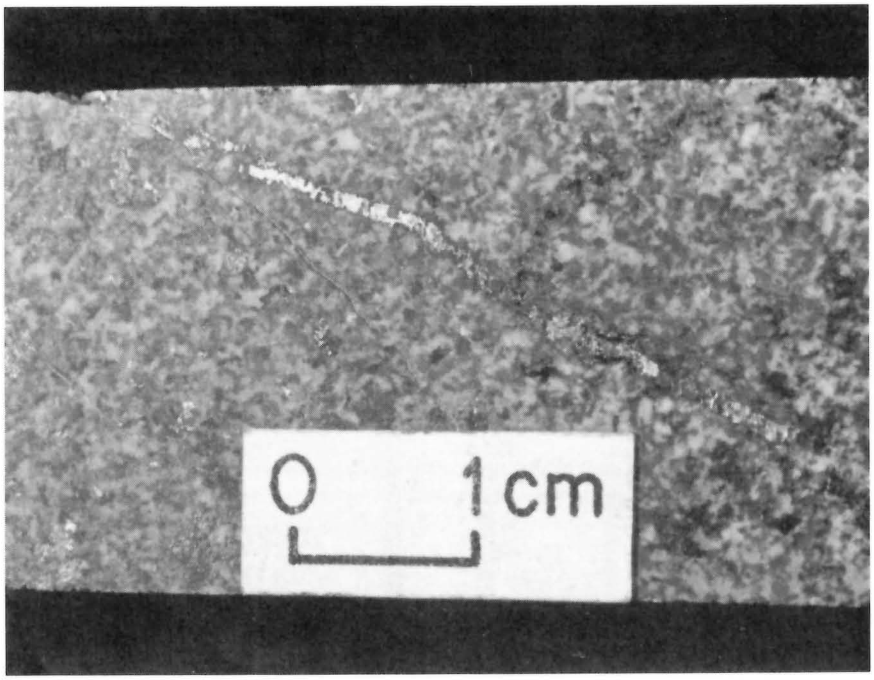


Plate 29: *Chalcopyrite-galena veinlet in plagioclase cumulate. Whitish-grey material is alteration after aggregates of cumulus, lath-like plagioclase. Mid-grey patches are clinopyroxene. MZ, plagioclase cumulate, DDH 38515-460.*

Drill hole 13217

The Middle sedimentary formation-MZ contact, as well as the MZ-LCLZ contact were intersected by drill hole 13217 (Fig. 37). Non-cyclic MZ rocks, restricted to a core length intersection of 12 m, were originally olivine melagabbronorite. MZ and LCLZ rocks are separated by 16 m (core length intersection) of unusual quartz-bearing rock that resembles HRZ material; it may represent a completely reconstituted inclusion of Middle sedimentary formation siltstone.

Middle sedimentary formation rocks adjacent to the contact comprise a suite of light to dark grey, laminated siltstone, argillite and shale, the latter unit possessing a well developed fissility. Although the rocks have been converted to hornfels by contact metamorphism, the original sedimentary lamination is preserved. The relatively small range in core axis angles to lamination (Fig. 37) suggests that the unit has been gently folded.

NON-CYCLIC UNIT

Olivine cumulate rocks

The rocks are light grey green to dark greenish grey, medium grained, and mottled, and are cut by numerous slip surfaces. These highly recrystallized rocks originally consisted of cumulus olivine ± chromite crystals, and numerous postcumulus oikocrysts. Lath-shaped, nearly isotropic areas indicate that plagioclase may have been an original cumulus phase. Red-brown hornblende and phlogopite oikocrysts accompanied clinopyroxene as postcumulus phases.

Olivine has been altered to fibrous and nonfibrous, plate-like serpentine. Clinopyroxene has been converted to colourless tremolite, and serpentine ± chlorite ± shredded, wispy tremolite veins are common.

The original rock is considered to have been an olivine melagabbronorite, and the olivine content probably did not exceed 30 percent.

Hybrid rocks

Separating olivine melagabbronorite from LCLZ serpentinized wehrlite is a dense, grey to slightly brownish grey, fine grained, massive quartz-bearing rock. The rock was originally composed of an interlocking mosaic of lath-like plagioclase that has been replaced by albite + quartz + epidote + muscovite. Wispy, shredded, colourless to pale green tremolite is a common phase. Sphene, ilmenite, pyrrhotite and apatite are less common phases. Carbonate + chlorite + epidote veins are common. Highly irregular patches of brown to red-brown hornblende represent relicts of original poikilitic crystals.

This highly recrystallized rock is similar to quartz-bearing rocks of the HRZ and it may represent a completely reconstituted inclusion of Middle sedimentary formation siltstone.

LAYER ATTITUDES

Planar structures are absent in MZ rock; however, serpentine ± magnetite foliation is well developed in LCLZ olivine cumulate (see Fig. 64). The foliation is parallel to the orientation of the direction of elongation of olivine crystals and therefore is interpreted to be equivalent to the layering direction of the serpentinized wehrlite. A progressive change in the angular relationships with depth (see Fig. 64), implies a progressive change in the dip angle of layering. The sense of the change in dip is the same as that previously described - a tendency for the dip angle to become more shallow inward or stratigraphically upward from the margin of the intrusion. MZ rocks and LCLZ rocks near the contact are considered to be parallel with the dip of the Sill contact (Fig. 37).

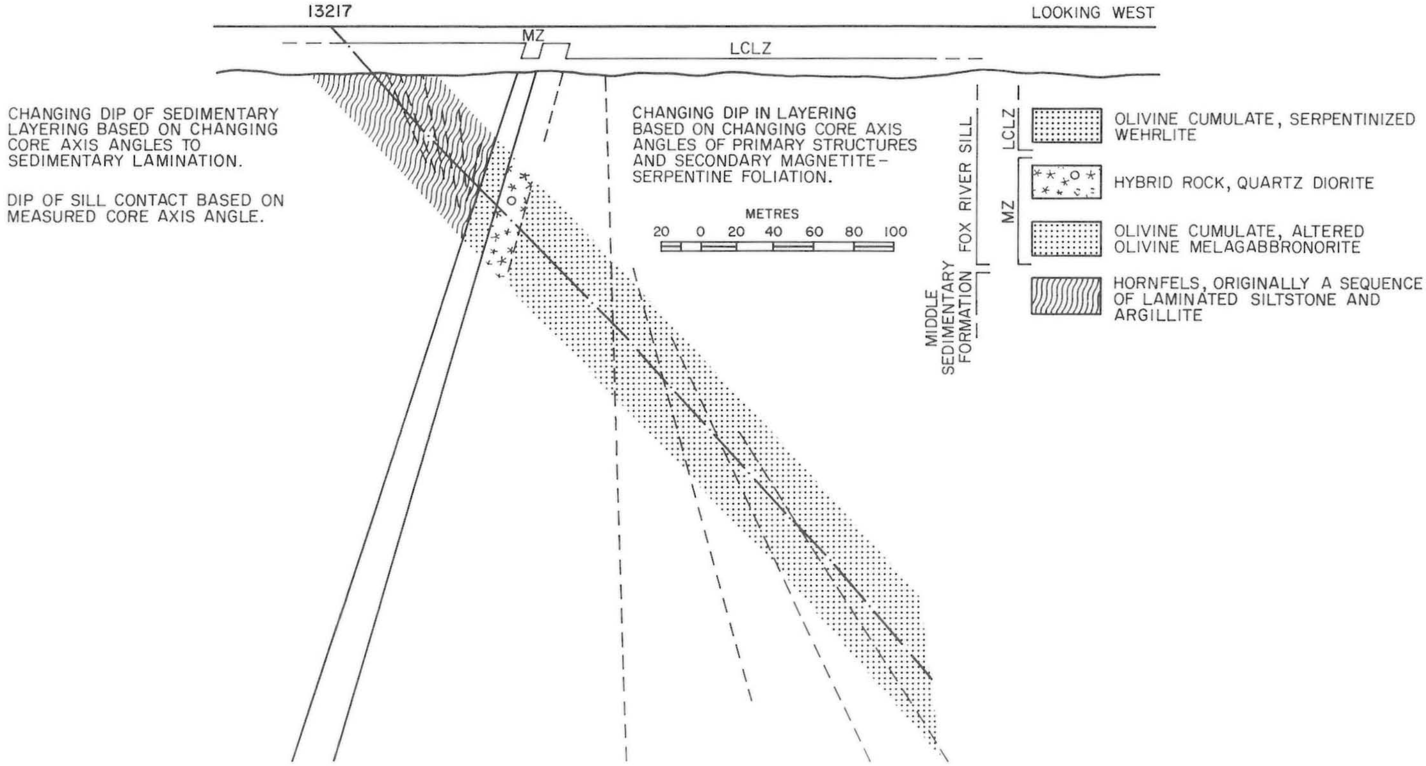


Figure 37: MZ and lowermost LCLZ geology, drill hole 13217.

Drill hole 38541

The uppermost part of drill hole 38541 intersects 5.5 m of highly altered, foliated and brecciated rock that is interpreted as representing original MZ gabbronorite (Fig. 38). The rock has a marbled appearance due to intersecting carbonate veins. The foliated character of LCLZ olivine cumulate rocks, and the numerous slickensided slip surfaces that characterize rocks close to the MZ-LCLZ contact, suggest that in this core interval the contact is a fault.

Drill hole 38527

The hole, part of 64W section, is 34 km east of 722E section, 46 km east of the Great Falls outcrop area, and approximately 4 km from the eastern end of the west lobe of the Fox River Sill (Map GR81-1-1). It intersects rocks that are interpreted as representing the upper part of a differentiated intrusion, sedimentary rocks that are interpreted as representing an eastward extension of the Middle sedimentary formation, pyroxene + plagioclase cumulate noncyclic MZ rocks, and LCLZ olivine cumulate rocks (Fig. 39).

The possible differentiated intrusion consists of granophyre-bearing gabbro, distinguished by large (up to 5 mm) sieve-like ilmenite crystals that have been partly altered to sphene. Quartz-rich rocks contain apatite, epidote, ilmenite and tourmaline associated with biotite ± chlorite. The presence of granophyre suggests that these rocks represent a possible hybrid roof zone of a larger differentiated intrusion.

A sequence of medium- to fine-grained, laminated sedimentary rocks is sandwiched between the differentiated intrusion and the base of the Fox River Sill (Fig. 39). The rocks, which consist of finely laminated siltstone, argillite, shale and carbonaceous shale, and slightly coarser grained quartz-rich layers including quartzite, have been converted to hornfels adjacent to the contacts with the intrusions. This suite of rocks contains more quartz-rich layers than Middle sedimentary formation rocks exposed in drill holes 34 km to the west. The abundance of siltstone and argillite is similar, however, and on that basis these rocks are correlated with Middle sedimentary formation rocks. Thus, it appears that MZ rocks are in contact with fine grained, laminated Middle sedimentary formation rocks along the entire 70 km length of the west lobe of the Fox River Sill.

NON-CYCLIC UNIT

Pyroxene and plagioclase cumulate rocks

The MZ consists of a 10.6 m core length intersection of gabbronorite. The rocks are medium- to fine-grained, slightly bluish- to brownish-grey, and delicately mottled. The rock at the contact with Middle sedimentary formation rocks is medium- to fine-grained and contains recognizable pseudomorphs after original plagioclase laths. The contact with LCLZ olivine cumulate rocks is sharp and irregular.

The rocks were originally composed of cumulus plagioclase, clinopyroxene and orthopyroxene crystals. Clinopyroxene possesses irregular shapes that probably were caused by postcumulus crystallization. Plagioclase has been entirely replaced by tremolite, and clinopyroxene has been partly replaced by tremolite. The latter occurs as discrete crystals and crystal aggregates, and individual crystals display parting and many are twinned. Clinopyroxene displays strain extinction toward the top of the zone. Elliptical patches of tremolite in one sample are interpreted to represent pseudomorphs after original olivine crystals. The rocks were logged as norite and anorthositic norite.

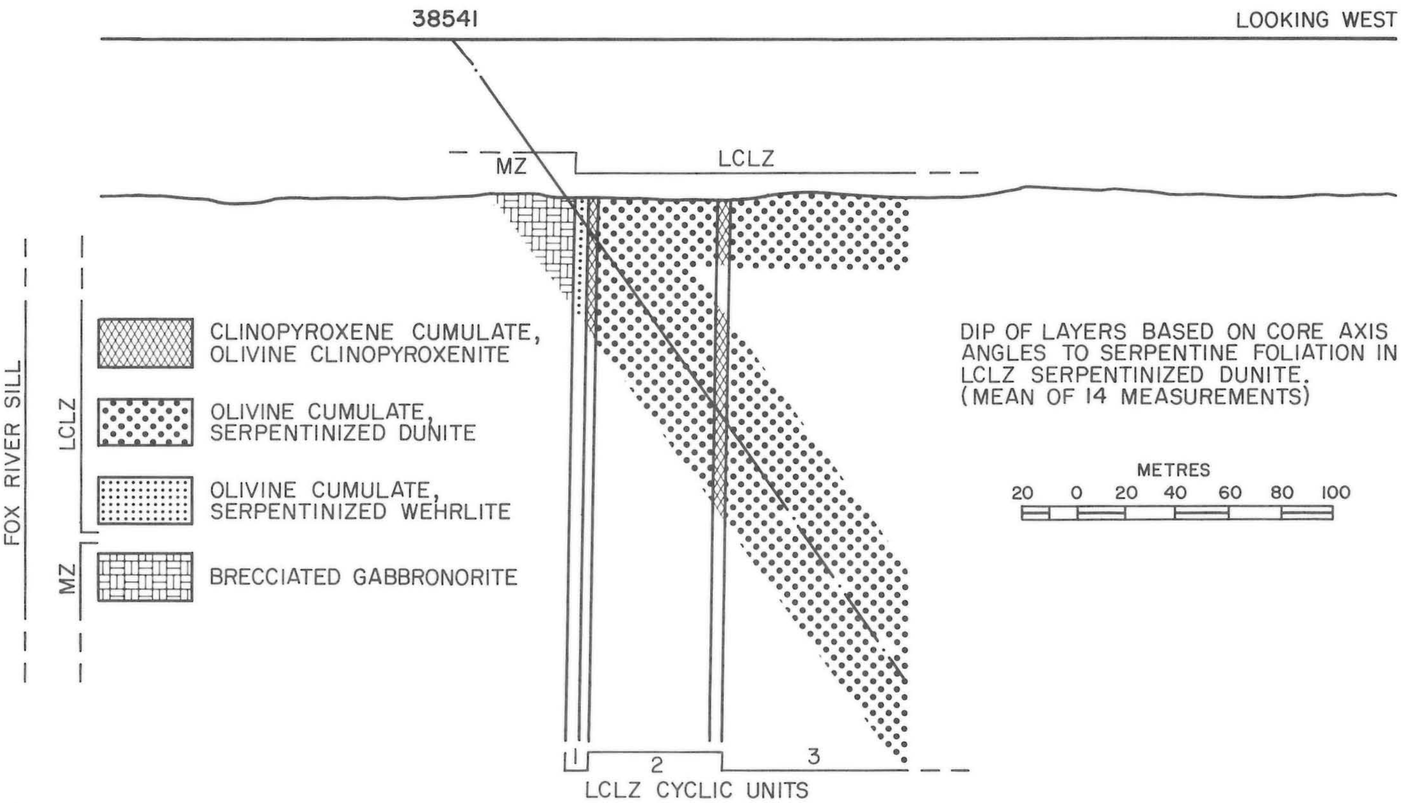


Figure 38: MZ and lowermost LCLZ geology, drill hole 38541.

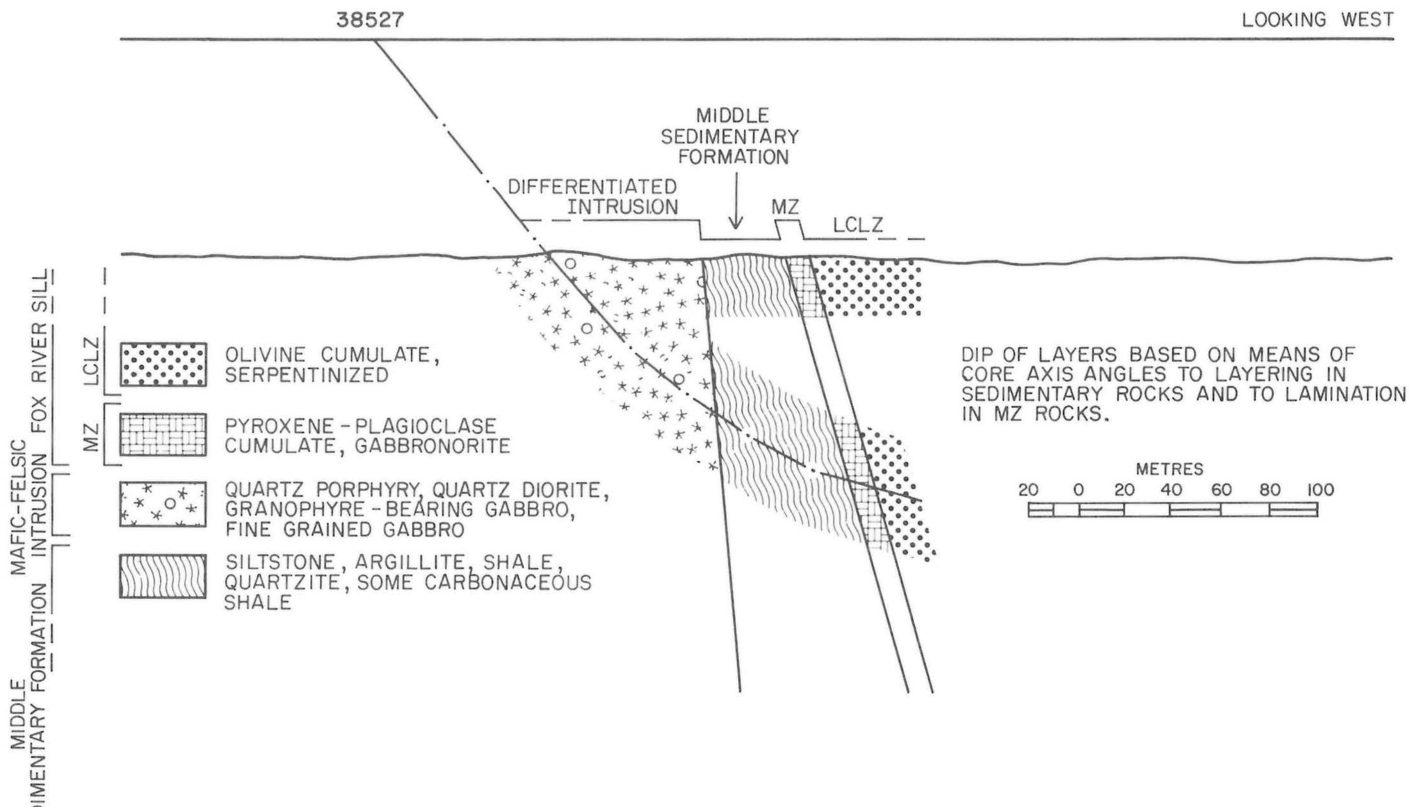


Figure 39: MZ and lowermost LCLZ geology, drill hole 38527.

LAYER ATTITUDES

Measurement of core axis angles to layering and lamination of sedimentary rocks indicates a change in dip of the layering with depth. The plunge of the drill hole decreases dramatically with depth, and the method of determining the dip of the layering is shown in Fig. 40.

Drill hole 38528

Drill hole 38528, collared within approximately 600 m of the eastern end of the west lobe of the Sill (Map GR81-1-1), intersects laminated Middle sedimentary formation rocks that are in contact with LCLZ olivine cumulate rocks (Figs. 41 and 42). MZ rocks are absent and LCLZ olivine cumulate rocks are in contact with Middle sedimentary formation carbonaceous shale. The presence of strongly foliated serpentinite at the contact suggests that the contact may be a fault; however, whether MZ rocks were originally absent or have been removed by faulting is not known. Drill hole 38527, collared approximately 3 km west of 38528 (Map GR81-1-1), intersected 10 m of MZ rocks so that the thickness of MZ rocks decreases significantly at the eastern end of the west lobe of the Sill.

CHARACTER AND SIGNIFICANCE OF MZ ROCKS

MZ rocks separate LCLZ olivine cumulate rocks from Middle sedimentary formation rocks along the 70 km length of the south contact of the west lobe of the Fox River Sill. They are composed of cyclic units, each cyclic unit consisting of olivine cumulate rocks at the base that are overlain in turn by clinopyroxene cumulate rocks and plagioclase cumulate rocks. Three cyclic units were mapped in the Great Falls outcrop area, where MZ rocks attain a thickness of approximately 270 m. Non-cyclic MZ rocks have been noted in a few areas and MZ rocks are missing in one area where LCLZ rocks are in contact with Middle sedimentary formation rocks. Evidence of deformation in this latter area suggests that the LCLZ-Middle sedimentary formation contact is a fault. Fine grained rocks, indicative of a chilled zone adjacent to Middle sedimentary formation rocks, are locally developed but are neither continuous nor abundant.

The fact that the MZ zone, in places, consists of cyclic units that represent differentiation of magma, indicates that crystallization proceeded, not from the contact inward, but rather from the top, with crystals accumulating from the bottom up. In other words, it appears that, at the time of formation of MZ rocks, the greatest heat loss was through the roof of the intrusion, not through the walls. This condition is the reverse of that observed in other layered intrusions. The MZ of the Muskox Intrusion ranges from 60 to 360 m wide, and grades inward from bronzite gabbro at the contact, through picrite and feldspathic peridotite to peridotite and in places dunite (Smith, 1962). Contacts are not recognizable in Muskox MZ rocks, the changes being gradational and accomplished by a decrease in plagioclase and an increase in olivine from the margin into the intrusion. In the Skaergaard Intrusion there is no evidence of extensive fractional crystallization preceding the formation of the exposed layered series, and the Marginal Border Group is considered to have crystallized inward from the intrusion walls (Hoover, 1978). In the Stillwater Complex, the Basal Zone consists of fine grained ophitic gabbro at the contact with country rocks, overlain by coarser grained feldspathic bronzitites that grade upward into bronzitite. The bronzitites are in sharp contact with olivine-rich layers of the ultramafic zone (Jackson, 1961; Wager and Brown, 1968).

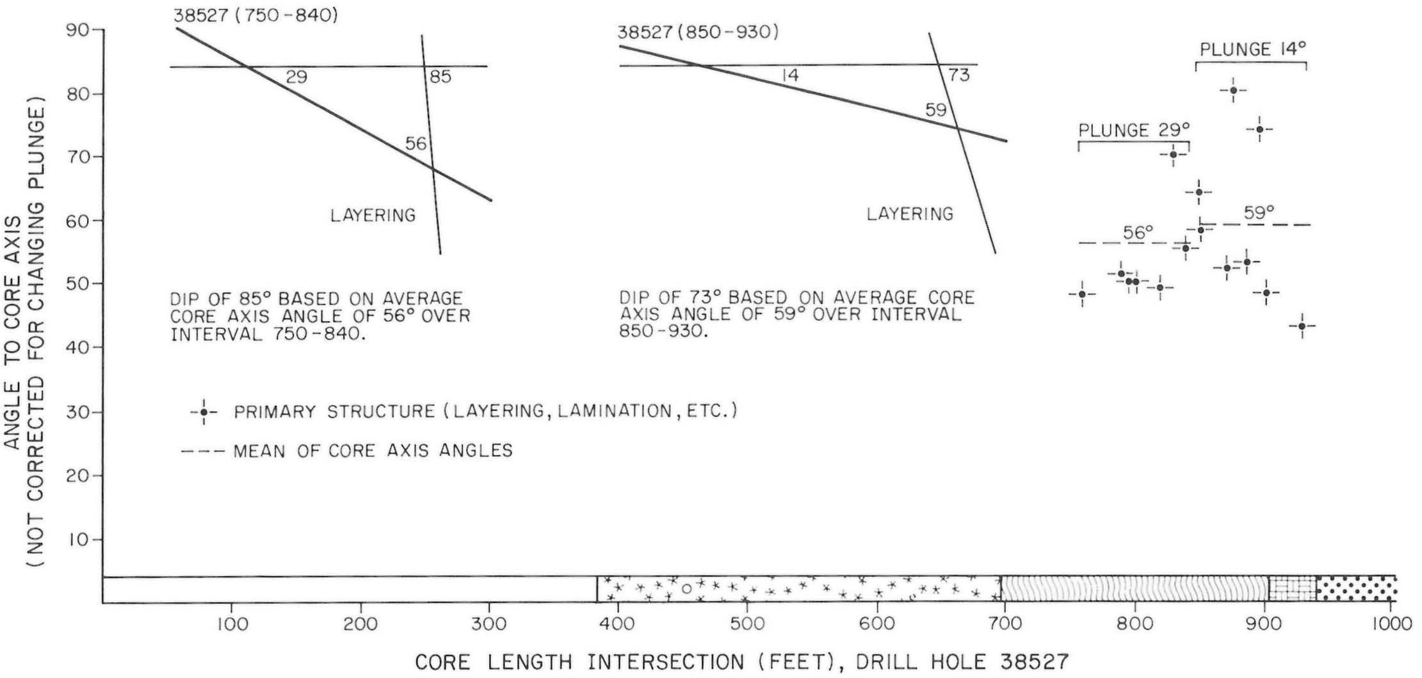


Figure 40: Core axis angles to planar structures, drill hole 38527.

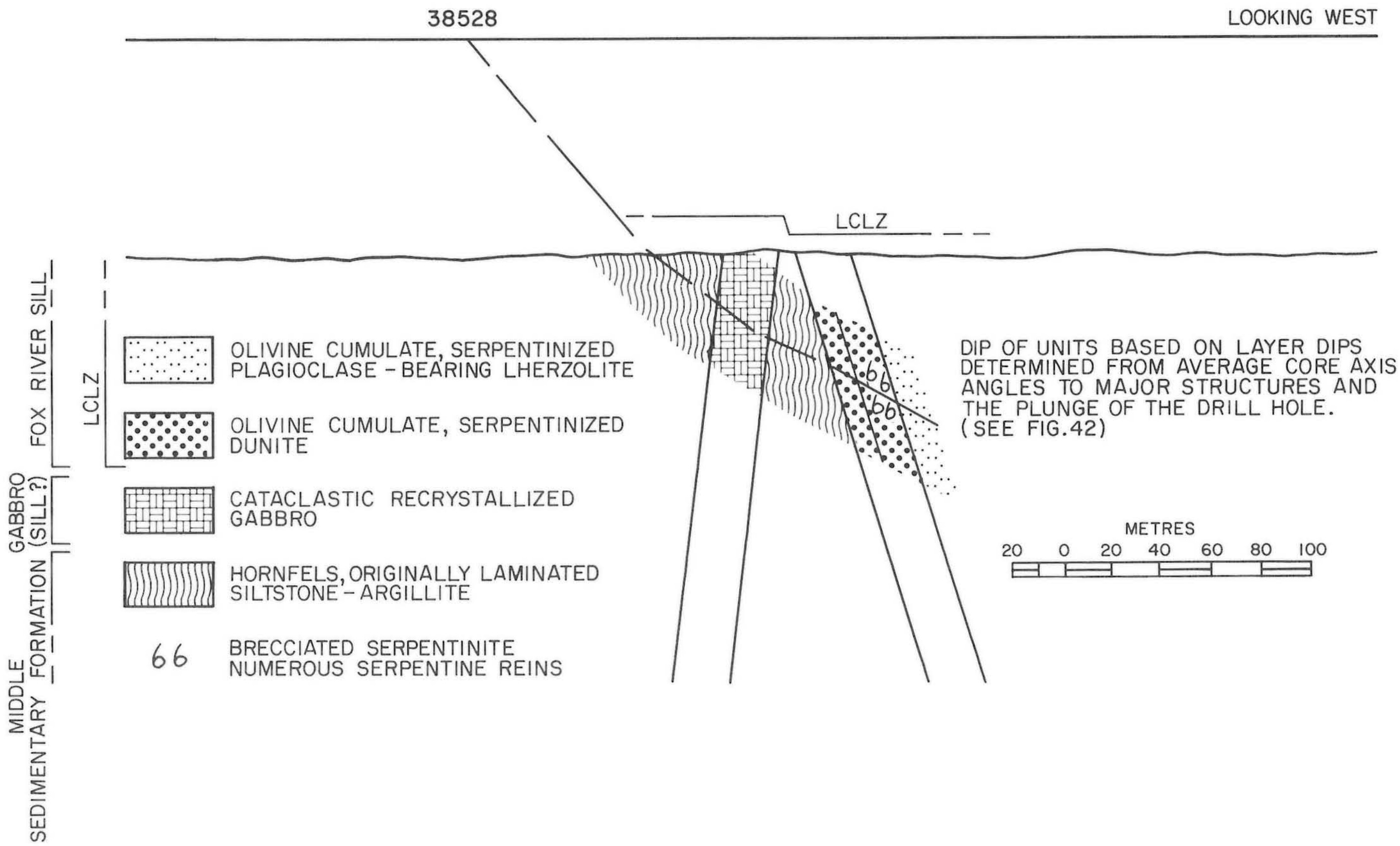


Figure 41: South Sill contact geology, drill hole 38528.

Variation in MZ cyclic units

Each MZ cycle represents the differentiation and fractional crystallization of basic magma. Thus, in places, the MZ is composed of successive differentiated intrusions. Although the presence of cycles implies crystallization of MZ rocks through crystal accumulation from the bottom up, evidence exists that conditions changed during the early stages of crystallization. The evidence includes a substantial increase in both grain size and abundance of cumulus olivine, stratigraphically upward, in olivine cumulate rocks adjacent to the contact. The increase in grain size involves postcumulus as well as cumulus minerals. Fine grained rocks near the contact reflect conditions of rapid cooling. Strongly zoned, postcumulus hornblende crystals near the contact are also interpreted as resulting from rapid cooling due to heat loss through the wall of the intrusion. In several areas, the lowermost part of the olivine cumulate layer, adjacent to the contact, is composed of highly altered hornblende-rich rocks that were originally pyroxene-rich and plagioclase-bearing. These original pyroxene-rich, olivine + pyroxene ± plagioclase cumulate rocks grade into fine grained rocks of the main part of the olivine cumulate layer. Although these rocks do not represent chilled margins, they may approach the original liquid composition of the initial magmatic injection into the chamber.

A substantial variation is present in both the total thickness and in the number of MZ cyclic units from place to place along the south contact of the Sill, and the presence of noncyclic MZ rocks has been documented. Evidence of movement in the vicinity of the MZ-LCLZ contact, in a number of areas, suggests the presence of faults that in turn may have been important in contributing to the observed variation in thickness and number of cycles. A significant range in variation of composition of cycles suggests that although faults may be a contributing factor, there may be additional fundamental, primary causes for the observed variations.

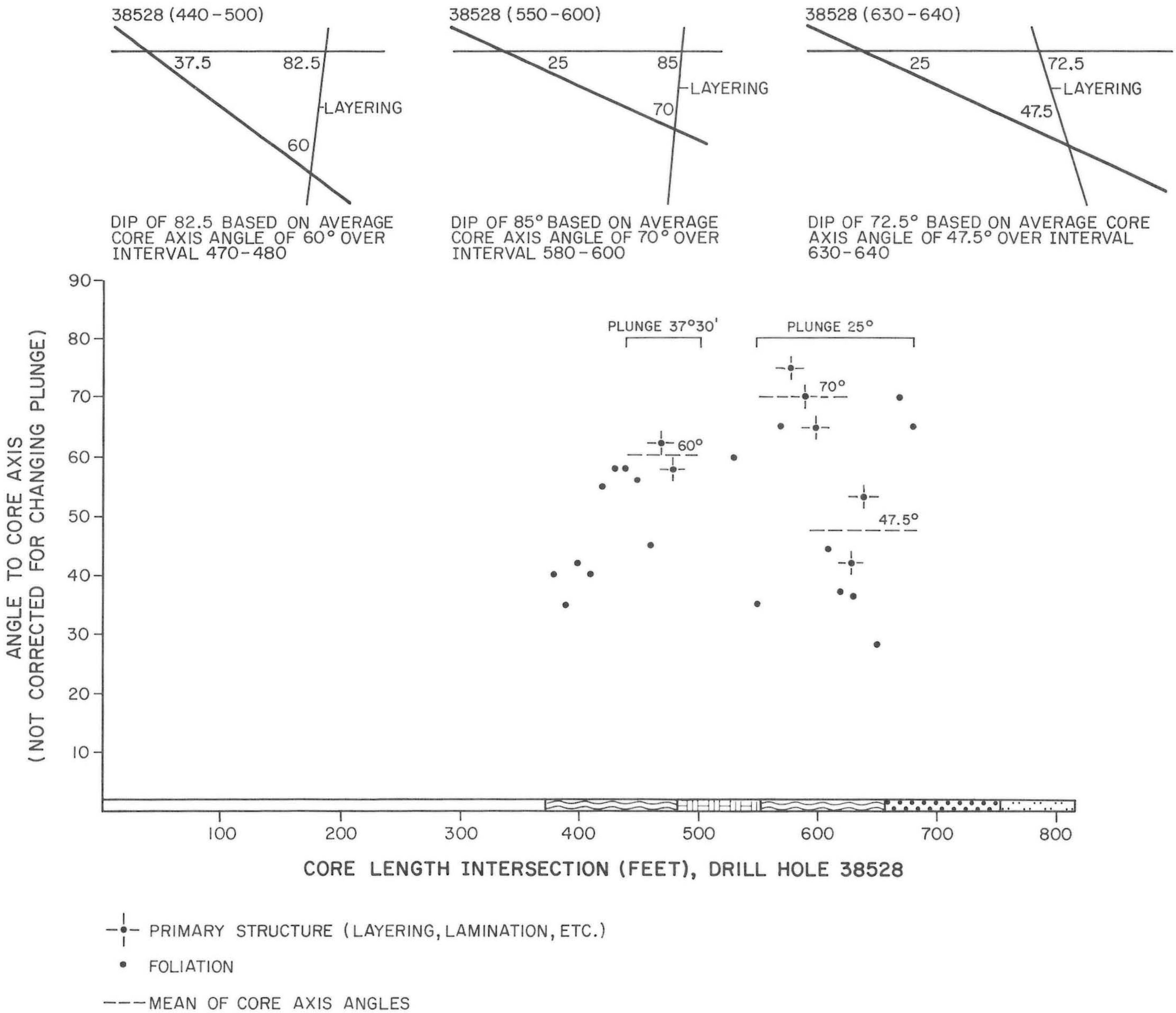


Figure 42: Core axis angles to planar structures, drill hole 38528.

The progressive decrease of the dip of layers from the Sill contact inward to the MZ-LCLZ contact would lead to individual layers and entire cyclic units pinching out updip. Thus, variations in the plunge of the intrusion axis could give rise to cyclic units of different thickness and to a different number of cyclic units from place to place along the south contact of the Sill. Undulations of the intrusion floor, that existed during the intrusion event, could govern the thickness of individual layers and cyclic units. The effect of undulations of the floor of a layered komatiite flow on an olivine cumulate layer suspended above the floor of the flow, illustrated by Baragar (1983), could be considered as a possible extrusive analogue of this concept.

Perhaps the most important factor is that the variation in thickness and composition of cyclic units reflects the volume and composition of the magmatic impulses responsible for individual MZ cyclic units. The number of MZ cyclic units in any given area is a consequence of the number of successive, relatively small-scale intrusions that issued from rifts in that area. Magmatic impulses of different volumes and compositions would give rise to MZ cyclic units of different thickness and composition. The MZ of the Fox River Sill can be considered to be composed of a number of overlapping intrusions of different volume. Thus, although olivine cumulates appear to be in contact with Middle sedimentary formation rocks along the length of the south contact of the Sill, the olivine cumulate rocks likely represent a number of different intrusions (Fig. 43 and 44). Note that sections CC' and DD' (Fig. 44) each intersect two MZ cyclic units; however, the cyclic units belong to different magmatic events, and the thickness of equivalent cyclic units is substantially different.

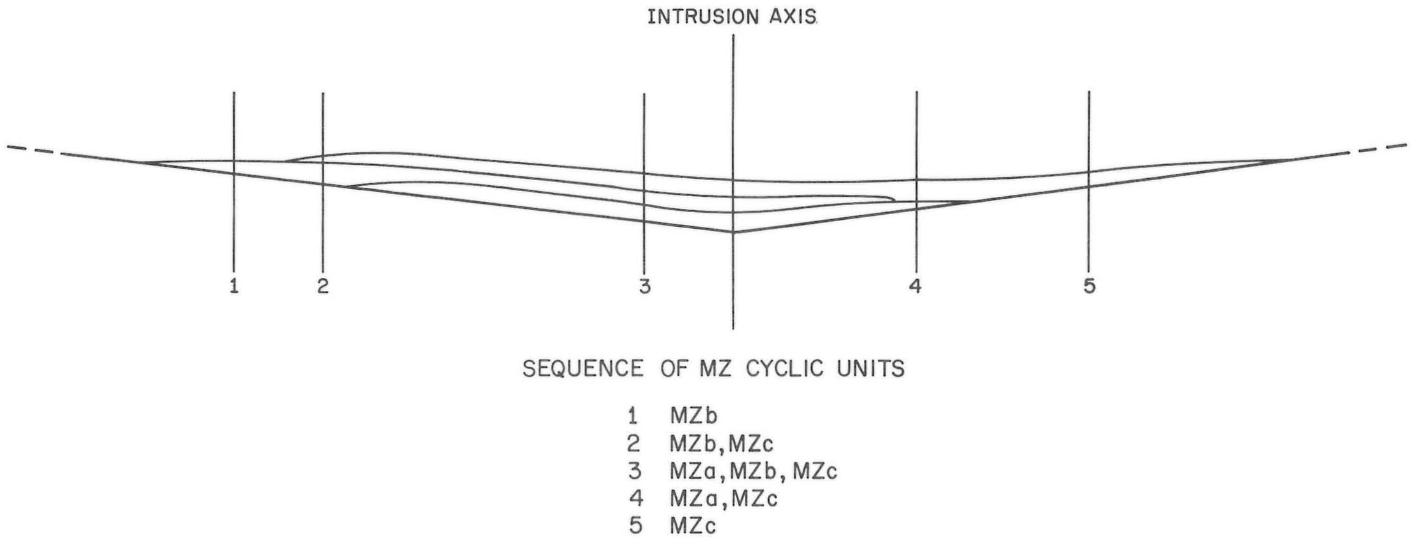


Figure 43: Hypothetical cross-section illustrating changes in sequence of MZ cyclic units updip from the intrusion axis.

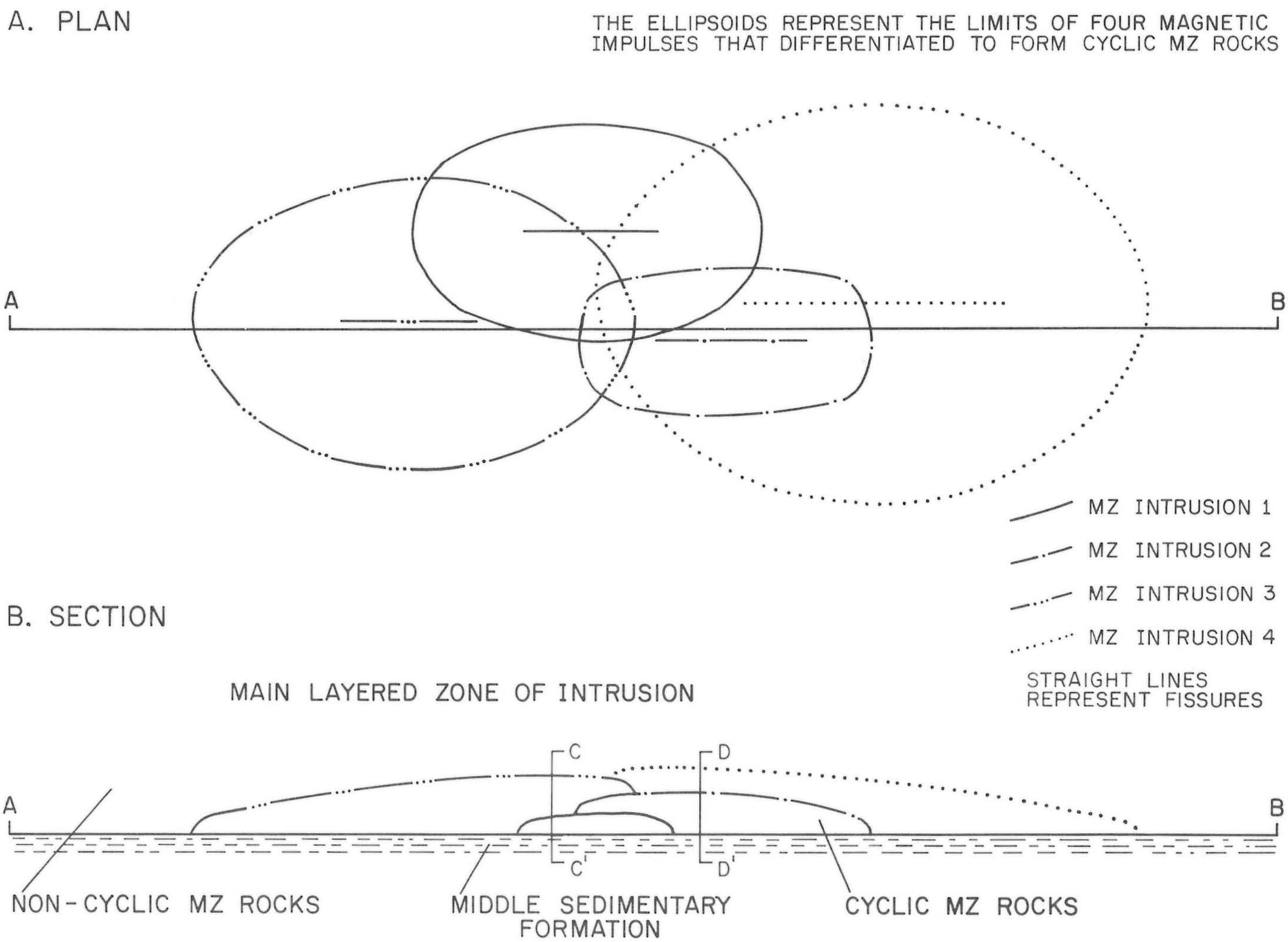


Figure 44: Sketch illustrating possible origin of cyclic and non-cyclic MZ rocks.

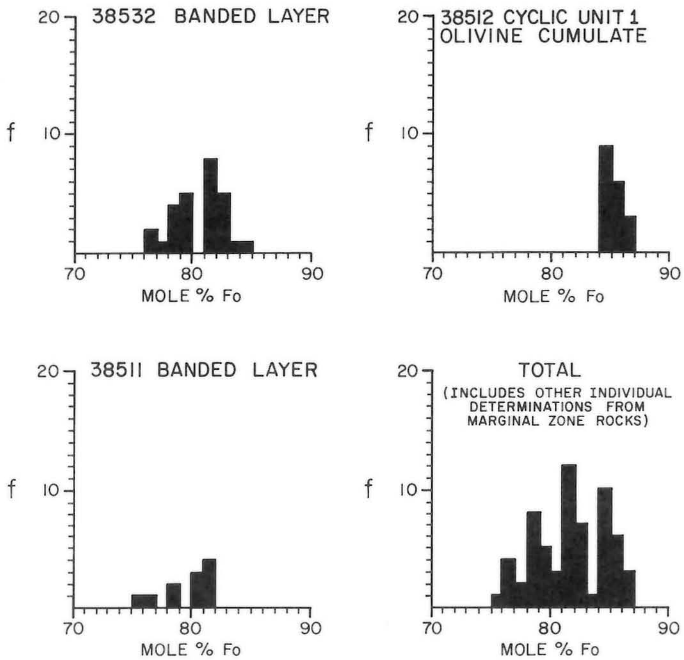


Figure 45: Olivine composition MZ rocks.

Environment of crystallization

MZ rocks have crystallized under a variety of conditions and environments. The development of rhythmic layering in some areas, and bull's-eye patterns in olivine C-axis fabric diagrams is strong evidence of magmatic currents. The range of olivine compositions within the Banded Layer (Fig. 45) is considered to reflect the possible mixing of early- and late-state olivines and consequently to reflect the dynamic character of the environment during accumulation. Other evidence for "reworking" involves observations concerning the possible redeposition of poikilitic orthopyroxene crystals. The broad range of olivine compositions in the Banded Layer contrasts with the narrow range of compositions for a homogeneous layer (Fig. 45); the latter is interpreted to represent "quiet water" conditions of crystal accumulation. Well defined girdles in olivine c-axis fabric diagrams in the homogeneous layer are further evidence of quiet water conditions.

The progressive decrease in dip of layering, inward from the contact, suggests that the intrusion may have a lopolithic or funnel shape in cross-section. Since the Fox River Sill is hosted by sedimentary rocks it is not unreasonable to assume that the initial magmatic impulse was horizontal, the magma spreading out under a cover of sedimentary rocks. Continuous rifting and successive magmatic impulses along the intrusion axis likely contributed to a progressive downwarping (graben?) of the central part of the intrusion. The progressive downward increase in dip of layering may reflect this downwarping and infilling event. Observation of changing dip within MZ rocks indicates that this change took place during the formation of MZ rocks. Rhythmic layers within the Banded Layer, that formed by deposition of crystals from magmatic density currents, are further evidence for an initial dip of the intrusion floor at the time of formation of those layers.

[1] The main magma is defined as that part of the magma where the accumulated crystals nucleated. The intercumulus liquid (magma) is liquid trapped by crystals that nucleated in the main magma and accumulated at the floor of the intrusion.

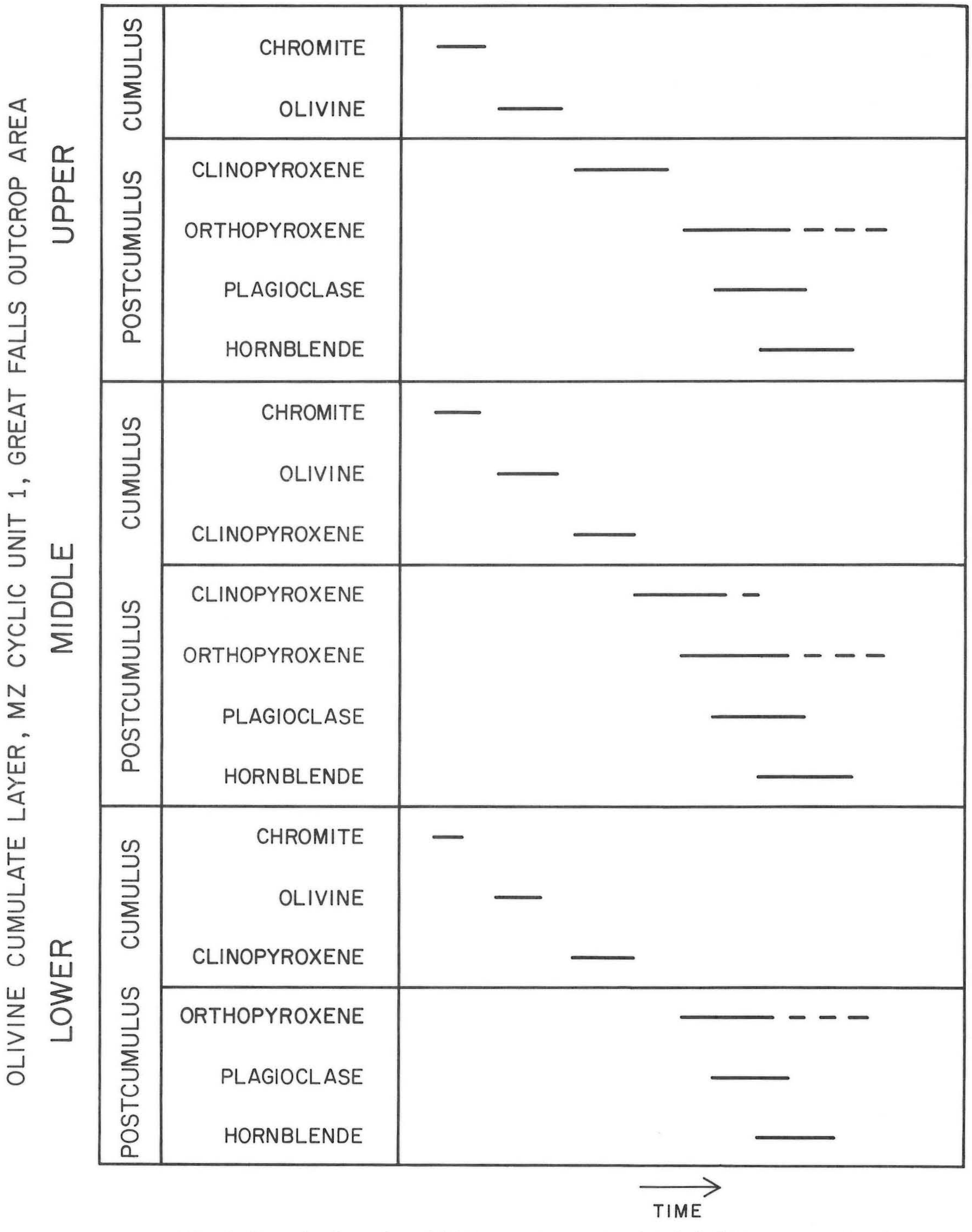
Order of crystallization

The general order of crystallization in the main magma[1] during the development of MZ cyclic units is olivine (olivine cumulate layers), clinopyroxene (clinopyroxene cumulate layers) and plagioclase (plagioclase cumulate layers) (Fig. 46). Orthopyroxene has been noted as a cumulus phase near the top of plagioclase cumulate layers of some uppermost MZ cyclic units. Thus, the order of crystallization in most MZ cyclic units is ol;cpx;pl, and in some it is ol;cpx;pl;opx, both consistent with Irvine's (1970a, 1979) crystallization order #1. Chromite is a cumulus phase associated with olivine and some clinopyroxene cumulate rocks. The order of crystallization of phases from intercumulus liquid is variable depending on the layer, and consequently, the composition of the liquid, and also the composition of the minerals with which the liquid is in contact. In olivine cumulate layers the order is clinopyroxene, orthopyroxene, plagioclase, and red-brown hornblende. In clinopyroxene cumulate layers the order is orthopyroxene, plagioclase, and red-brown hornblende. In plagioclase cumulate layers the order is orthopyroxene, red-brown hornblende. In the plagioclase and clinopyroxene cumulate layers, original cumulus clinopyroxene has been modified by postcumulus crystallization. In these examples, clinopyroxene should be added to the list of minerals crystallized from intercumulus liquid. Cumulus olivine has been modified by postcumulus crystallization in the clinopyroxene cumulate layer of cyclic unit 1.

The intercumulus liquid crystallized a different suite of minerals than the main magma. This was accomplished in part by reactions of early formed cumulus minerals with intercumulus liquid that formed new minerals. Clinopyroxene in some olivine cumulate rocks formed through reaction of olivine and liquid. Orthopyroxene was formed by reaction of olivine and/or clinopyroxene and liquid. Red-brown hornblende likely represents final crystallization of volatile-rich intercumulus liquid, although the presence of granular olivine crystals, as inclusions, suggests that some reaction between olivine and liquid to produce hornblende may have taken place.

Orthopyroxene contains olivine and clinopyroxene inclusions, and rare inclusions of plagioclase and red-brown hornblende. Plagioclase and red-brown hornblende inclusions tend to occur at or near orthopyroxene grain boundaries. This suggests that orthopyroxene crystallization may have continued for some time and in some cases eclipsing the period of crystallization of plagioclase and red-brown hornblende. The longer period of orthopyroxene crystallization is reflected in its very large grain size.

The accumulated cumulus crystals are not densely packed, resulting in a substantial volume of intercumulus material in the rocks, from approximately 25 percent in plagioclase cumulate rocks, to greater than 50 percent in some olivine cumulate rocks. The main magma and intercumulus liquid originally must have been identical in composition, however, the fact that the intercumulus liquid crystallized to produce a mineral suite that differs from that produced by the main magma, suggests that the two magmas had little or no contact. If there was diffusion between the intercumulus liquid and the overlying magma their compositions should have been similar. Jackson (1961) and Hess (1939) have pointed out that the effect of diffusion between the main magma and intercumulus liquid would be to precipitate intercumulus minerals of the same phase and composition as were being generated in the main magma above the floor of an intrusion. If the intercumulus liquid were separated from the main magma, the order of crystallization would be such that successive residual fractions would be enriched in sodium, silicon, iron and volatiles (Jackson, 1961). That the latter is the case in Fox River Sill MZ rocks is demonstrated by red-brown hornblende and rare phlogopite being the last phases to crystallize in all layers, regardless



The left end of each solid bar represents the initial crystallization (nucleation) of the crystal, and the length of the line represents the time of crystallization. Longer bars for postcumulus crystals reflect their coarser grain size.

The dashed line for orthopyroxene indicates that in some rocks the crystallization of orthopyroxene extends beyond the period of crystallization of plagioclase and hornblende.

Clinopyroxene, a cumulus phase in the lower and middle part of the layer becomes a postcumulus phase in the upper part of the layer. Cumulus clinopyroxene displays postcumulus growth in the middle part of the layer.

Figure 46: Order of crystallization in olivine cumulate layers, MZ cyclic unit 1, Great Falls outcrop area.

of the composition of the associated cumulus phases.

Thus, two periods of crystallization are interpreted to have taken place in the formation of MZ rocks:- an early crystallization of phases in the main magma that accumulated to become cumulus crystals, and later matrix or intercumulus crystallization of trapped intercumulus liquid.

Non-cyclic MZ rocks

Non-cyclic MZ rocks comprise olivine cumulates (13206, 12317) and pyroxene-plagioclase cumulates (38527). The olivine cumulates range from 12 m thick (13217) to 59 m thick (13206), and the pyroxene-plagioclase cumulate is 10 m thick (38527). These zones apparently represent areas along the south contact of the Sill where initial magmatic impulses of the kind that gave rise to cycles never existed. These noncyclic rocks, which crystallized from later magmatic injections that gave rise to thick LCLZ olivine cumulate layers, may be indicative of the liquid composition of the magmatic injection from which they were derived. The problem in estimating an original liquid composition from these rocks is that, to some extent, they are all partly cumulate.

Non-cyclic rocks that display the greatest amount of *in situ* crystallization are the olivine cumulates, where approximately 60 percent of the rock is composed of postcumulus phases. If the intercumulus liquid maintained continuous contact with the main magma, it could be representative of the liquid composition. The rocks (including cumulus olivine) were originally olivine melagabbronorite, close to plagioclase-bearing olivine websterite in composition (Fig. 47). Discounting olivine moves the composition to melagabbronorite (Fig. 47). The original liquid composition is estimated to lie somewhere between olivine melagabbronorite and melagabbronorite, and the liquid composition of the magmatic impulses that gave rise to noncyclic MZ olivine cumulates was much more basic than basalt.

The MZ represents the initial magmatic event that gave rise to a number of intrusions that fractionally crystallized to produce a number of differentiated sequences or cyclic units. A range in proportion of olivine to pyroxene to plagioclase cumulate rocks from cyclic unit to cyclic unit suggests some range in composition of the magma from which each cyclic unit crystallized. Non-cyclic MZ rocks represent areas where magma related to the main magmatic event (LCLZ-UCLZ) came in contact with host sedimentary rocks.

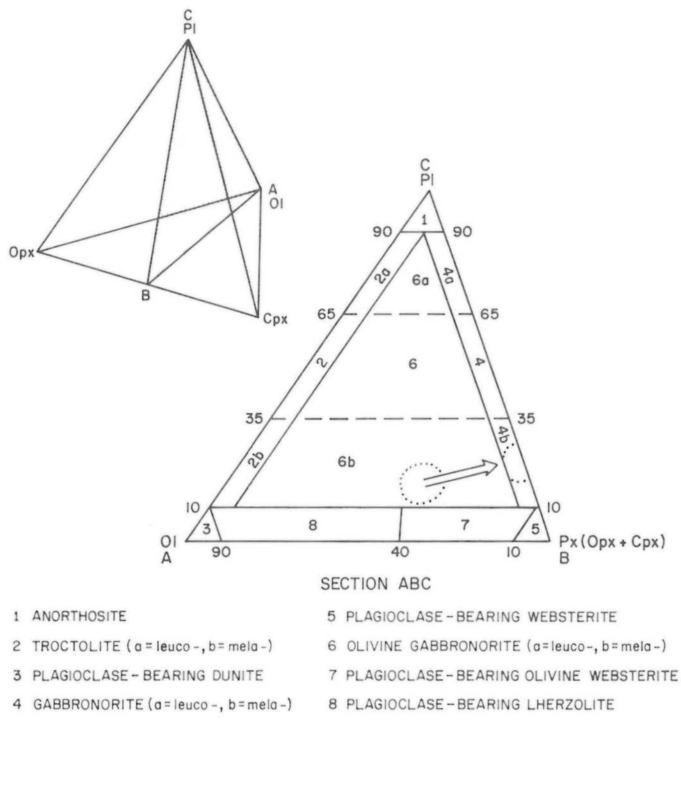


Figure 47: Portion of olivine-clinopyroxene-orthopyroxene-plagioclase diagram illustrating fields for non-cyclic cumulate rocks.

LOWER CENTRAL LAYERED ZONE

Lower Central Layered Zone (LCLZ) rocks, which represent the product of fractional crystallization of magma during the initial stages of the main magmatic event, have been found along the entire length of the west lobe of the Sill (Fig. 48 and Map GR81-1-1). The rock succession is composed predominantly of relatively thick, olivine-rich, olivine cumulate layers (original dunite) overlain by relatively thin clinopyroxene-rich, clinopyroxene cumulate layers (olivine clinopyroxenite). Each olivine cumulate-clinopyroxene cumulate pair represents a cyclic unit, and the repetitive sequence is identical to the sequence in the lower part of the main layered zone of the Muskox Intrusion (Irvine and Smith, 1967). These cyclic units are interpreted as beheaded or incomplete units (Jackson, 1970) on the basis that several cycles in the upper part of the LCLZ possess an uppermost plagioclase cumulate layer. These beheaded cyclic units are considered to represent interruptions in the process of fractional crystallization caused by influxes of fresh magma into the chamber, that in turn cause a resetting or starting over of the fractional crystallization process.

For purposes of description the LCLZ has been divided into a lower part, a middle and upper part, and western and eastern extremities.

LOWER PART

GREAT FALLS OUTCROP AREA

LCLZ rocks are exposed in the rapids and falls of the Great Falls outcrop area on the Fox River (Fig. 6 and 49). Twelve layers, exposed over approximately 760 m, represent about 730 m of true section thickness, based on an average layer dip of 75 degrees north. The layers are exposed intermittently across a width of approximately 600 m in the braided stream complex (Plate 30). The contact between LCLZ and MZ rocks is not exposed; however, in one area, MZ cyclic unit 3 plagioclase cumulate (gabbronorite) is overlain by clinopyroxene cumulate (websterite), that in turn grades into an olivine + clinopyroxene cumulate. The gradation takes place over approximately 6 m in discontinuous outcrop. The olivine + clinopyroxene cumulate (wehrlite) constitutes the lower zone of the lowermost LCLZ layer in the Great Falls outcrop area.

In this area, LCLZ rocks consist of serpentinites, originally olivine cumulates, and olivine clinopyroxenites (clinopyroxene ± olivine cumulates), the latter forming narrow (6 m) resistant ridges that give rise to waterfalls (Plate 30). The rocks have been grouped into olivine cumulate-clinopyroxene cumulate pairs, with each pair representing a cycle of fractional crystallization and crystal accumulation. Five pairs or cyclic units and the lowermost portion of the olivine cumulate part of a sixth cycle are exposed (Fig. 49). The term "cyclic unit" is used here in the same sense as that proposed by Jackson (1961), to describe repeated sequences of sharply defined layers. Contacts between olivine and clinopyroxene cumulates (upper and lower contacts) are gradational over 40 cm to 1 m.

The abundance of olivine-rich cumulates and the presence of olivine cumulate (dunite) - clinopyroxene cumulate (clinopyroxene) cyclic units characterizes LCLZ rocks in this area.

Individual serpentinite layers range in thickness from 30 m to approximately 225 m, and are among the thickest layers of the exposed units of the Sill. The rocks are highly weathered and consequently most outcrops are poor quality. They are massive and dark to light apple-green and contain many crosscutting serpentine ± magnetite veinlets that render a boxwork effect to many of the outcrops.

Individual clinopyroxenite layers form resistant ridges that give rise to topographic linears that can be traced easily across the width of the braided stream complex (Plate 30). The layers are relatively narrow compared to the serpentinites and range from 6 to 12 m thick.

CYCLIC UNIT 1

Olivine cumulate layer

Cyclic unit 1 olivine cumulate layer is composed of a lower zone (about 45 m thick) that forms a transition between the MZ and the main zone of the layer. Rocks of the lower zone have a grey green to buff

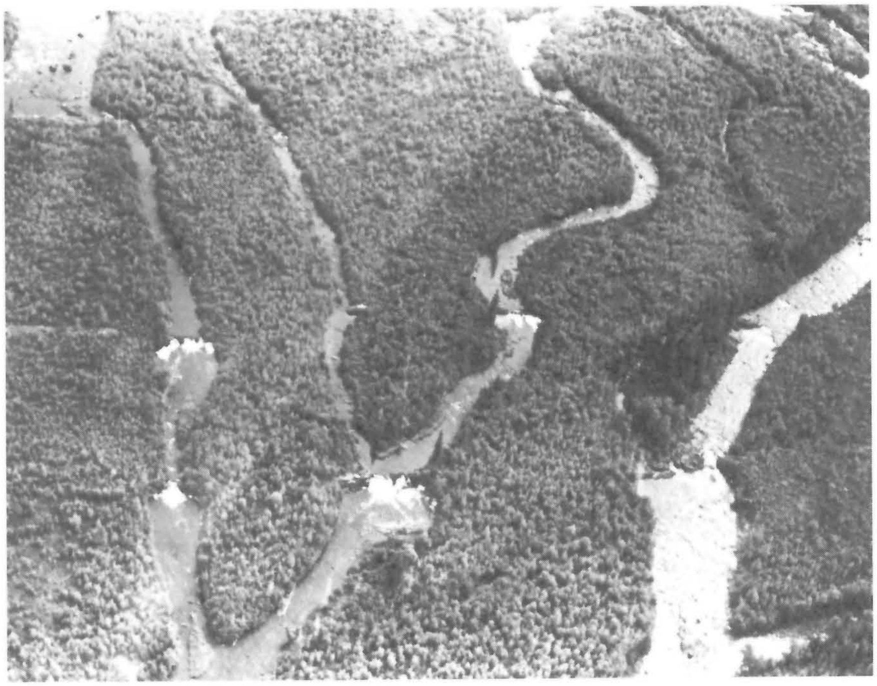
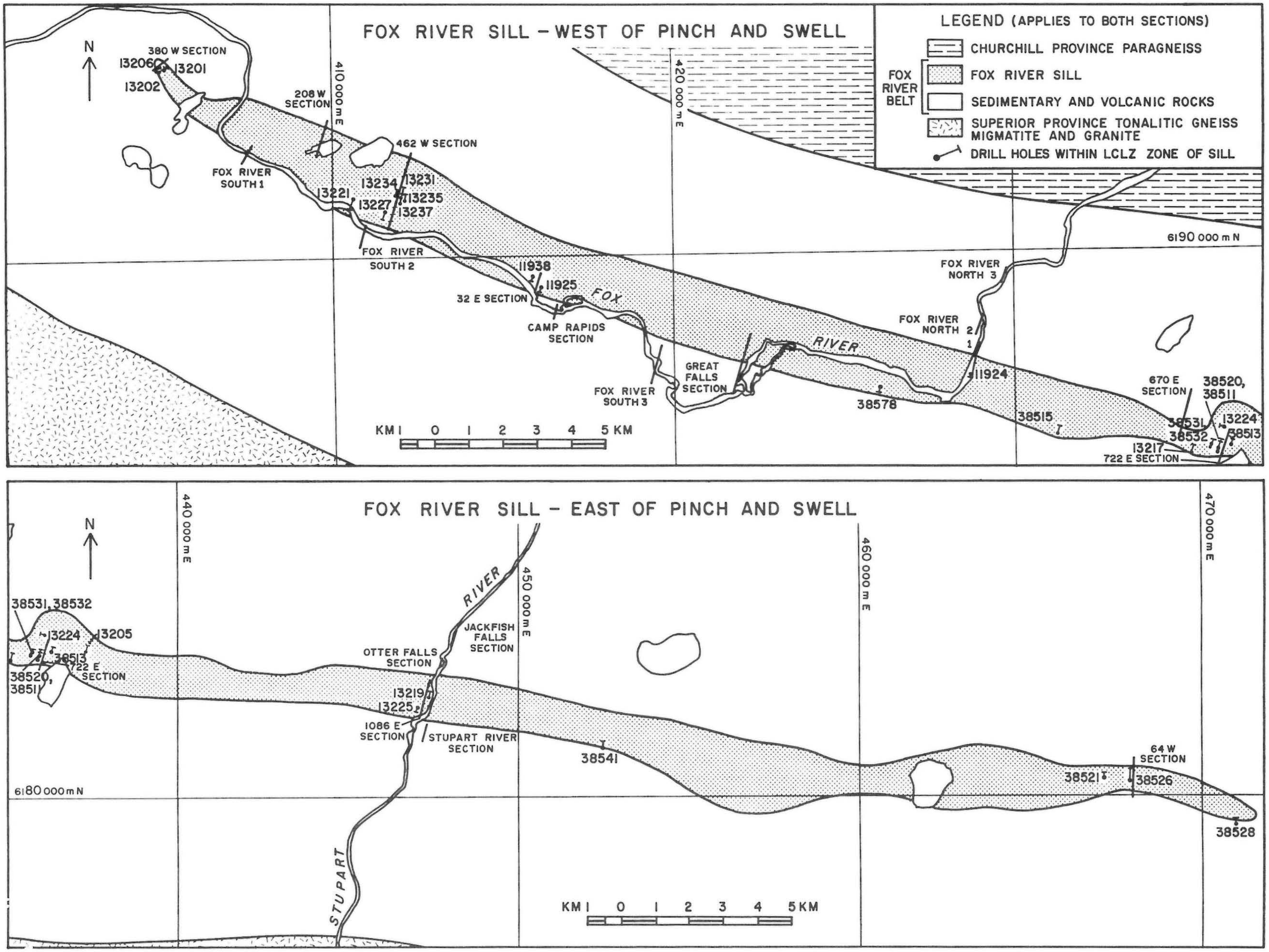


Plate 30: Braided stream complex, Great Falls outcrop area. This oblique aerial photograph (looking south) illustrates the resistant nature of the clinopyroxene cumulate layers that cap LCLZ cyclic units. The set of waterfalls at the bottom of the photo is caused by the clinopyroxene cumulate layer of LCLZ cyclic unit 3. Great Falls outcrop area, Fox River.

Figure 48: Drill hole and outcrop locations LCLZ.



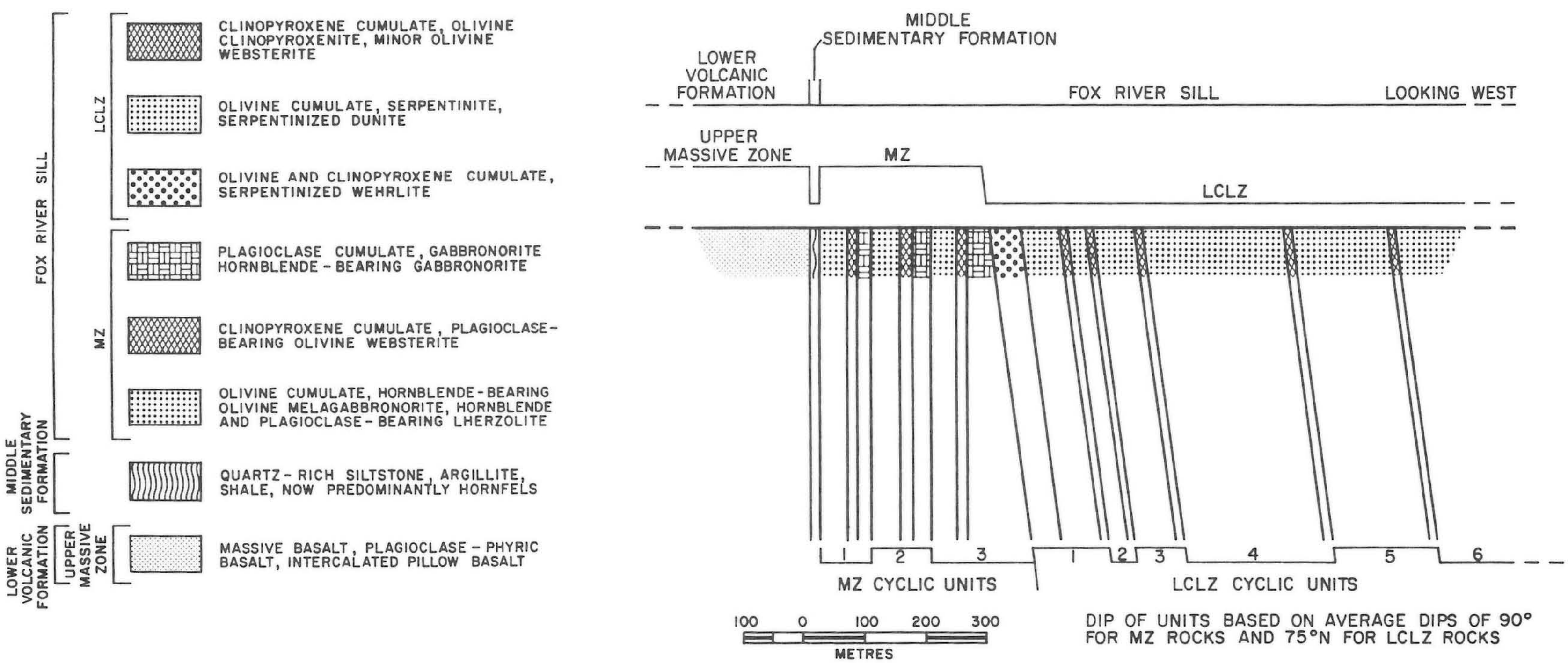


Figure 49: Cross-section, Great Falls outcrop area.

weathered surface and a dark green, mottled fresh surface characterized by numerous parallel serpentine veinlets. The mottled character and serpentine veinlets give this rock a distinctive appearance on the fresh surface.

Much of the lower zone was originally an olivine + clinopyroxene cumulate, although cumulus plagioclase and postcumulus orthopyroxene and red-brown hornblende occur in rocks at the base of the zone in one area. This illustrates the transitional nature of the zone, whereby its base is composed of the complex mineralogy and textural characteristics of MZ rocks, whereas the rest of the zone is composed of olivine (+ chromite) and clinopyroxene, an assemblage that reflects the simple mineralogy diagnostic of LCLZ rocks.

Clinopyroxene is preserved throughout the zone. Olivine is only partly preserved near the base of the zone, otherwise it has been completely altered to curtain-growth serpentine. The ratio of olivine to pyroxene was approximately 1:1 and the rocks are serpentinized wehrlites. Disseminated, euhedral chromite makes up 1 percent of the rock, and patches and discontinuous veinlets of magnetite are associated with the curtain-growth serpentine.

Rocks of the main zone weather dark greenish brown to buff and are dark apple-green to olive-green on the broken surface. The original texture is reasonably well preserved despite complete serpentinization of the primary assemblage. The rock originally was olivine-rich and intercumulus space between olivine crystals was 5 percent or less. Olivine crystals possessed rounded polyhedral shapes and averaged 1 mm in long axis dimension with some crystals up to 2.5 mm. The intercumulus areas were originally occupied by clinopyroxene that formed oikocrysts and that contained euhedral chromite crystals. Secondary magnetite forms irregular patches and discontinuous veinlets. The rock was originally a dunite.

Clinopyroxene cumulate layer

The rock weathers grey green to grey buff, possesses a dark green fresh surface and is composed of irregularly shaped clinopyroxene crystals that form a complicated, interlocking crystal mosaic. Postcumulus orthopyroxene, plagioclase and minor postcumulus, irregularly shaped olivine crystals constitute less than 10 percent of the rock. The rock, which is well preserved with olivine and plagioclase only partly recrystallized, is a plagioclase-bearing websterite.

CYCLIC UNIT 2

Olivine cumulate layer

The rock is exposed in one location where it forms low, highly weathered outcrops at the river's edge. The serpentinite is brownish apple-green on weathered and broken surfaces, and is considered to represent completely serpentinized dunite.

Clinopyroxene cumulate layer

The clinopyroxenite forms a 6 m thick layer (Plates 31 and 32) that weathers buff brown and has a dark green fresh surface. Many of the irregularly shaped clinopyroxene crystals have strongly interdigitated contacts with adjacent crystals that result in complex crystal relationships. The irregular shape of the crystals and their interdigitated contacts imply substantial postcumulus clinopyroxene crystallization. The absence of inclusions in the irregularly shaped olivine crystals suggests that they may also have been cumulus and had their shapes modified by postcumulus crystallization. The rock, which consists of clinopyroxene and olivine in the approximate proportion 95:5, is an olivine clinopyroxenite.

CYCLIC UNIT 3

Olivine cumulate layer

The serpentinite has a buff weathered surface and a dark apple-green to olive-green broken surface. The rock appears to have been

Plate 31: Clinopyroxene cumulate layer of LCLZ cyclic unit 2, forming a waterfall in the braided stream complex. The layer ranges between 3.0 and 4.0 m high. The low area in the foreground is underlain by the olivine cumulate (original dunite, now serpentinite) of LCLZ cyclic unit 3. Great Falls outcrop area, Fox River.

Plate 32: *As Plate 31. Smooth face on downstream side is joint surface that is parallel to layer dip.*

a dunite with less than 5 percent postcumulus clinopyroxene, although the original texture is not well preserved by the mesh-texture serpentine. The original olivine crystals appear to have been polygonal and this suggests substantial adcumulus growth and consequent modification of olivine crystal morphology. Disseminated euhedral chromite constitutes one percent of the rock.

Clinopyroxene cumulate layer

The clinopyroxenite that forms a 6 m thick layer, has a buff weathered surface and a dark green fresh surface. In one part of the layer the rock is composed of a mosaic of irregularly shaped clinopyroxene crystals, many with interdigitated and/or serrated contacts. Approximately 500 m west, along strike, the rock is composed of polygonal clinopyroxene crystals with simple crystal boundary relationships, thus indicating that textural relations vary along strike in the layer. Olivine forms irregularly shaped crystals that lack inclusions.

CYCLIC UNIT 4

Olivine cumulate layer

The serpentinite forms a layer approximately 225 m thick (Plate 33) and possesses a buff weathered surface, has an earthy, lustreless apple-green broken surface and is composed almost entirely of mesh-textured serpentine. The lack of magnetite makes it difficult to discern the shapes of the original olivine crystals; however, there does not appear to have been any intercumulus space. In some rocks the original olivine crystals appear to have formed large (up to 4 mm) polygonal crystals, with simple crystal contacts. Disseminated euhedral chromite crystals (0.2 mm) constitute up to 4 percent of some rocks. The rock was originally a dunite.

Clinopyroxene cumulate layer

The clinopyroxenite forms a layer approximately 10 m thick and, with individual crystals up to 4 mm in size, is somewhat coarser grained than other clinopyroxenites. The polygonal crystals have simple grain boundary relationships, and the rock possesses a texture similar to that observed in the clinopyroxenite layer of cyclic unit 3. The rock is an olivine clinopyroxenite.

CYCLIC UNIT 5

Olivine cumulate layer

The serpentinite weathers grey green to buff and possesses an apple-green broken surface. The original rock was composed of polygonal olivine crystals up to 4 mm in size that have been completely converted to mesh-texture serpentine. There is no interstitial space and the original rock was a dunite. Euhedral chromite crystals constitute 3 percent of the rocks.

Clinopyroxene cumulate layer

The clinopyroxenite forms an 8 m thick layer, has a grey green to buff weathered surface, a dark olive-green fresh surface with individual crystals up to 4 mm in size. Olivine, as irregularly shaped crystals constitutes 10 percent of the rock. Compared to other clinopyroxene layers in the Great Falls outcrop area this layer is coarse grained and olivine is slightly more abundant. The polygonal clinopyroxene crystals possess simple grain boundary relationships. Sulphide minerals, dominantly pyrrhotite, make up 5 percent of the rock in one part of the outcrop.

Plate 33: *Thick olivine cumulate layer (more than 225 m thick) of LCLZ cyclic unit 4. Photo taken looking north (downstream). Great Falls outcrop area, Fox River.*

CYCLIC UNIT 6

Olivine cumulate layer

The serpentinite weathers green to buff and has an apple-green fresh surface. It was originally composed of equidimensional to elongate polygonal olivine crystals up to 4 mm in long axis dimension. The rock is composed of mesh-textured serpentine. Disseminated euhedral chromite constitutes one percent of the rock.

OLIVINE COMPOSITIONS

Olivine compositions display a progressive increase in Fo-content stratigraphically upward in Great Falls outcrop area LCLZ rocks (Fig. 50), and they are slightly more Fo-rich than MZ olivines (Fig. 51). Most of the compositions were determined on olivines of clinopyroxenites, as the olivines of the original dunites have been totally serpentinized. Olivine determinations were made on three samples from widely separated locations along strike in each of two different layers (strike separation up to 500 m), yet the olivine compositions from the individual determinations within each layer have a limited range (0.8 percent Fo in the clinopyroxenite layer of unit 3 and 1.4 percent Fo in the clinopyroxenite layer of unit 2). In clinopyroxenite, olivines occur as irregularly shaped interstitial crystals. The lack of inclusions suggests that olivines were original cumulus crystals whose shapes were modified by adcumulus growth.

722E SECTION - DRILL HOLES 38513, 38520, 38531 AND 38532

Drill holes of 722E section (Fig. 52) intersect a sequence of LCLZ serpentinites and in contrast to LCLZ rocks of the Great Falls outcrop area, this sequence of serpentinites does not contain narrow clinopyroxenite layers. However, it should be noted that the true thickness of serpentinite intersected is estimated to be 135 m, a width substantially less than the thickest serpentinite (olivine cumulate) layer observed in the Great Falls outcrop area. The lack of clinopyroxenite layers or other distinctive layers makes correlation between drill holes difficult. Correlation is based on megascopic comparison of drill core and the subdivision of serpentinite into rocks that were originally dunite (less than 10 percent postcumulus pyroxene $\pm$ plagioclase), or originally peridotite (more than 10 percent postcumulus pyroxene $\pm$ plagioclase). Further difficulty in correlation is caused by the availability of telescoped core for drill hole 38513. The rubbly nature of much serpentinite core has resulted in petrographic data being determined for 38532 and 38520 only.

LCLZ rocks

Black foliated serpentinite

The rock is characterized by parallel serpentine veinlets and by an abundance of secondary magnetite. The parallel serpentine veinlets contribute to the rock fabric (Figs. 53, 54 and 55), and the abundance of magnetite (up to 10 percent of some rocks) contributes to the rock's dark colour. Numerous breccia zones have resulted in an abundance of broken and rubbly core. The strong fabric, presence of slickensided surfaces, and abundance of picrolite-carbonate breccia zones are evidence of movement.

In most rocks, the abundance of secondary magnetite (up to 10 percent) and serpentine veinlets masks the primary rock texture. Serpentine occupying intercumulus areas is interpreted as clinopyroxene bastite on the basis of inherited parting that characterizes Fox River Sill clinopyroxene. Chlorite in intercumulus areas likely replaces original postcumulus plagioclase. Disseminated, euhedral chromite ranges from 1 to 3 percent. The black foliated serpentinite is interpreted to have been derived from an original plagioclase-bearing wehrlite.

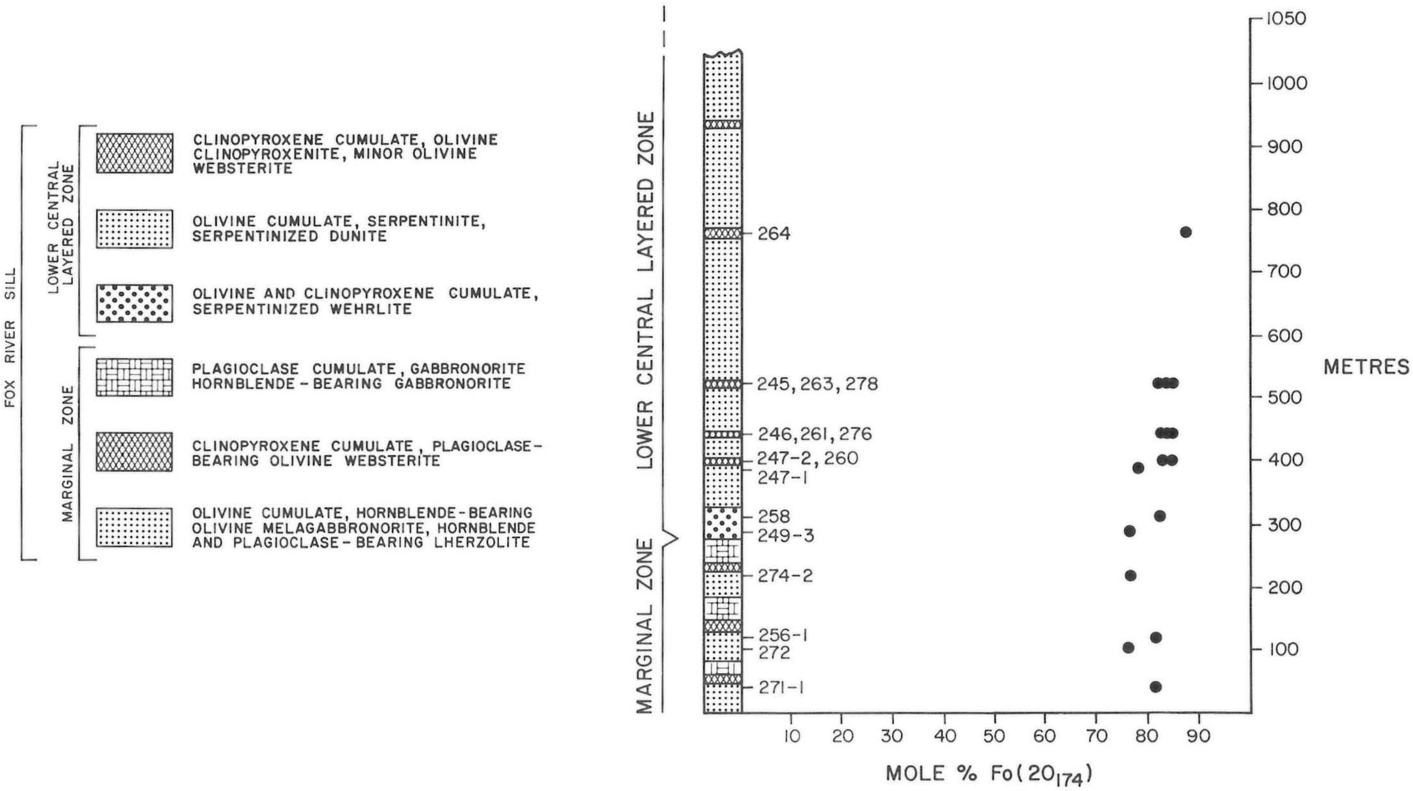


Figure 50: Olivine compositions, LCLZ rocks, Great Falls outcrop area.

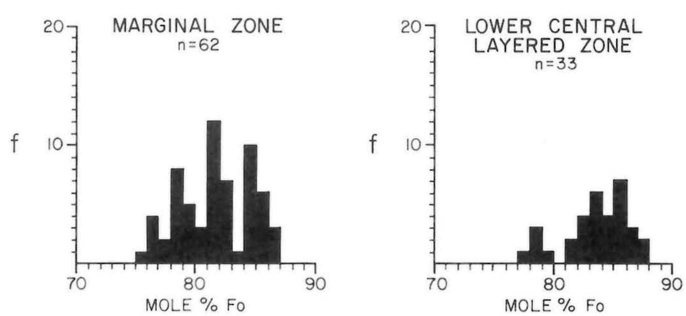


Figure 51: Comparison of olivine compositions, MZ and LCLZ.

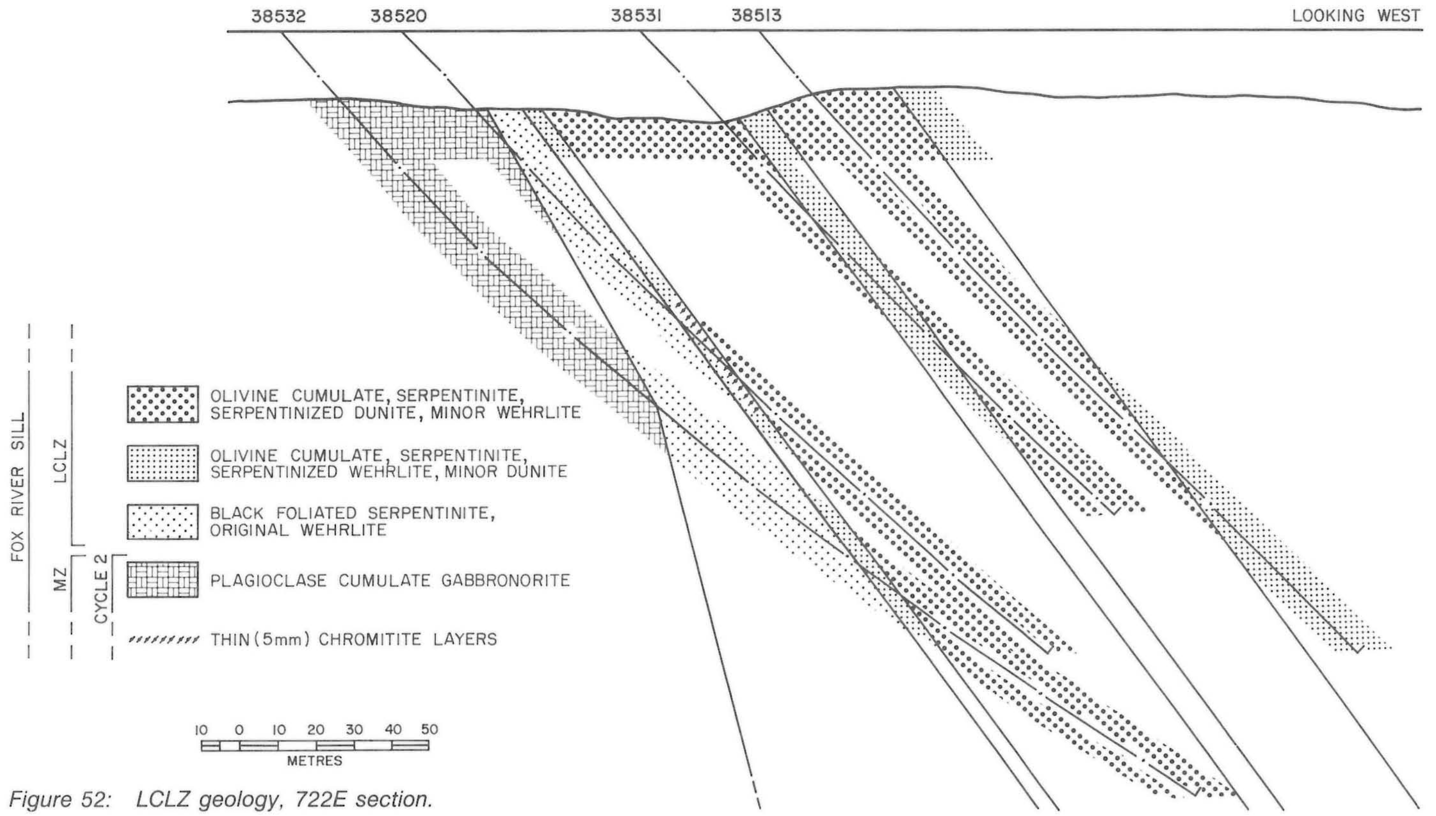


Figure 52: LCLZ geology, 722E section.

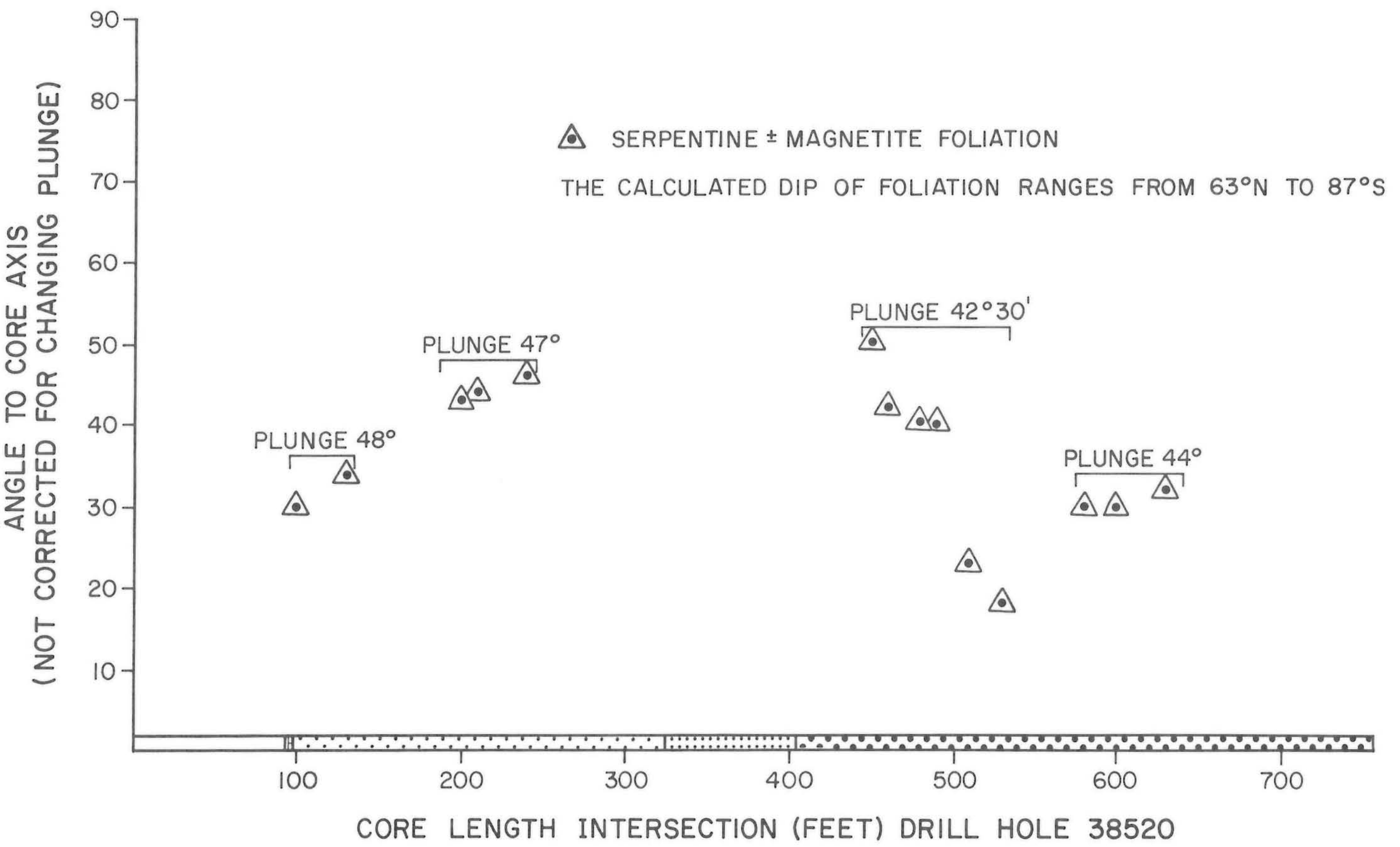


Figure 53: Core axis angles to planar structures, drill hole 38520.

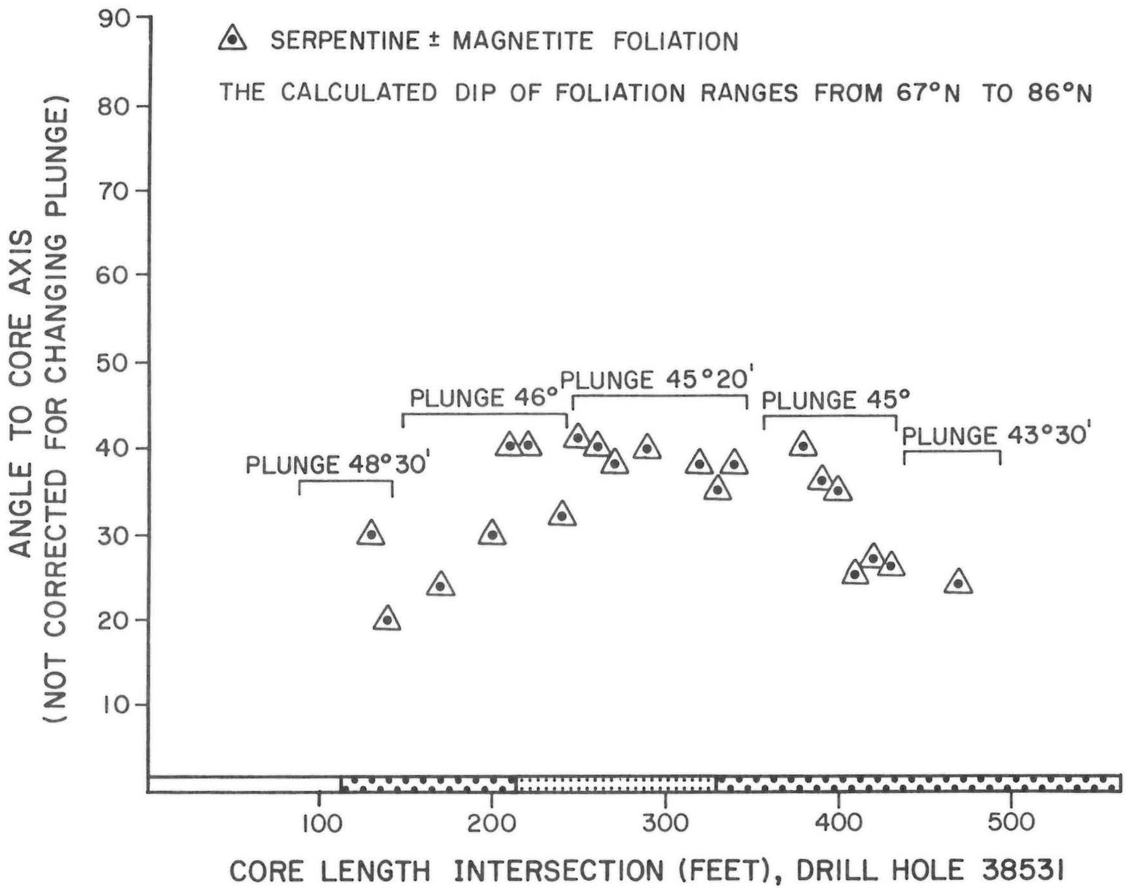


Figure 54: Core axis angles to planar structures, drill hole 38531.

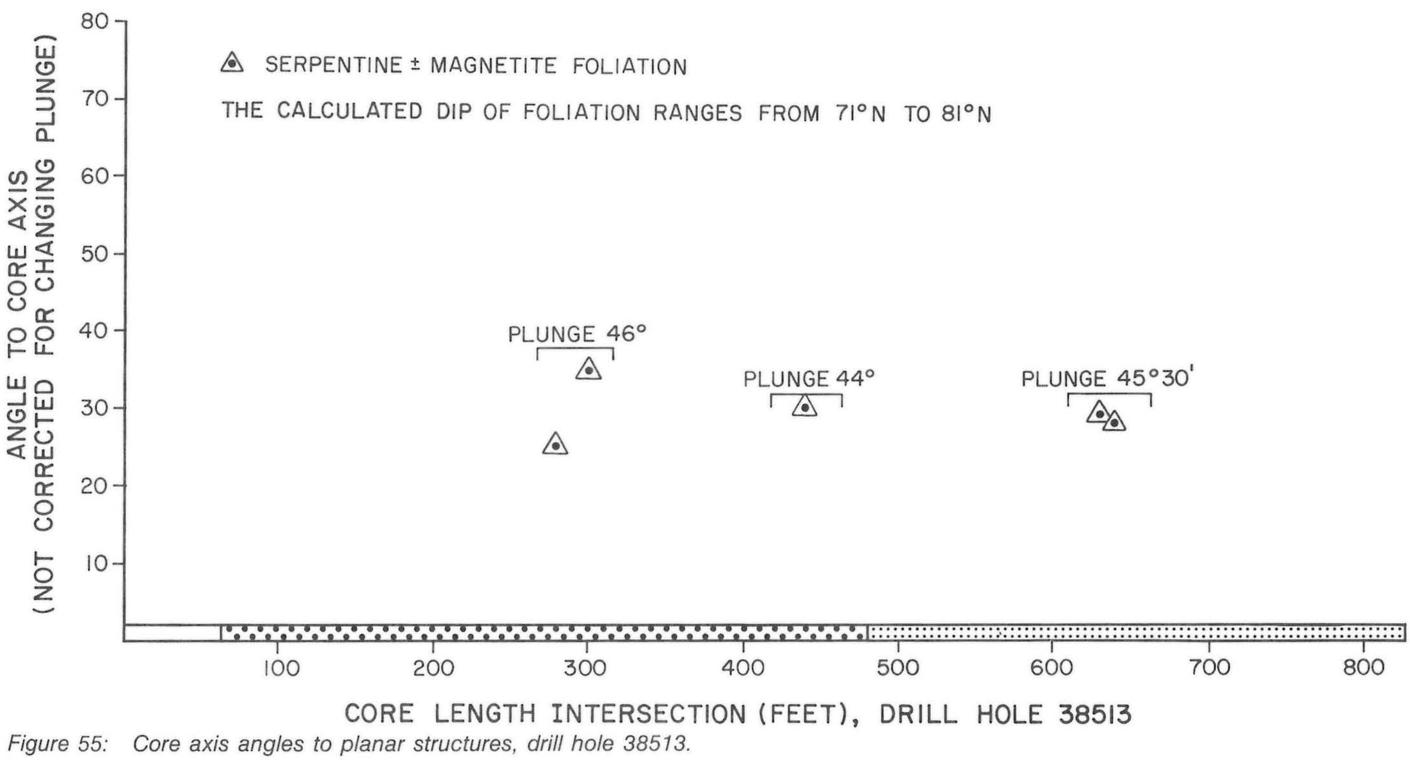


Figure 55: Core axis angles to planar structures, drill hole 38513.

Serpentinite (olivine cumulate)

The contact between black foliated serpentinite and black to greenish-black serpentinite is gradational over 5 m (core length interval). LCLZ serpentinites range from dark greenish black, and dark apple green to medium and light apple green. Rocks that were originally peridotite tend to be slightly darker than those that were originally dunite. However, in some cases, a change from apple green to black may take place abruptly over 1 to 2 cm without an accompanying change in original lithology. In many rocks, the primary texture is discernible megascopically. Changes in rock type from dunite to peridotite are gradational over widths of several centimetres to several metres. Within portions of drill holes logged as original dunite, a number of 10 to 20 cm (core length interval) zones of peridotite commonly occur. Conversely, within original peridotite, narrow widths of dunite are common. Waxy brittle serpentine (logged as picrolite) ± carbonate form numerous zones throughout the serpentinite. These zones result in intervals of lost core and/or intervals of broken and rubbly core.

The serpentinites were originally olivine-rich olivine cumulate rocks. In rocks that were originally dunite, the serpentine pseudomorphs after olivine display heterogeneous grain size and shape. The grain size of the original olivine crystals averages between 1 and 2 mm; however, large individuals up to 3 mm may occur and an exceptional crystal 1 cm long was observed. The olivines ranged from polyhedral to granular to polygonal.

The equidimensional polygonal shape of original olivine crystals precludes determination of an original olivine fabric. However, the relationships previously observed between secondary serpentine veinlets, curtain-growth serpentine, and orientation of original elongate olivine crystals have been observed in some 722E section LCLZ rocks. Some serpentine ± magnetite veinlets and curtain-growth serpentine appear to be parallel with the preferred orientation of elongate olivine crystals, whereas in other rocks in the same drill hole curtain-growth serpentine and serpentine ± magnetite veinlets are at right angles to the preferred orientation of originally elongate olivine crystals.

The original olivine crystals have been altered to mesh-textured serpentine. Curtain-growth serpentine is common and some rocks are composed of mesh-texture and curtain-growth serpentine. Hourglass serpentine is present but not common. Clinopyroxene bastite, recognized by its inherited parting, preserves the character of original clinopyroxene oikocrysts. Chlorite occupies intercumulus areas and likely has replaced original postcumulus plagioclase. Phlogopite ± chlorite is sporadically developed in intercumulus areas as is fine grained plate-like serpentine and microcrystalline serpentine. Late stage, parallel serpentine veinlets are well developed throughout the serpentinite sequence. Where there is a great number of these veinlets the original character of the rock is difficult to discern. Secondary magnetite commonly ranges from 1 to 3 percent and forms irregular patches and discontinuous veinlets that parallel the late serpentine veinlets. In one rock, fine grained, dusty magnetite completely occupied former intercumulus areas between original olivine crystals. Pyrrhotite forms irregular crystals (less than 1 percent) associated with magnetite in a few rocks. A fine grained, brown crystalline mineral has been identified by X-ray as brugnatellite. Apart from the concentration of chromite in the chromite layers, chromite forms discrete euhedral crystals or clusters of crystals that make up from less than 1 to 4 percent of the rock.

Chromitite layers

Two thin chromite layers observed in 38520 (Plates 34 and 35) in an interval of broken core are 1.5 and 4 mm thick, respectively. The rock adjacent to the chromitite layers contains up to 10 percent chromite as dense clusters of crystals occupying the intercumulus area between olivine crystals. Because of the broken nature of the core, the overall thickness of chromite-rich rocks is not known, although it likely does not exceed 10 cm. Similar chromite concentrations have not been found in the other 722E section holes. As the interval of chromite concentration is probably 10 cm or less, it is possible that it could be missed in areas of broken and rubbly core. An analysis of a chromite concentrate from one of these chromite layers is listed in Table 14.

32E SECTION - DRILL HOLES 11925 and 11938

Drill hole 11925

The contact between MZ and LCLZ rocks was intersected by drill hole 11925 (Fig. 56). Brecciated rocks at the contact suggest that the contact may be a fault. LCLZ rocks were dominantly original olivine cumulates (serpentinites) that ranged in composition from wehrlite to dunite. A narrow olivine clinopyroxenite layer marks the end of the lowermost LCLZ cyclic unit in this area (Fig. 35).

CYCLIC UNIT 1

Olivine cumulate rocks display a progressive change in composition from the MZ contact inward (upward) to the clinopyroxene cumulate. This is reflected in a change from medium grey to grey, granular and mottled rocks (mottled wehrlite) to grey and grey-green rocks (wehrlite) with carbonate breccia zones, to predominantly apple-green rocks (dunite-wehrlite).

Mottled wehrlite is distinguished by numerous 2 to 3 mm crudely equidimensional clinopyroxene and plagioclase oikocrysts containing numerous inclusions of polyhedral to granular olivine. These oikocrysts give rise to a distinctive mottled or spotted rock. Olivine is locally preserved although for the most part it has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. Chlorite ± epidote replaces original plagioclase. Secondary magnetite constitutes up to 5 percent of the rock and forms clot-like masses with chlorite in intercumulus areas.

Original wehrlite and dunite are essentially similar to mottled wehrlite, but contain less intercumulus space, and are more highly recrystallized. Original clinopyroxene oikocrysts have been replaced by chlorite ± magnetite giving rise to bastite-like pseudomorphs. Shapes of original olivine range from polyhedral to granular and patches of polygonal crystals are common in original dunites. Although olivine has been replaced by parallel curtain-growth serpentine, an original preferred orientation of olivine is not obvious. Disseminated chromite constitutes from 1 to 3 percent of the rock.

A 5.5 m (approximate true thickness) grey green, granular olivine clinopyroxenite marks the termination of the lowermost LCLZ cyclic unit in this area.

CYCLIC UNIT 2

The lowermost part (33 m, approximate true thickness) of the olivine cumulate layer of the second LCLZ cyclic unit is exposed in the upper part of the hole. The rocks are grey green to greyish apple green and were originally dunite. Mesh-texture, hourglass and curtain-growth serpentine pseudomorphs after original polygonal olivine crystals are dominant.

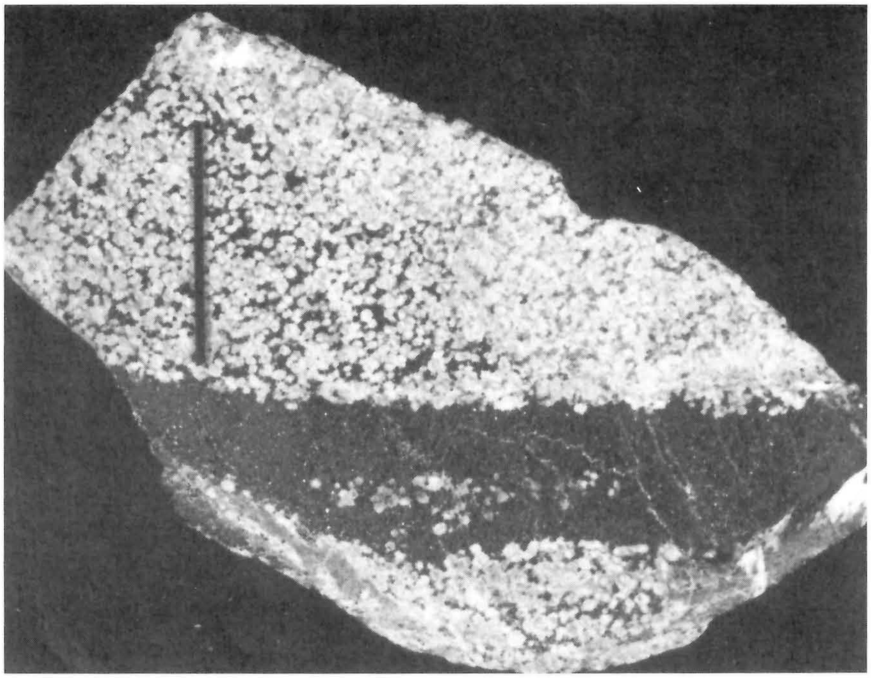
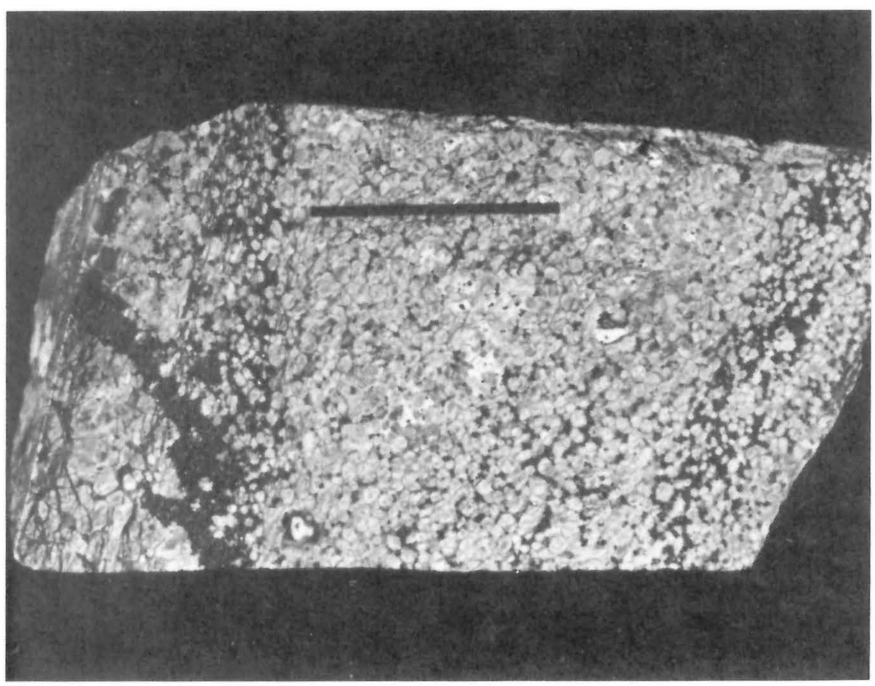


Plate 34: Chromitite layer and heavily disseminated chromite in an olivine-rich, olivine cumulate (original chromiferous dunite). Note scalloped nature of contacts. Black bar is 1.0 cm long. LCLZ, olivine cumulate, DDH 38520-394.0.

Plate 35: As Plate 34. Heavily disseminated chromite in original chromiferous dunite. Sample from same area of broken core as that illustrated in Plate 34. Black bar is 1.0 cm long.



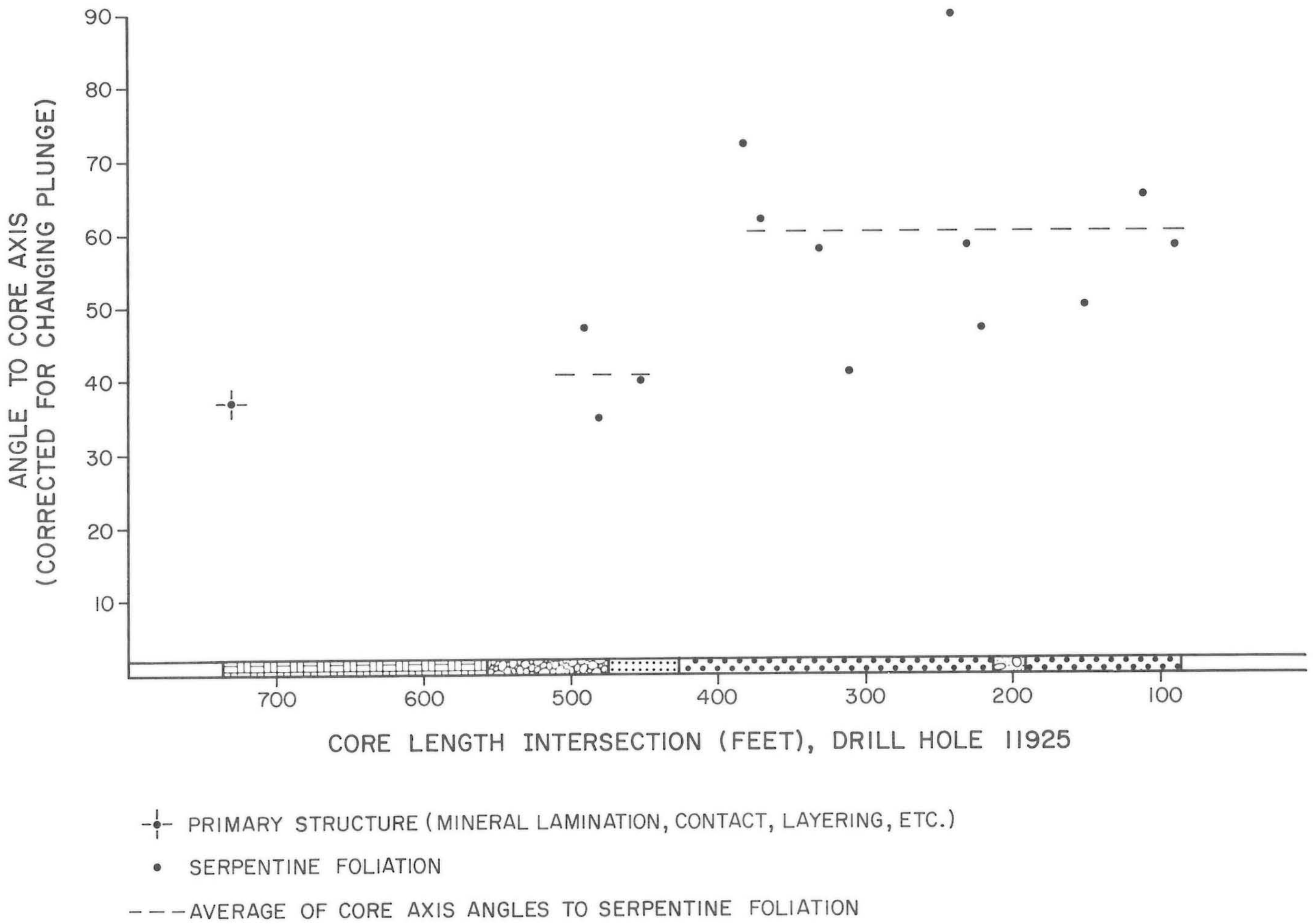


Figure 56: Core axis angles to planar structures, drill hole 11925.

Drill hole 11938

Drill hole 11938 intersects 187 m (core length) of greenish-grey, grey green and apple green LCLZ serpentinized dunite. The rocks are uniform in grain size (original olivine crystals about 1 mm) and texture (mosaic of polygonal olivine crystals), the single variation being a progressive change in colour from apple green at the top of the hole, through grey green, to greenish grey at the base. This section of serpentinized dunite represents a portion of the olivine cumulate layer of a relatively thick LCLZ cyclic unit. Thin sections were not prepared from the weathered small diameter (EX) drill core.

OTHER DRILL HOLES

Drill hole 13221

The lowermost 142 m (approximate true thickness) of LCLZ rocks intersected by drill hole 13221 is composed of two incomplete or beheaded cyclic units (olivine cumulate-clinopyroxene cumulate), and a thick portion of the olivine cumulate of the next cyclic unit (Fig. 30). Successive cycles (the cycles are numbered from the MZ contact inward or northward) become progressively thicker: cycle 1, 12 m; cycle 2, 36 m; and a part of the olivine cumulate layer of cycle 3, about 94 m.

CYCLIC UNIT 1

Olivine cumulate layer

The original olivine cumulate ranges from grey, mottled and granular to dark greenish black and waxy. Polyhedral to granular olivine and euhedral chromite (1 to 2 percent) were the original cumulus phases. Clinopyroxene forms large oikocrysts, and orthopyroxene, partly replaced by talc, forms irregularly shaped, poikilitic plate-like crystals. Some clinopyroxene has been replaced by clinopyroxene bastite. Chlorite patches in intercumulus areas replace original postcumulus plagioclase. Red-brown hornblende forms smaller oikocrysts, and phlogopite $\pm$ magnetite occupies small intercumulus areas. The uneven distribution of postcumulus minerals contributes to the heterogeneous character of the rock. The original rock ranged in composition from hornblende- and plagioclase-bearing lherzolite to plagioclase-bearing wehrlite.

Clinopyroxene cumulate layer

The clinopyroxene cumulate is grey green and granular, and consists of an aggregate of irregularly shaped clinopyroxene crystals. The rocks are distinguished by polycrystalline aggregates with individual crystals displaying complex interdigitated mutual contacts.

Regularly shaped elliptical areas, now occupied by colourless chlorite, replace original olivine. Sparsely disseminated opaque minerals include chromite and sulphide. A few chlorite-filled fractures and locally developed strain extinction have been observed.

CYCLIC UNIT 2

Olivine cumulate layer

The original olivine cumulate is dark greenish black and waxy, and was composed originally of cumulus polyhedral to granular olivine and euhedral chromite. The original olivines display preferred orientation in a few rocks. It has been noted that the grain size of chromite in intercumulus areas is commonly from 0.1 to 0.2 mm, whereas chromite contained as inclusions in olivine is usually less than 0.05 mm. Clinopyroxene, now clinopyroxene bastite, formed large (5 to 7 mm) oikocrysts along with plagioclase that has been converted to chlorite. Olivine has been pseudomorphously replaced by mesh-texture serpentine, and in places by curtain-growth serpentine. The latter is developed at right angles to the direction of olivine elongation and consequently enhances the lamination. In some rocks, late stage magnetite ± serpentine veinlets develop parallel to the lamination direction. The olivine cumulate rocks were originally plagioclase-bearing wehrlite.

Clinopyroxene cumulate layer

The clinopyroxene cumulate layer is predominantly grey green and granular, and contains olivine cumulate interlayers toward its upper contact. The underlying olivine cumulate at the contact is characterized by large euhedral chromite crystals (up to 1 mm) that occupy the intercumulus areas between the original polyhedral olivine crystals. Chromite is absent in the clinopyroxenite and the contact is sharp, although clusters of cumulus olivine occur in the clinopyroxenite. At the contact the original clinopyroxenite appears to have been composed of regularly shaped, prismatic crystals. Clinopyroxene has been replaced by a peculiar alteration composed of chlorite and a sphene-like, partly opaque mineral.

In the lower part of the layer, the clinopyroxene cumulate displays a highly variable texture that ranges from equidimensional to prismatic cumulus crystals, to polygonal crystals with simple mutual contacts forming a crystal mosaic, to polycrystalline aggregates with individual crystals displaying complex interdigitated mutual contacts. Olivine, a cumulus phase, and plagioclase, a postcumulus phase, are partly preserved. Large (up to 1 cm) irregularly shaped, poikilitic orthopyroxene crystals containing numerous clinopyroxene inclusions are sporadically distributed throughout the rock, as are pinpoint sulphide grains.

An examination of the orientation of cumulus phases from the lower part of the layer has revealed that olivine c-axes define a maximum and a partial girdle (Fig. 57), and clinopyroxene c-axes, in the same thin section, define a girdle with two less well defined maxima (Fig. 58). The combined data define a broad girdle (Fig. 59). The well defined girdle illustrates that the majority of olivine and clinopyroxene crystals are oriented with their c-axes parallel to the plane of layering. The well defined maximum for olivine suggests that some olivine crystals have a preferred orientation within the layering plane, perhaps caused by magma currents at the time of olivine crystal accumulation. The clinopyroxene maxima are not coincident with the olivine maximum suggesting some other control for their orientation.

In the uppermost part of the layer, the rock becomes an olivine + clinopyroxene cumulate, and contains sparsely disseminated euhedral chromite. Clinopyroxene displays highly variable textural relations as previously described, and olivine originally occurred as polyhedral to granular crystals. Orthopyroxene, now as orthopyroxene bastite, forms poikilitic crystals and chlorite replaces original plagioclase oikocrysts. Disseminated irregularly shaped sulphide patches constitute less than 1 percent of the rock. The composition of the original rock in the upper part of the layer ranged from olivine clinopyroxenite to olivine melagabbronorite close to plagioclase-bearing olivine websterite. The upper contact of the clinopyroxene cumulate with the overlying olivine cumulate of cyclic unit 3 is not exposed in the telescoped core. However, the changing character of the rock suggests that the contact may be gradational.

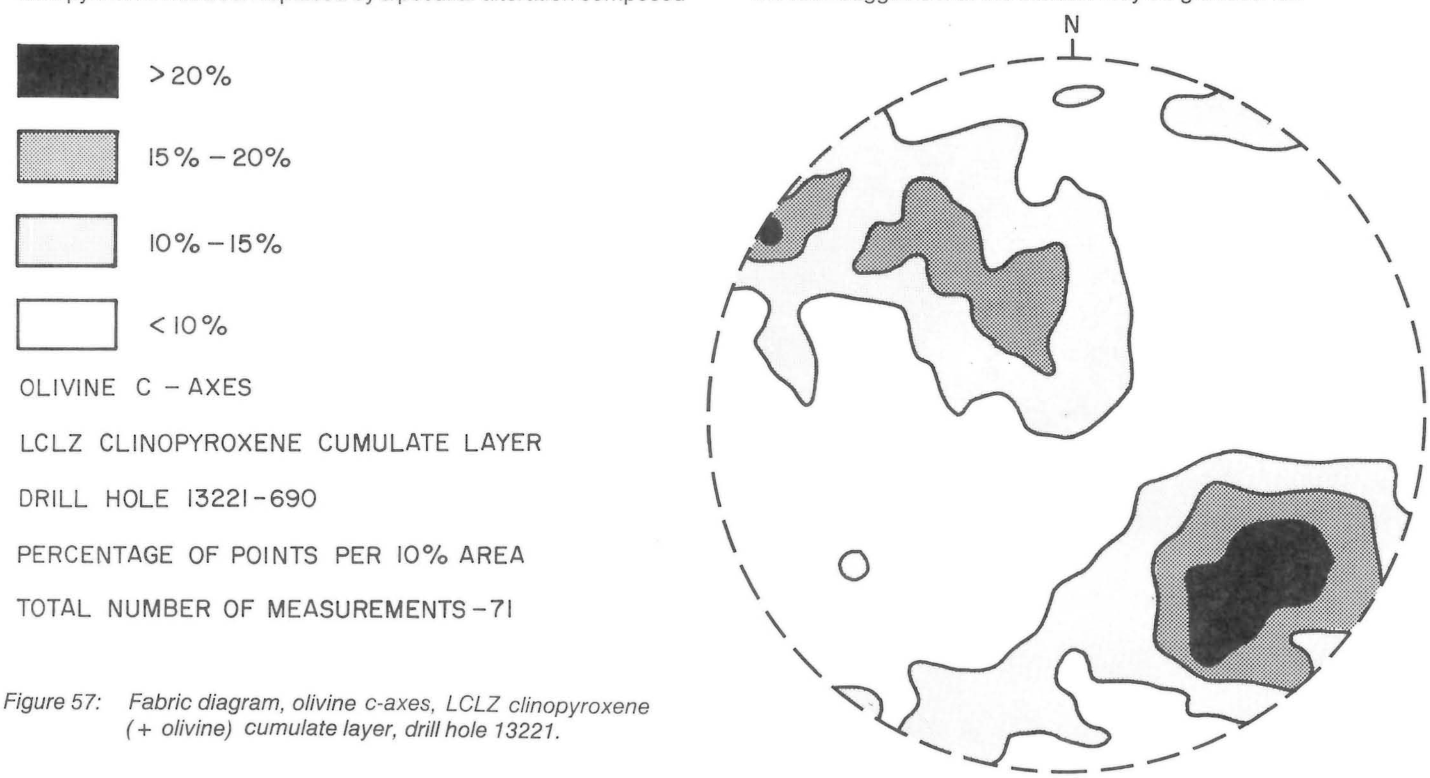


Figure 57: Fabric diagram, olivine c-axes, LCLZ clinopyroxene (+ olivine) cumulate layer, drill hole 13221.

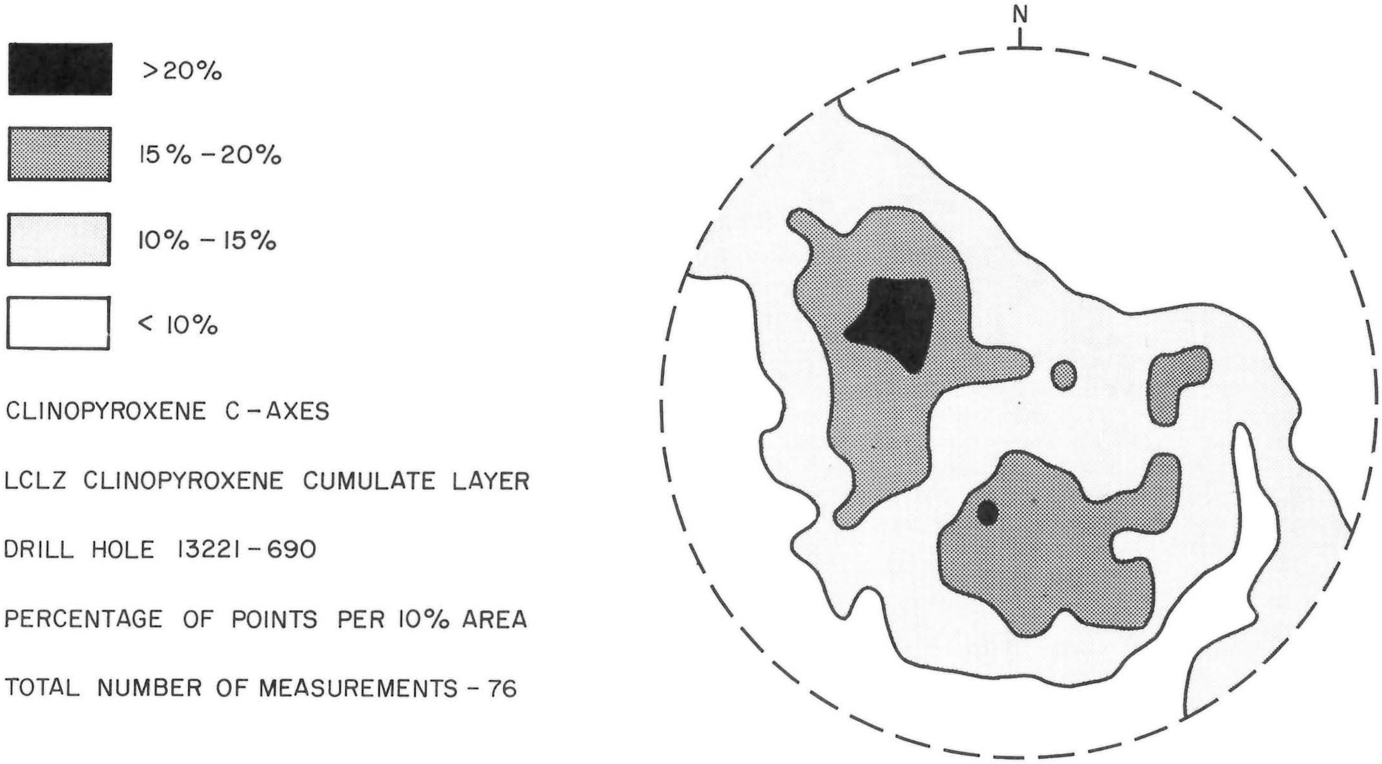


Figure 58: Fabric diagram, clinopyroxene c-axes, LCLZ clinopyroxene + olivine cumulate, drill hole 13221.

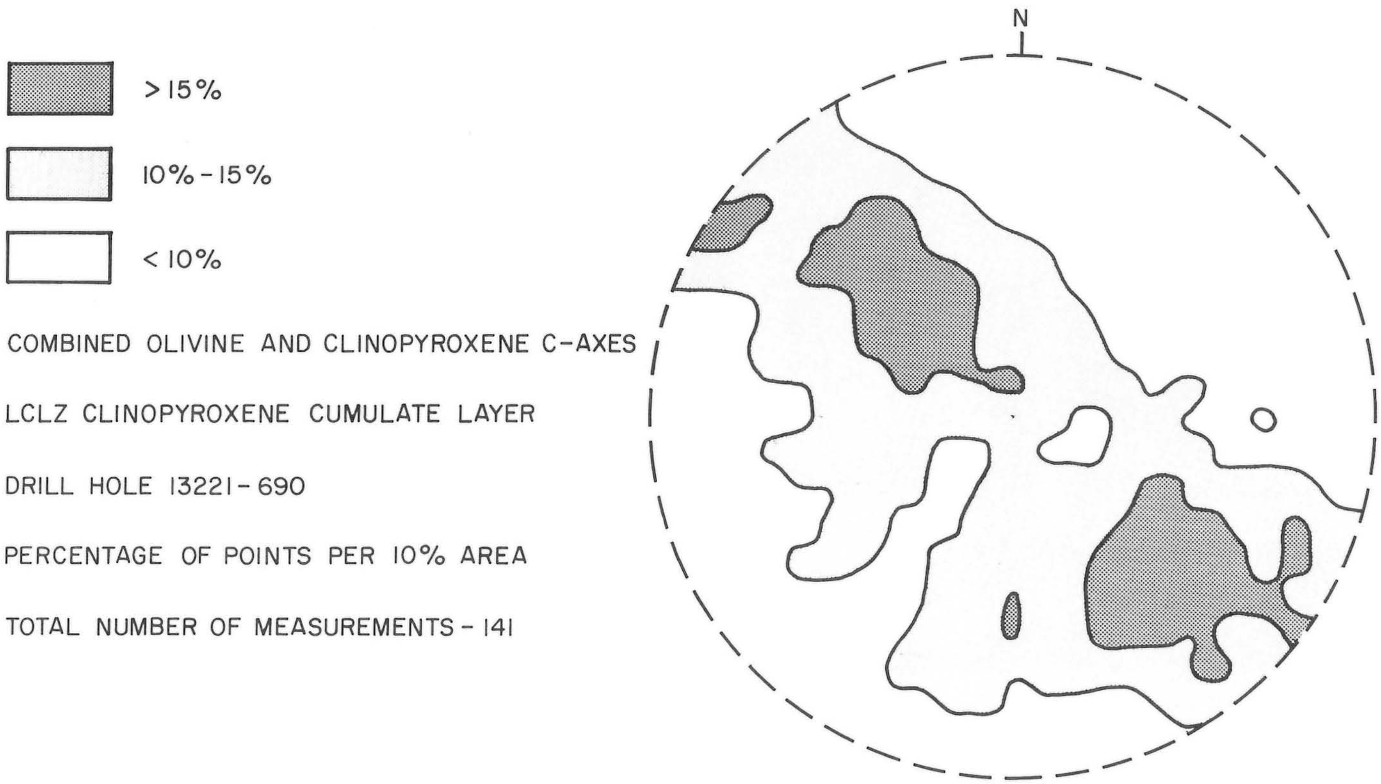


Figure 59: Fabric diagram, combined olivine + clinopyroxene c-axis, drill hole 13221.

CYCLIC UNIT 3

Olivine cumulate layer

The thick olivine cumulate ranges from light- to dark-apple green, and the rock has been intersected by a number of cm-scale breccia zones characterized by milky green, hard fibre picrolitic serpentine ± magnetite. Intercumulus volume is commonly less than 10 percent, and the shapes of the original olivine crystals range from polyhedral and granular to polygonal. Olivine crystals commonly display a random orientation, although preferred orientation of elongate crystals causes a crude lamination in a few rocks. Clinopyroxene bastite and chlorite replace original clinopyroxene and plagioclase oikocrysts, respectively. Disseminated euhedral chromite crystals constitute from less than 1- to approximately 4-percent of the rock. Intercumulus minerals make up approximately 10 percent of the rock near the top of the drill core and the original rock approaches a plagioclase-bearing wehrlite in composition. Original olivine crystals have been pseudomorphously replaced by mesh-texture to curtain-growth serpentine, the latter being developed at right angles to the direction of elongation of olivine crystals in laminated rocks. The rocks were originally dunite in composition.

Drill hole 13227

Drill hole 13227 intersects the lowermost 239 m (approximate true thickness) of LCLZ rocks in this area (Fig. 34). The sequence is composed of an incomplete or beheaded cyclic unit (olivine cumulate-clinopyroxene cumulate) and a thick portion of the olivine cumulate of the overlying cyclic unit.

CYCLIC UNIT 1

Olivine cumulate layer

The olivine cumulate ranges from light- to dark-apple green, and is mottled. A few cm-scale veins composed of milky green, picrolitic serpentine ± magnetite have been observed, as well as parallel, hair-like cross-fibre serpentine veinlets. The ratio of olivine to postcumulus phases changes from approximately 1:4 at the base of the layer to 2:1 toward the top of the layer.

The rocks at the base of the layer are characterized by relatively abundant (about 20%) poikilitic red-brown hornblende crystals, and granular to polyhedral olivine crystals that are less than 0.5 mm in size. The olivine crystals are contained in irregularly shaped oikocrysts of hornblende, clinopyroxene, orthopyroxene and plagioclase. The rocks have been substantially recrystallized, with clinopyroxene, orthopyroxene and hornblende being partially to completely replaced by tremolite. Olivine has been replaced by tremolite ± chlorite ± magnetite and plagioclase has been replaced by chlorite. Magnetite occurs as irregular clot-like masses and as a finely dispersed, dust-like phase.

Progressing upward (inward) from the contact, the original constituent minerals remain the same although their proportions and grain size change. Olivine becomes more abundant and coarser grained, and postcumulus oikocrysts become larger. Hornblende becomes less abundant, whereas clinopyroxene becomes more abundant. Here olivine is replaced by mesh-texture serpentine; many pseudomorphs contain spears of randomly oriented amphibole in mesh centres. Large (up to 5 mm) poikilitic orthopyroxene crystals have been replaced by a felted mat of tremolite that forms bastite-like pseudomorphs.

Within a centimetre of the contact with the overlying clinopyroxene cumulate, the chromite content increases to approximately 40 percent. Many chromite crystals are distinctive because of nearly circular inclusions that are filled with brown hornblende ± chlorite ± phlogopite ± opaque minerals. In some grains the inclusions are so large that the margins of the euhedral chromite crystals are breached, resulting in c-shaped crystals.

The contact between the olivine cumulate and clinopyroxene cumulate is gradational, and cumulus clinopyroxene crystals are sporadically distributed throughout the olivine cumulate a few centimetres from the contact, as are clusters of cumulus polyhedral olivine crystals in the clinopyroxene cumulate (Plates 36 and 37).

The rocks display a progressive change upward (inward) in original modal mineralogy and consequently rock types range from hornblende-bearing plagioclase lherzolite to plagioclase-bearing wehrlite. The transition from orthopyroxene-bearing to orthopyroxene-free rocks represents a gradational change from LCLZ rocks that possess MZ mineralogical characteristics to those that possess LCLZ mineralogy.

Clinopyroxene cumulate layer

The clinopyroxene cumulate is grey green and granular. The upper and lower contacts with olivine cumulate rocks are sharp. The rocks consist of accumulations of discrete clinopyroxene as equidimensional to prismatic crystals, and polycrystalline aggregates composed of irregularly shaped clinopyroxene crystals with complex interdigitated mutual contacts. Individual crystals within polycrystalline aggregates contain abundant opaque minerals, dominantly magnetite, although fine pinpoint sulphide grains have been observed. Orthopyroxene occurs as large (up to 6 mm) poikilitic crystals containing inclusions of clinopyroxene, olivine, and chromite. Olivine crystals contain inclusions of clinopyroxene and likely represent postcumulus crystallization. The rocks are reasonably well preserved, orthopyroxene displays incipient recrystallization to a felted mat of tremolite, and plagioclase is completely recrystallized to chlorite. The original rock was a plagioclase-bearing olivine websterite.

Three cyclic unit 1 olivine compositions plotted in Figure 60 average Fo_{80} and display little variation.

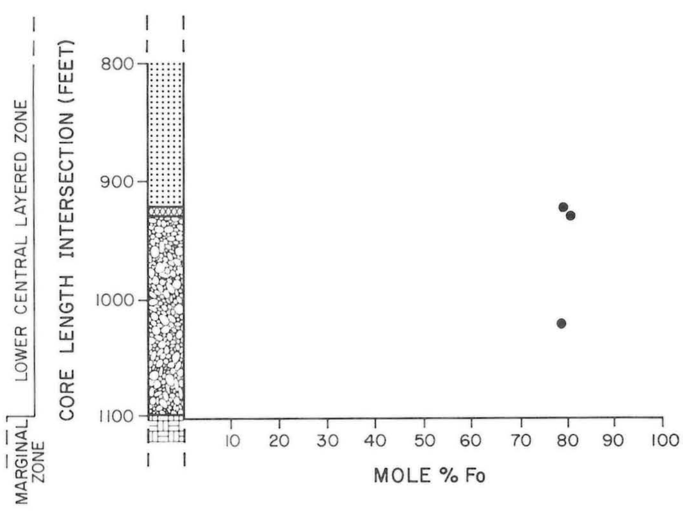


Figure 60: Olivine compositions, drill hole 13227.

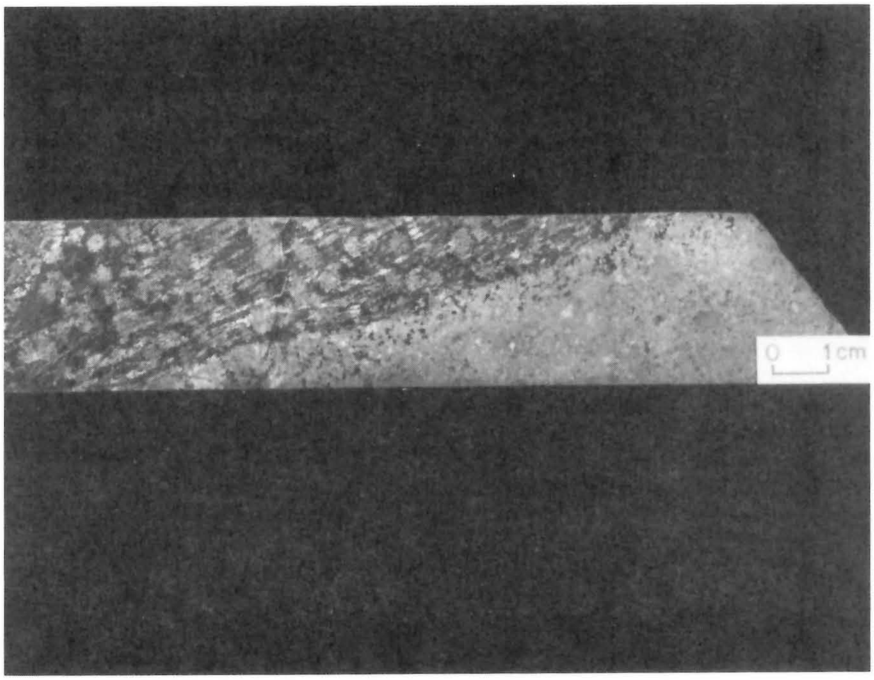
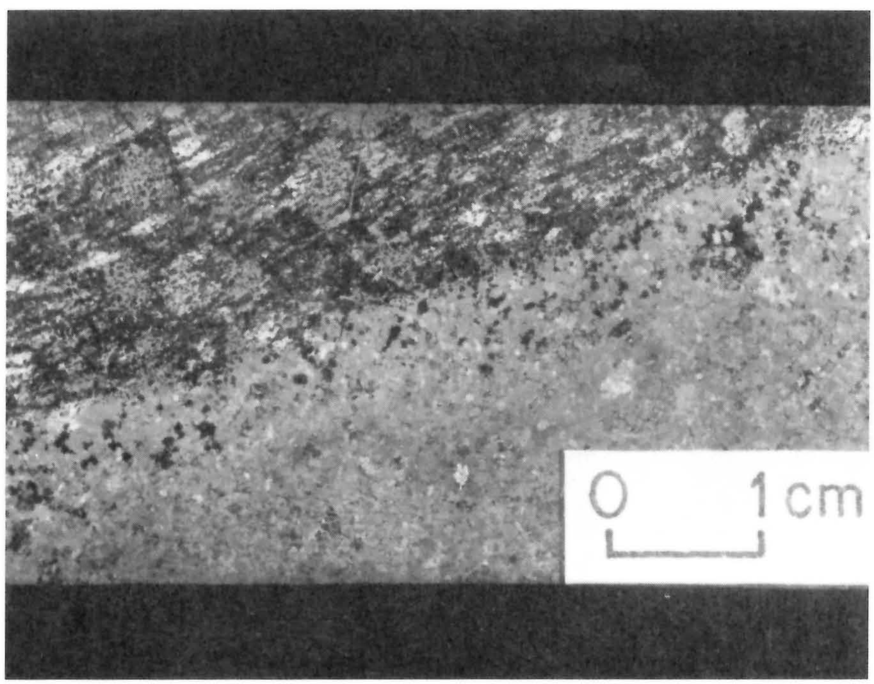


Plate 36: *Contact between LCLZ cyclic units 1 and 2. The mid-grey granular rock to the right of (below) the contact is the clinopyroxene cumulate layer of cyclic unit 1. The mottled rock to the left of (above) the contact is the olivine cumulate layer of cyclic unit 2. Note the gradational character of the contact with clusters of cumulus olivine crystals occurring 5 to 7 mm below the contact. The olivine cumulate is distinguished by 5 to 7 mm ovoid clinopyroxene oikocrysts. Lamination parallel to contact in olivine cumulate is caused by parallel serpentine ± magnetite veinlets. LCLZ, DDH 13227.*

Plate 37: *Detail of contact seen in Plate 36.*



CYCLIC UNIT 2

Olivine cumulate layer

The exposed part of the olivine cumulate ranges from dark greenish black to grey green and apple green. Some rocks are delicately mottled due to concentrations of clinopyroxene oikocrysts (up to 1 cm). Parallel sets of serpentine ± magnetite veinlets are common, and carbonate veins, some forming vein networks, are sporadically distributed over the upper 129 m (core length) of the exposed part of the layer. A few cm-scale picrolite-carbonate ± magnetite breccia zones were encountered.

The rock adjacent to the contact with the underlying clinopyroxene cumulate is distinguished by numerous 3 to 4 mm equidimensional to spherical clinopyroxene oikocrysts with numerous inclusions of olivine (Plates 36 and 37). The original elongate polyhedral olivine crystals are aligned with their long axes parallel to the contact. Chlorite replaces plagioclase that originally formed oikocrysts, and orthopyroxene formed small (2 to 4 mm) oikocrysts. Finely disseminated, fine grained chromite constitutes approximately 1 percent of the rock.

Olivine has been pseudomorphously replaced by curtain-growth serpentine that is developed at right angles to the preferred direction of olivine elongation and consequently to the contact with the underlying clinopyroxene cumulate (Fig. 61). Late stage serpentine ± magnetite veinlets are developed parallel to the contact and the direction of aligned elongate olivine crystals. Orthopyroxene has been replaced by orthopyroxene bastite. The rock adjacent to the clinopyroxene cumulate was originally a plagioclase-bearing lherzolite.

The remainder of the olivine cumulate is characterized, in part, by clinopyroxene oikocrysts (up to 1 cm) and by rare orthopyroxene. Chlorite ± phlogopite ± magnetite in intercumulus areas may represent alteration of original postcumulus plagioclase. Disseminated euhedral chromite constitutes from less than 1 to about 2 percent of the rock.

Original polygonal olivine crystals, which display straight to slightly curving mutual contacts, form a mosaic-like aggregation, characteristic of original dunite. Polyhedral and granular olivine crystals characterize rocks where the intercumulus volume exceeds 10 percent.

Olivine is commonly pseudomorphously replaced by mesh-texture and curtain-growth serpentine. In some rocks, olivine has been replaced by nonpseudomorphous serpentine as intersecting plate-like masses and as bundles of interlocking subradially disposed fibres. Late stage serpentine ± magnetite veinlets cut all previous serpentine varieties in most rocks. Clinopyroxene, which is partly preserved in a few rocks, has been pseudomorphously replaced by clinopyroxene bastite and by chlorite. The original rocks ranged from plagioclase-bearing wehrlite to dunite in composition.

Drill hole 38578

The upper part of a cyclic unit composed of an olivine cumulate layer and clinopyroxene cumulate layer, and the lowermost part of the olivine cumulate layer of the succeeding LCLZ cyclic unit were penetrated by drill hole 38578 (Fig. 62).

CYCLIC UNIT 1

Olivine cumulate layer

The exposed part of the lowermost olivine cumulate layer ranges from greenish black to dark apple green. The rock is distinguished by sporadically distributed clinopyroxene oikocrysts that form large reflecting patches in the drill core (one irregularly shaped oikocryst measures 3 cm in size). Several picrolitic serpentine ± carbonate breccia zones and one zone of chlorite + tremolite alteration were observed as were a number of carbonate veins that locally form vein networks.

The olivine cumulate consists of serpentine pseudomorphs after original polyhedral, rounded polyhedral, and granular olivine crystals. In rocks with little or no intercumulus space, isolated patches of original polygonal olivine crystals form a mosaic-like mass. Original clinopyroxene oikocrysts range from 3 mm up to 1 cm in size, and their sporadic distribution contributes to the general heterogeneous nature of these rocks, even at thin-section scale. Chlorite ± magnetite replaced original plagioclase that may have formed oikocrysts similar to clinopyroxene in size and distribution. Orthopyroxene, as large (up to 5 mm) irregularly shaped poikilitic crystals with inclusions of olivine, is rare and sparsely distributed. Chromite occurs as large (0.15 to 0.25 mm), euhedral, disseminated crystals that constitute from 1 to 3 percent of the rock. Chromite occupies intercumulus space between olivine crystals; however, in some rocks it is much more abundant in nonclinopyroxene oikocryst areas and rare as inclusions in clinopyroxene oikocrysts.

Original elongate olivine crystals display imperfect preferred orientation in some rocks; in rocks characterized by clinopyroxene oikocrysts and by preferred orientation of elongate olivine crystals, the olivine crystals in the oikocrysts commonly display random orientation.

Mesh-texture and curtain-growth serpentine pseudomorphously replace olivine crystals and in rocks that display an original preferred orientation of olivine crystals, curtain-growth serpentine is developed perpendicular to the direction of elongation. Clinopyroxene is partly preserved in some rocks; in other rocks it has been pseudomorphously replaced by bastite, and tremolite forming bastite-like pseudomorphs. Plagioclase has been replaced by chlorite, and orthopyroxene, which is partly preserved, has been replaced by bastite. Secondary magnetite forms irregular patch-like masses in intercumulus areas and forms discontinuous veinlets with serpentine. Serpentine ± magnetite and carbonate form parallel vein sets in some rocks.

The original rock ranged in composition from dunite and plagioclase-bearing wehrlite, the dominant lithologic units, to plagioclase-bearing lherzolite.

Clinopyroxene cumulate layer

The clinopyroxene cumulate represents the termination of the lowermost cyclic unit; it is grey green and granular, and cut by picrolitic serpentine-filled fractures. The rock is an aggregation of irregularly shaped crystals with complex interdigitated mutual contacts. Some individual crystals are twinned and some display parting. Olivine and plagioclase crystals range from partly to completely preserved, occupy irregular spaces between clinopyroxene crystals and likely represent postcumulus crystallization.

CYCLIC UNIT 2

Olivine cumulate layer

The lowermost part of the olivine cumulate is a dark grey to greenish black, somewhat granular rock, with a number of narrow (less than 1 mm) picrolitic serpentine ± carbonate veins. Some clinopyroxene oikocrysts (3 to 5 mm) occur as nearly equidimensional, reflective, patches in the drill core. In areas where clinopyroxene oikocrysts are absent, original olivine crystals display polygonal

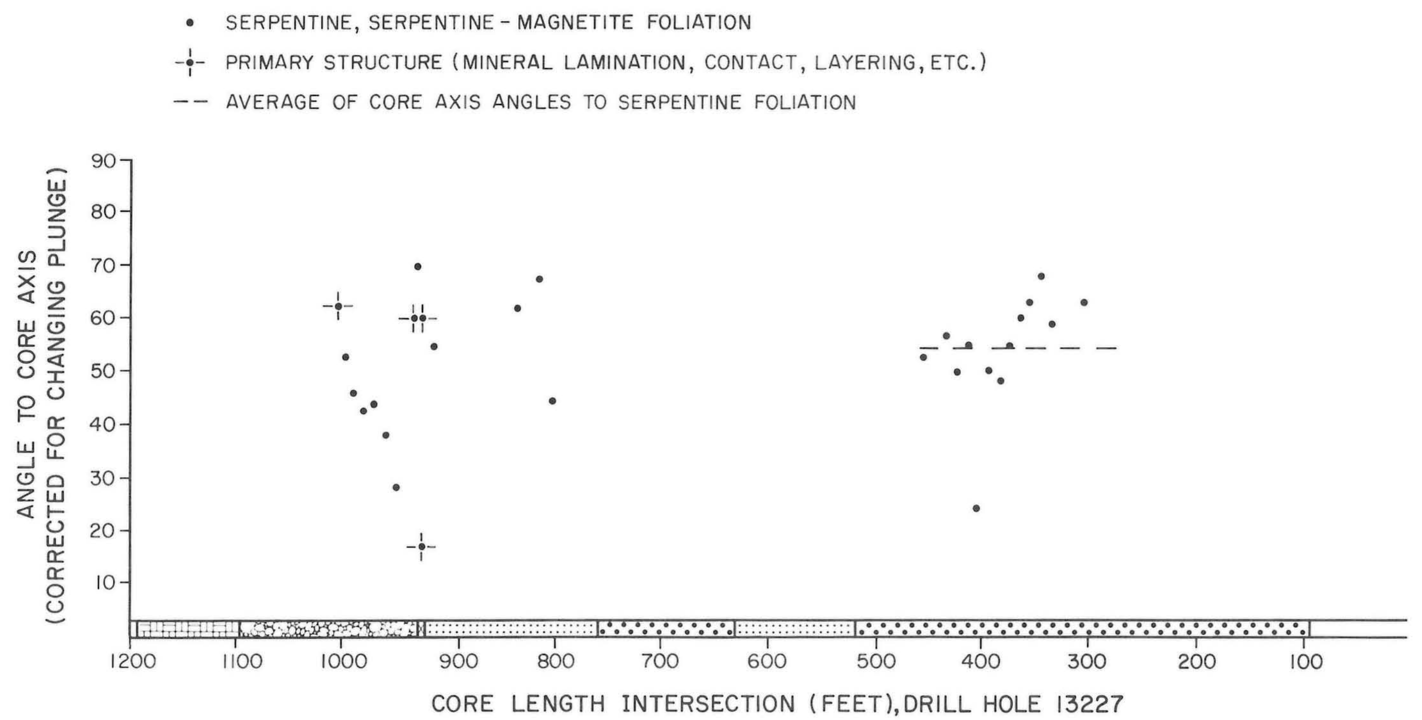


Figure 61: Core axis angles to planar structures, drill hole 13227.

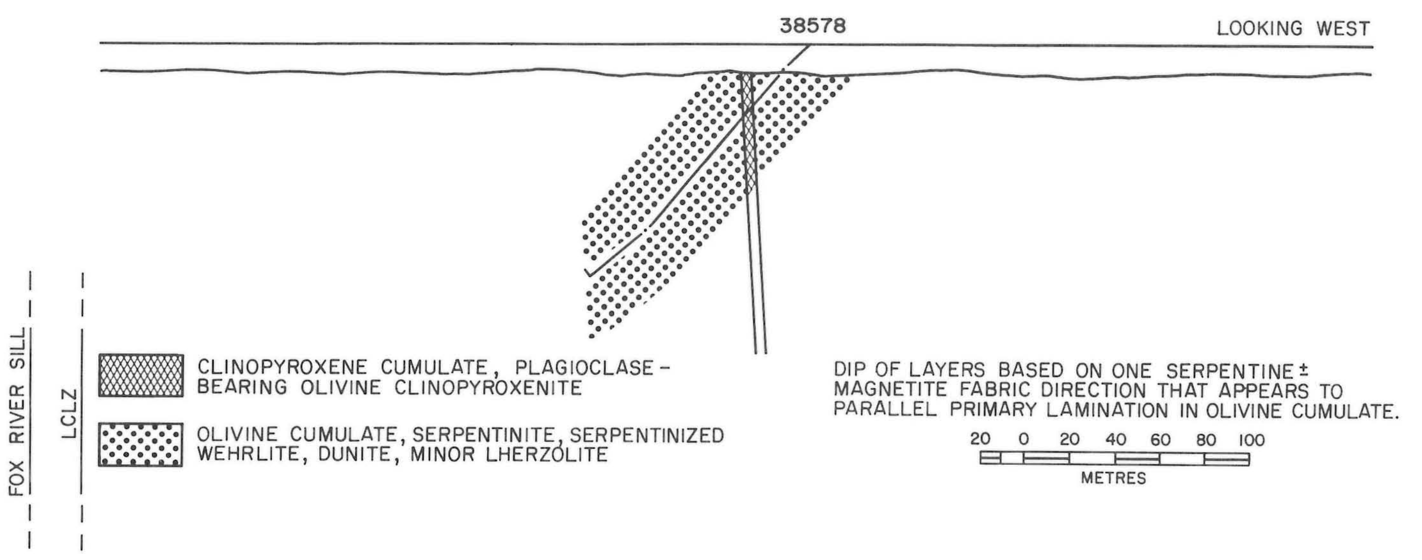


Figure 62: LCLZ geology, drill hole 38578.

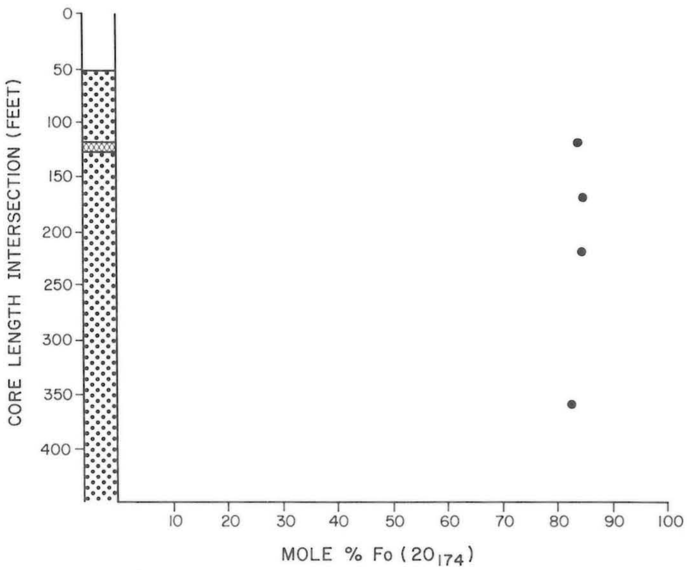


Figure 63: Olivine compositions, drill hole 38578.

shapes with simple mutual grain boundaries and the rock possesses a mosaic-like texture. Original olivine crystals enclosed in clinopyroxene oikocrysts range from rounded polyhedral to granular in shape. The rocks apparently lack orthopyroxene and are similar to olivine cumulates of the underlying cyclic unit. The original rocks ranged from dunite to wehrlite in composition.

OLIVINE COMPOSITIONS

Olivine compositions in the lowermost cycle olivine cumulate layer range from $Fo_{82.5}$ at the base of the hole to $Fo_{84.7}$ near the top of the layer (Fig. 63). Olivine in the overlying clinopyroxenite that represents the top of the cyclic unit is $Fo_{83.6}$. Within the olivine cumulate there is a suggestion of a trend of increasing Fo-content stratigraphically upward. However, the interval between determinations is large and the possibility of small-scale cyclic units within the olivine cumulate cannot be discounted.

Drill hole 38515

A sequence of LCLZ olivine cumulate rocks has been intersected by drill hole 38515. These serpentinites have been intruded by an olivine diabase dyke and consequently have been modified by metamorphic effects related to dyke emplacement. The serpentinites are moderately to strongly foliated, indicating that the MZ-LCLZ contact in this area is probably a fault.

CYCLIC UNIT (?)

Olivine cumulate rocks

The rocks between the MZ contact and the contact with the olivine diabase are brownish-green to greenish-black, strongly foliated serpentinite. The rocks break along surfaces that are highly polished and possess slickensides, and they are cut by numerous hair-like, subparallel serpentine veinlets. The rock at the contact with the olivine diabase is a massive dense hornfels.

The rocks consist of nonpseudomorphous serpentine that is not obviously fibrous, and that contains irregular, fine grained (0.3 to 0.5 mm) masses of chlorite. The nonpseudomorphous serpentine is decorated by numerous patches, clots and disseminated crystals of magnetite. Larger elongate magnetite masses form discontinuous veins. Nearly equidimensional talc plates (1 to 2 mm) replace original oikocrysts. Groups of carbonate $\pm$ serpentine veins form subparallel, branching and intersecting networks. The foliated serpentinite may represent an original wehrlite.

The hornfels adjacent to the olivine diabase is dominated by a continuous sponge-like mass of hematite in which the intervening spaces or holes are occupied by a marly isotropic mineral. Ghost-like masses of serpentine, that resemble bastite-like pseudomorphs, are sporadically distributed within the hematite. Carbonate veins are common.

North of the olivine diabase, the original olivine cumulate rocks display a progressive change from greenish black near the contact to apple-green near the base of the hole. The rocks display serpentine $\pm$ magnetite fabric and are cut by (1 to 3 mm) cross-fibre serpentine veins. Near the olivine diabase contact, the rocks are composed of nonpseudomorphous nearly isotropic serpentine. They appear to have been originally wehrlite. Toward the base of the hole, olivine has been pseudomorphously replaced by mesh-texture serpentine, and the rocks are distinguished by a mosaic-like mass of polygonal olivine crystals. Fine grained serpentine in intercumulus areas may represent alteration of original clinopyroxene. Disseminated, relatively coarse grained (0.15 mm) chromite crystals constitute 2 percent of the rock that was originally dunite.

MACKENZIE DYKE (?)

Olivine diabase

The olivine diabase is grey-green and granular and displays an increase in grain size from the contacts toward the centre of the unit. An inclusion of serpentinite occurs near the north contact. The rocks consist of zoned plagioclase (cores An_{78}, rims An_{44}) as well formed, randomly disposed lath-like crystals. Clinopyroxene occupies the space between plagioclase crystals and consequently possesses highly irregular grain shapes. Some clinopyroxene poikilitically enclosed rounded olivine crystals, and some olivine crystals ($Fo_{52.8}$ to $Fo_{58.9}$) occupy the space between plagioclase laths. The rocks are distinguished by disseminated skeletal ilmenite crystals. Grass-green to emerald-green chlorite partly replaces olivine and clinopyroxene. Patches of clear quartz (about 1.0 percent) are present in one sample.

The presence of hornfels in the serpentinite at the olivine diabase contacts, and the progressive increase in grain size toward the centre of the diabase suggest that this unit is a dyke. Mackenzie swarm diabase dykes are interpreted to cut across the Fox River Belt (Manitoba Mineral Resources Division, 1979) and this olivine diabase likely belongs to that swarm.

Drill hole 13217

Drill hole 13217 intersects the contact between Middle sedimentary formation rocks and the Sill, a narrow MZ section, an unusual hybrid rock, and a thick sequence of original olivine cumulate rocks (Fig. 37). The latter sequence is considered to represent the lowermost part of the LCLZ, in this area, on the basis of its abundant olivine content (estimated 80 to 90 percent). The presence of orthopyroxene in these rocks is unusual for LCLZ olivine cumulate, although not entirely unknown. It occurs as oikocrysts rather than large poikilitic plates as in MZ rocks.

CYCLIC UNIT (?)

Olivine cumulate rocks

The original olivine cumulate forms a monotonous suite of dark greenish-black to black rocks that are delicately mottled or spotted. The mottling is caused by the widespread distribution of original oikocrysts, the most common being clinopyroxene.

These olivine-rich rocks are composed of serpentine pseudomorphs after elongate polyhedral to rounded polyhedral olivine crystals. In some rocks the original elongate olivine crystals display a preferred orientation, and serpentine ± magnetite veins are parallel to and consequently enhance the fabric (Fig. 64). The rocks are well preserved, and relict olivine displays little compositional variation, ranging from $Fo_{85.3}$ to $Fo_{87.1}$ in 9 determinations over 275 m (900 feet) of core length interval (Fig. 65). The relatively high Fo-content reinforces the interpretation that these rocks represent lowermost LCLZ rocks in this area. The ratio of olivine to intercumulus minerals increases from approximately 4:1 near the contact with the hybrid rock to 9:1 near the base of the hole, where, although the rocks are predominantly peridotitic (greater than 10% intercumulus material), patches of polygonal olivine crystals with simple mutual grain boundaries have been observed. The circular to elliptical inclusions in olivine crystals previously described from some MZ olivine cumulate rocks have been observed here, one example containing euhedral chromite crystals. Clinopyroxene forms large (0.5 to 2 cm) oikocrysts; orthopyroxene, now largely bastite, and plagioclase, now entirely replaced by chlorite ± epidote ± phlogopite, originally formed smaller oikocrysts (less than 5 mm). Disseminated euhedral chromite constitutes from 1 to 3 percent of the rock.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. Fine grained, hair-like, fibrous amphibole forms complex interwoven mats in the cores of many serpentine pseudomorphs. Clinopyroxene is commonly altered to bastite, and in a similar fashion orthopyroxene has been pseudomorphously replaced by bastite. Plagioclase has been completely replaced by nearly isotropic mixtures of chlorite ± epidote ± phlogopite ± garnet. Magnetite, as sponge-like masses, commonly accompanies secondary alteration products in intercumulus areas.

Drill hole 13225

Drill hole 13225, the southernmost of the drill holes of 1086E section, and drilled in a southerly direction, penetrates a thick (approximately 150 m) section of serpentinite before intersecting clinopyroxene cumulate (olivine clinopyroxenite) rocks at its base (Fig. 66). The clinopyroxene cumulate represents the top of a beheaded cyclic unit and the thick serpentinite (serpentinized dunite) represents the base of the next overlying LCLZ cyclic unit.

CYCLIC UNIT 1

Clinopyroxene cumulate layer

The rocks are granular, massive and grey green, and possess a sharp contact with the overlying wehrlite. Clinopyroxene is preserved and olivine is partly altered. Clinopyroxene forms complex polycrystalline aggregates with complicated crystal relationships. Mutual boundaries are interdigitated. Coarse blebby exsolution is locally developed, many of the crystals are twinned, and some display parting. Olivine occupies the spaces between clinopyroxene aggregate crystals and consequently has highly irregular shapes.

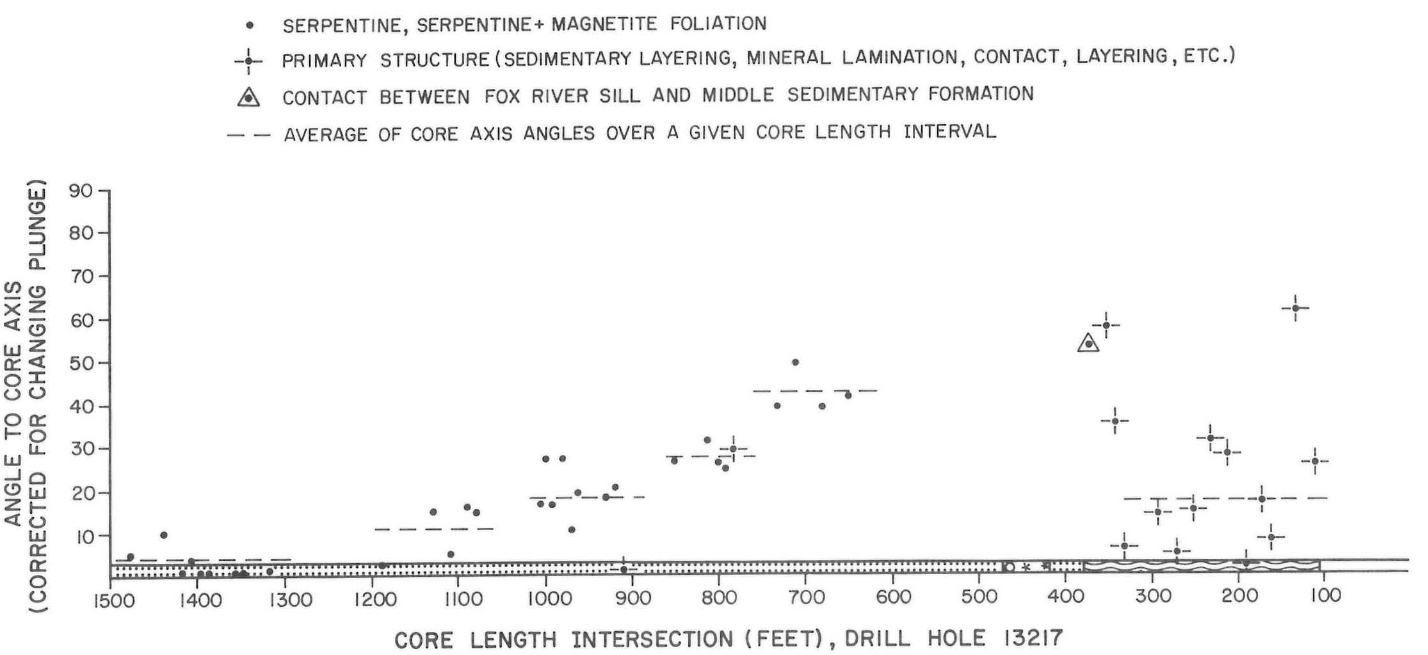


Figure 64: Structural synopsis, drill hole 13217.

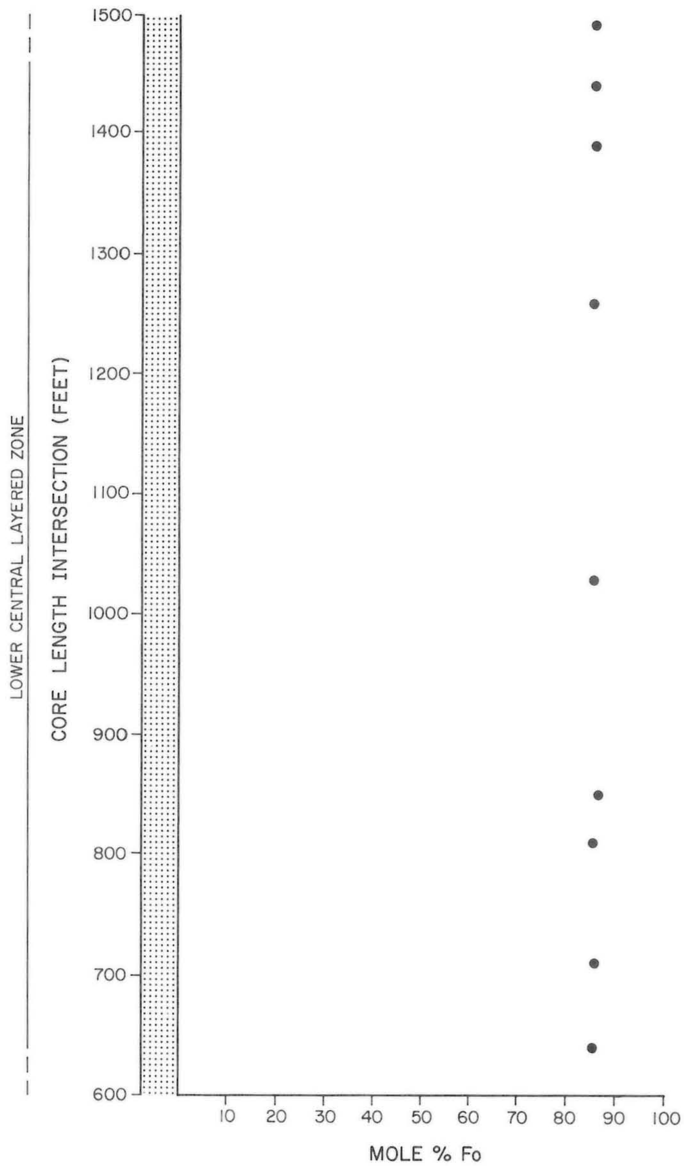


Figure 65: Olivine compositions, drill hole 13217.

CYCLIC UNIT 2

Olivine cumulate layer

LOWER OLIVINE + CLINOPYROXENE CUMULATE SUBLAYER

The olivine cumulate layer has been divided into a lower, mottled olivine + clinopyroxene cumulate (3 m approximate true thickness), overlain by a thick olivine cumulate.

The rocks are massive, mottled grey green to dark greenish black and display a range of recrystallization. Olivine and clinopyroxene were original cumulus phases, the latter displaying a substantial range of postcumulus growth. Olivine has been pseudomorphously replaced by mesh-texture serpentine, and clinopyroxene ranges from being preserved to being completely replaced by clinopyroxene bastite. Original postcumulus plagioclase has been replaced by chlorite ± epidote. The contact between the wehrlite and the overlying serpentinized dunite is not exposed (telescoped core); however, changes in the nature of the wehrlite suggest that the contact may be gradational over approximately 1 m.

MAIN LAYER

The rocks are a monotonous sequence of medium- to light-apple green, dull, earthy, lustreless, crumbly serpentinite. Serpentine ± magnetite fabric is somewhat variably developed as are magnetite-filled fractures (Fig. 67). The original olivines give the impression of having been very tightly packed where the original texture can be discerned.

The rocks were originally composed almost entirely of olivine, interstitial minerals being 2 percent or less. Slightly rounded chromite crystals constitute approximately 1 percent of the rock. The original olivine crystals formed crudely equidimensional polygons to slightly elongate crystals that possessed straight to gently curving mutual boundaries. Rocks that contain original elongate crystals tend to have a crude preferred orientation. The olivines have been replaced by mesh-texture serpentine.

Drill hole 38541

Drill hole 38541 penetrates the contact between MZ and LCLZ rocks which in this area appears to be a fault. Approximately 130 m of LCLZ rocks composed of serpentinite, serpentinized dunite and thin (1.5 to 4.6 m) olivine clinopyroxenite layers have been intersected by the hole (Fig. 38). These layers represent two beheaded or incomplete cyclic units and a portion of another cyclic unit.

CYCLIC UNIT 1

Black foliated serpentinite (olivine cumulate)

Approximately 5.7 m of black foliated serpentinite separate MZ brecciated gabbro from the lowermost olivine clinopyroxenite layer. The serpentinite is characterized not only by its colour, but by numerous serpentine-filled fractures, some of which possess slickensided surfaces. The rock is similar to that intersected by drill holes 38532 and 38520 in 722E section.

Clinopyroxene cumulate layer

The grey green, granular olivine clinopyroxenite consists of an aggregation of polygonal and irregularly shaped clinopyroxene crystals and rare complex polycrystalline aggregates. Individual crystals possess well developed parting and twinned crystals are common. Irregularly shaped serpentine-filled areas, interstitial to clinopyroxene, replace original olivine crystals. The rock is cut by numerous serpentine veins.

CYCLIC UNIT 2

Olivine cumulate layer

The layer is composed of rocks that range from grey green to apple-green. They are cut by numerous serpentine-filled fractures, have a somewhat waxy lustre and are soapy or slippery to the touch. The original texture can be discerned in some rocks despite the intense serpentinization.

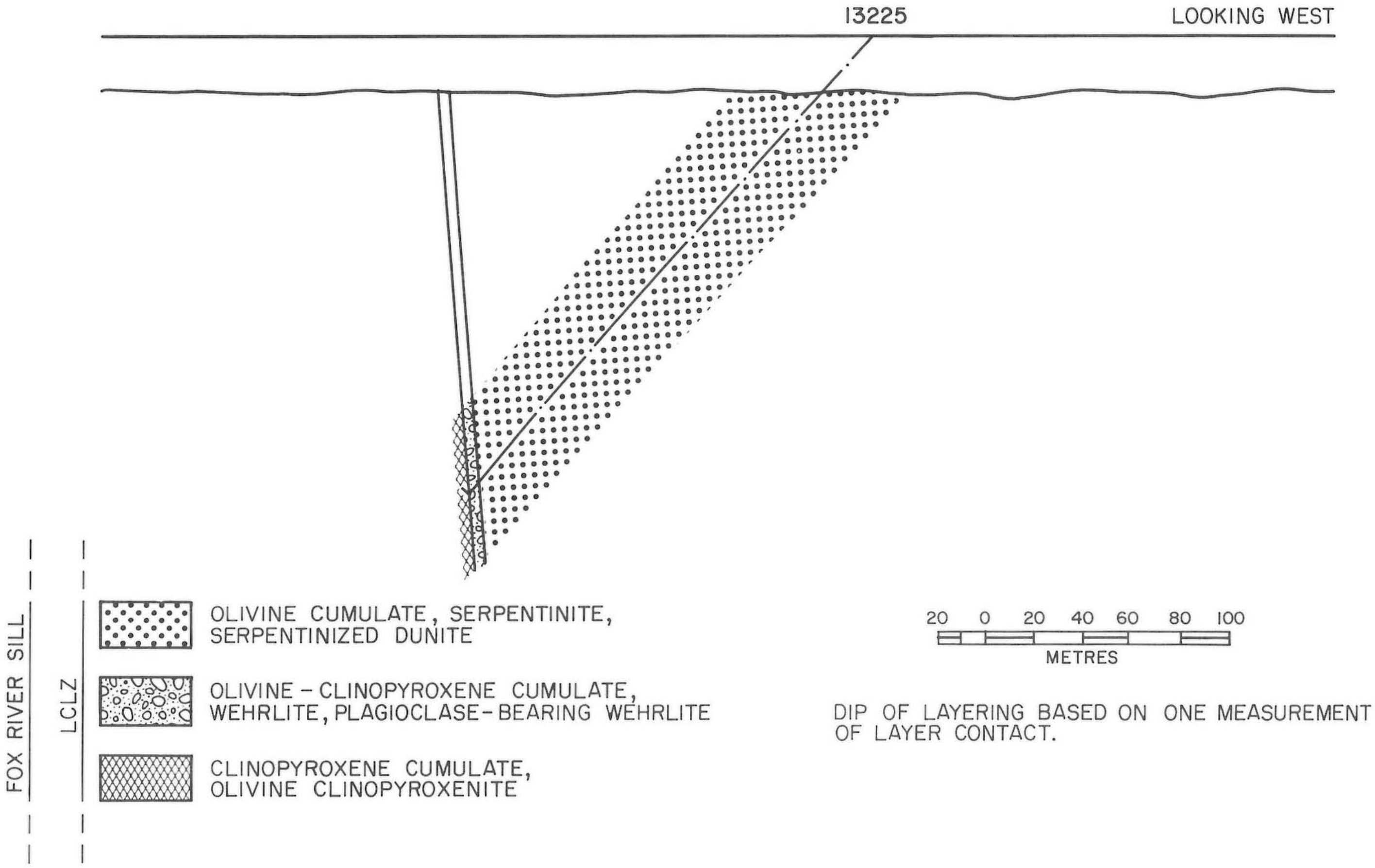


Figure 66: LCLZ geology, drill hole 13225, 1086E section.

The rock originally consisted of an accumulation of granular- to polygonal-olivine crystals that average 1.5 mm in size. Intercumulus minerals, estimated at less than 5 percent, were originally composed of clinopyroxene oikocrysts and plagioclase. Serpentine veinlets that have a preferred orientation partially outline original olivine grain boundaries. Original olivine crystals have been replaced by fine grained granular serpentine and/or interlocking blades of serpentine. Bastite replaces original clinopyroxene oikocrysts and chlorite replaces original intercumulus plagioclase. Sparsely disseminated rounded chromite crystals compose less than 1 percent of the rock as does rounded to irregularly shaped patches of pyrrhotite. Magnetite as irregular patches and discontinuous veins makes up approximately 3 percent of the rock.

Clinopyroxene cumulate layer

The olivine clinopyroxenite layer consists of clusters of irregularly shaped clinopyroxene crystals that form a mosaic-like aggregate. Individual crystals possess complex grain boundary relationships with adjacent crystals, and many display interdigitated contacts. Parting and twinned crystals are common. Irregularly shaped, serpentine-filled areas replace original olivine and the rock is cut by numerous serpentine-filled fractures. Disseminated, ragged clots of sulphide make up less than 1 percent of the rock.

CYCLIC UNIT 3

Olivine cumulate layer

The uppermost olivine cumulate layer is composed of rocks that are dark apple green to brownish green, and become dull, earthy and lustreless toward the bottom of the hole. The brownish character of the rock appears to be the result of a fine, powder-like hematite staining of serpentine. The rocks were originally dunite with intercumulus minerals being almost nonexistent. The original olivine crystals were polygonal to crudely polyhedral and in a few examples late stage serpentine veinlets are parallel to the preferred direction of olivine elongation. Olivine has been replaced by mesh-texture serpentine. Disseminated euhedral to slightly rounded chromite averages approximately 2 percent of the rock.

ROCK FABRIC

In three of the 14 core axis angles of serpentine $\pm$ magnetite foliation, the fabric direction is parallel to the direction of elongation of olivine crystals. The three angles, 37°, 38° and 40° are close to the overall mean (36°) for the 14 measurements (Fig. 68). This angle (36°) is interpreted as representing the angle of intersection of layering and the core axis.

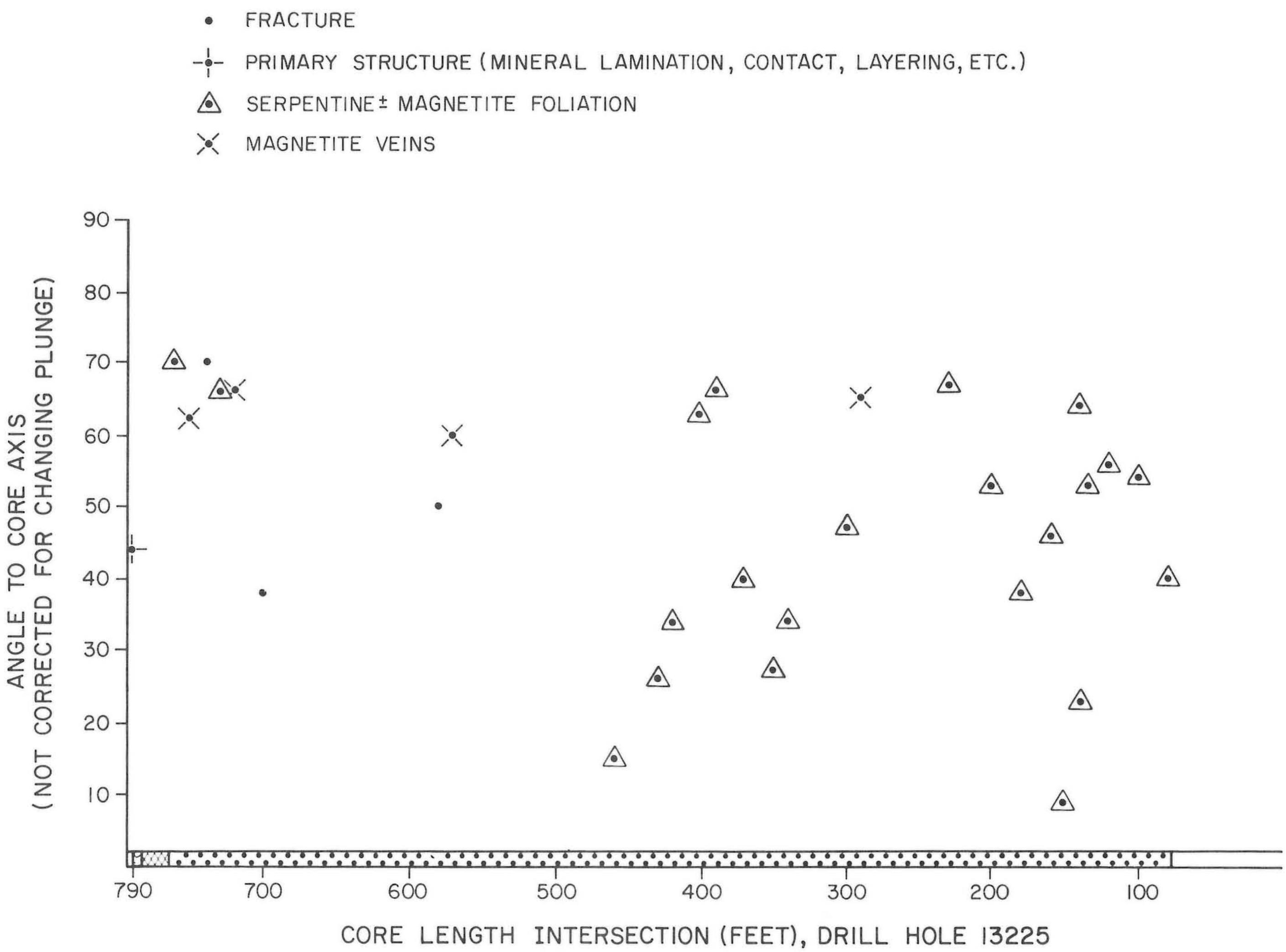


Figure 67: Core axis angles to planar structures. drill hole 13225.

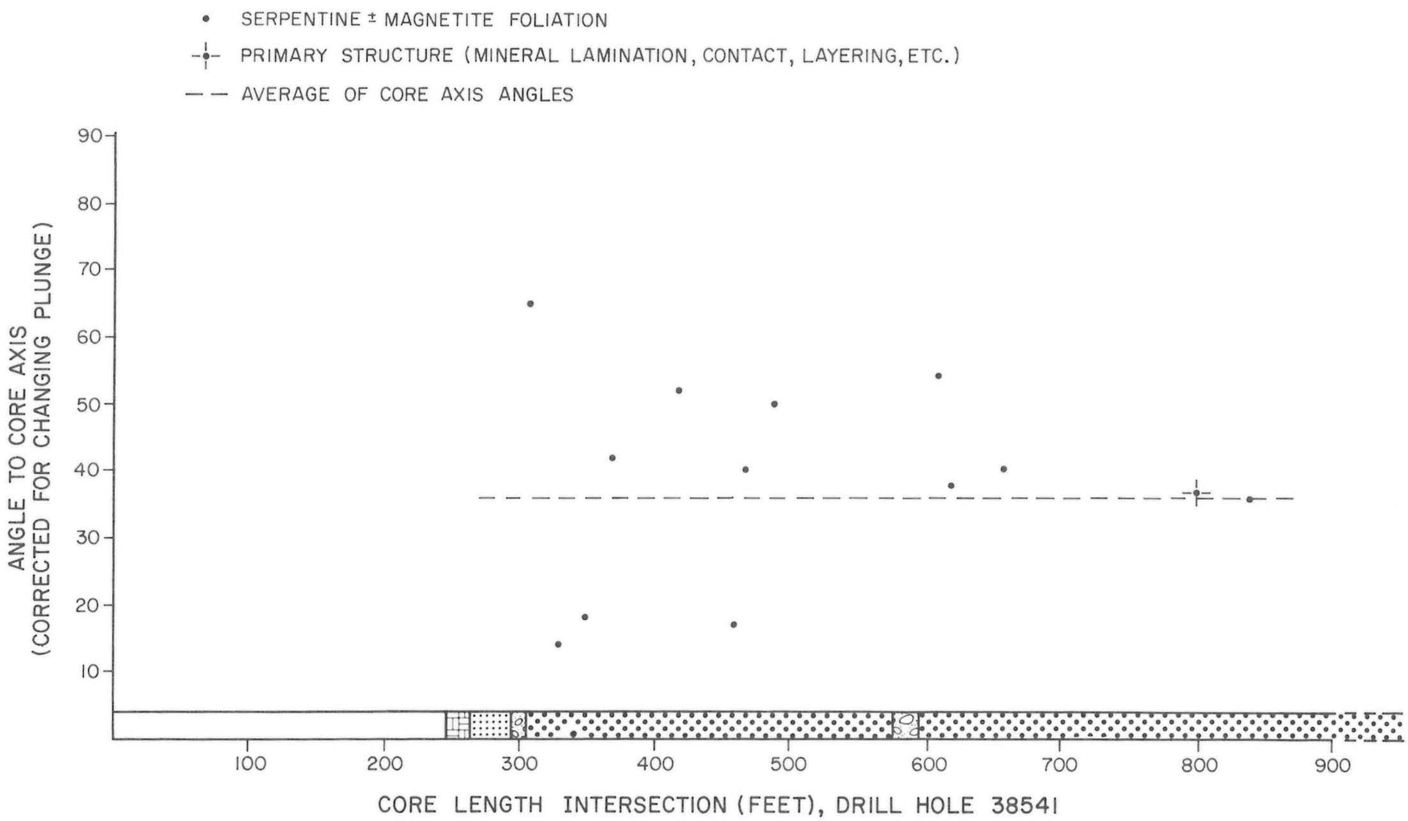


Figure 68: Core axis angles to planar structures, drill hole 38541.

MIDDLE AND UPPER PART

1086E SECTION - DRILL HOLE 13219

The 1086E section area contains two drill holes (13213 and 13219; Fig. 69) on the same section line (1086E) drilled in a northerly direction, and one hole (13225) drilled parallel to 13213 and 13219 but in the opposite direction (southerly) on a line approximately 240 m (800 feet) west of 1086E section (Map GR81-1-1). The holes penetrate a succession of LCLZ and UCLZ rocks and the contact between LCLZ and UCLZ rocks is intersected by 13219. One complete, two nearly complete, and portions of three other cyclic units are intersected by the drill holes. The uppermost LCLZ cyclic unit in this area is intersected by hole 13219. Approximately 300 m of LCLZ rocks are represented by the gap between drill holes 13225 and 13219.

Drill hole 13219

Drill hole 13129 intersects what is interpreted to be the uppermost LCLZ cyclic unit and a portion of the olivine cumulate part of the lowermost UCLZ cyclic unit in this area. The contact between LCLZ and UCLZ rocks has been placed so as to separate nonorthopyroxene-bearing rocks (LCLZ) from orthopyroxene-bearing rocks (UCLZ). The contact placed at this strategic interval, on the basis of the presence or absence of orthopyroxene, also effectively separates olivine cumulate rocks that are predominantly dunite (LCLZ) from olivine cumulate rocks that are predominantly lherzolite-wehrlite (UCLZ). The near-parallel nature of the layering in drill holes 13219 and 13213 suggests that the LCLZ-UCLZ contact is conformable although the layer dips have been determined from only a few observations of primary structures (Figs. 70, 71 and 72).

UPPERMOST LCLZ CYCLIC UNIT

Olivine cumulate layer

LOWER DUNITE

The rocks are a sequence of dull, earthy, lustreless, crumbly serpentinite. The original texture is not easily discerned megascopically. Serpentine foliation is present, as are closely spaced (1 to 2 cm) fractures and magnetite $\pm$ serpentine $\pm$ carbonate veins.

The original olivine crystals possessed equidimensional, polygonal shapes, and crystals shared straight to slightly curving mutual boundaries. Their grain size ranged from 0.7 to 5 mm and averaged 1.5 mm. Intercumulus minerals generally constitute less than 2 percent of the rock, and are composed of clinopyroxene bastite and chlorite $\pm$ epidote likely replacing original plagioclase. Chromite makes up 1 to 2 percent of the rock as disseminated, slightly rounded crystals.

Olivine crystals have been recrystallized to mesh-texture serpentine with mesh centres being composed of finely interwoven serpentine. Clinopyroxene bastite preserves the parting of the original clinopyroxene crystals.

UPPER WEHRLITE

The rocks range from grey green to olive drab or greenish black and possess a resinous or waxy lustre towards the top of the layer. Intercumulus minerals make up greater than 10 percent of the rock and are represented by alteration products after original clinopyroxene oikocrysts and intercumulus plagioclase. Rock fabric (serpentine foliation, fractures, and magnetite $\pm$ serpentine $\pm$ carbonate veins) is not as well developed as in the underlying dunite.

Original olivine crystals possess rounded polyhedral to granular shapes. The rocks become coarser grained and better preserved toward the middle of the layer, where original olivine crystals up to 4 mm, clinopyroxene oikocrysts up to 2.5 cm and chromite crystals up to 2.5 mm occur. Some of the large chromite crystals are anhedral and contain inclusions of clinopyroxene and olivine. Many rounded chromite crystals have circular inclusions, some of which are partly occupied by pleochroic red-brown hornblende $\pm$ serpentine $\pm$ chlorite. Many of these large crystals have been substantially veined by serpentine.

A narrow layer (less than 1 m) of laminated gabbro that occurs in the middle of the coarse grained zone, displays evidence of strain, as do the wehrlites on either side. The lamination within the layer is caused by mm-scale alternation of clinopyroxene-rich and garnet-rich laminae. Individual, elongate clinopyroxene crystals are oriented with their long axes parallel to the laminae. The garnet is similar to that identified as a mixture of hydrogrossular and grossular in rocks near the base of the hole. Hydrogrossular is an alteration product after original plagioclase.

The laminated gabbro separates wehrlite that is similar in composition and grain size except for chromite, which is much finer grained (0.15 mm) and less abundant above the gabbro than below it.

Olivine has been recrystallized to mesh-texture serpentine that in places approaches curtain-growth serpentine. In a few examples, curtain-growth serpentine is propagated at right angles to the direction of preferred orientation of original elongate olivine crystals. Intercumulus areas are occupied by fine grained serpentine, chlorite and clinopyroxene bastite. The original rock was plagioclase-bearing wehrlite.

Clinopyroxene cumulate layer

The rock is granular, grey green and massive. At the base of the layer it is composed of equidimensional prismatic crystals that possess simple mutual grain boundaries. Irregularly shaped olivine crystals that occupy intercumulus areas lack clinopyroxene inclusions and may represent original cumulus crystals whose crystal shape was modified by postcumulus crystallization. In the middle of the layer the clinopyroxene crystals have apparently been modified by adcumulus growth that results in a mosaic of crystals forming complex polycrystalline aggregates. Mutual grain boundaries are complex and strongly interdigitated. Stubby, prismatic, cumulus olivine crystals in this rock contrast with the irregular crystals at the base of the layer. In the upper part of the layer, clinopyroxene crystals possess polyhedral shapes and share straight to slightly curving boundaries with adjacent crystals (Plate 38). The character of these crystals is similar to the polyhedral olivine crystals of many dunites. Olivine occurs as irregular crystals similar to that at the base of the layer.

The rocks are well preserved; the original intercumulus plagioclase has been replaced by chlorite and olivine displays incipient alteration to bipartite serpentine veins.

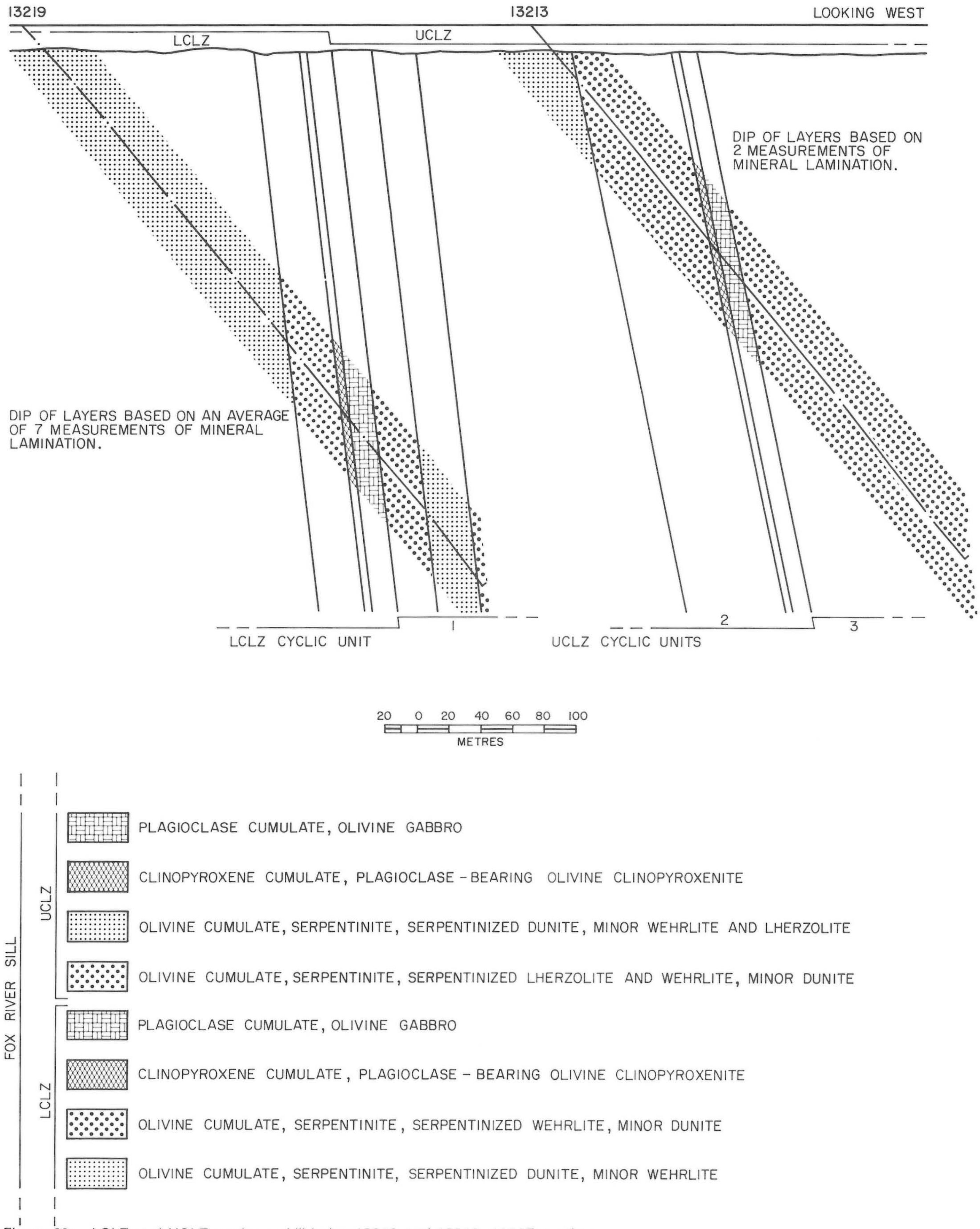


Figure 69: LCLZ and UCLZ geology, drill holes 13219 and 13213, 1086E section.

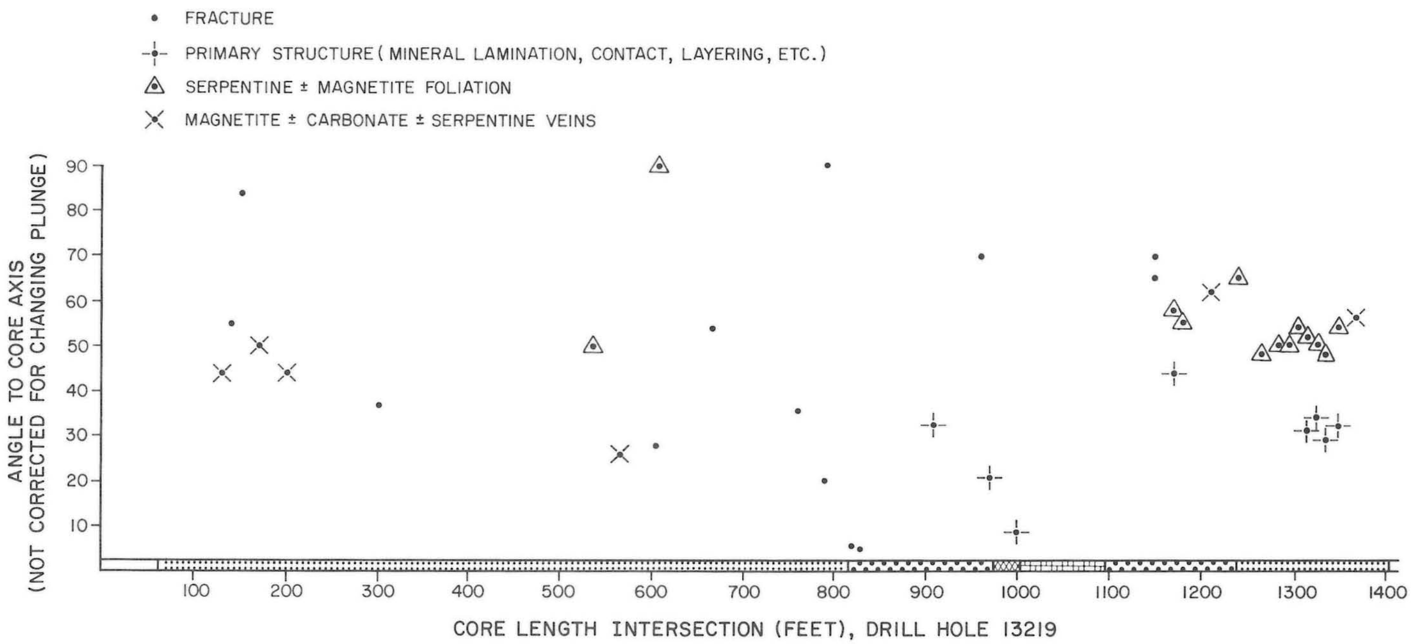


Figure 70: Core axis angles to planar structures, drill hole 13219.

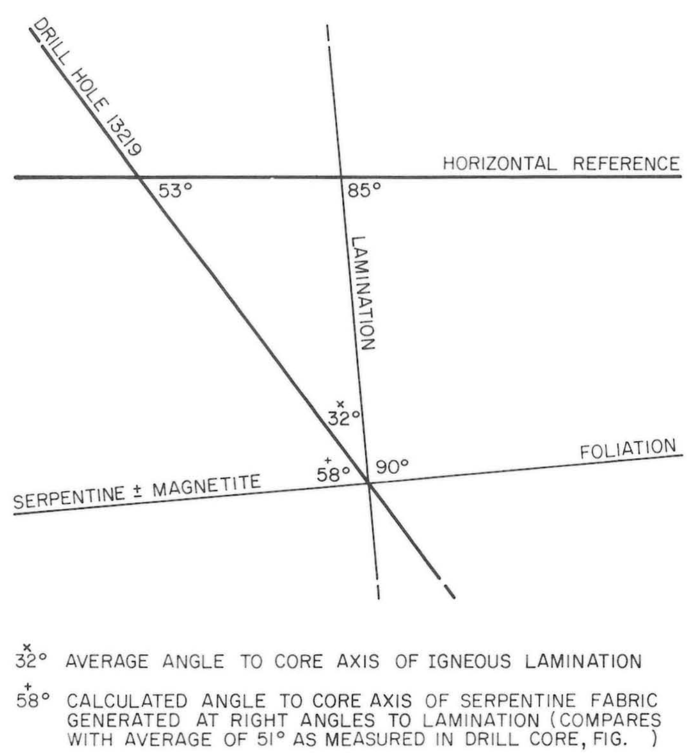


Figure 71: Angular relationship between serpentine fabric and igneous lamination in dunite, drill hole 13219.

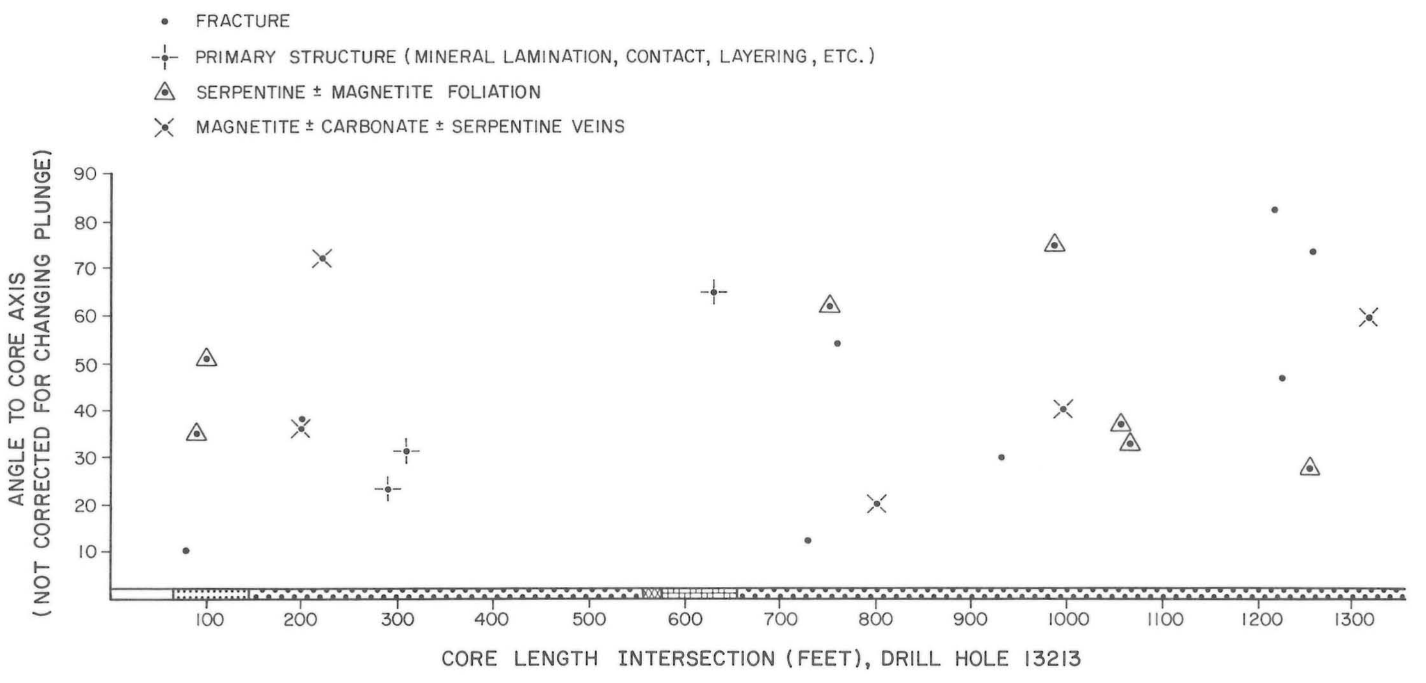
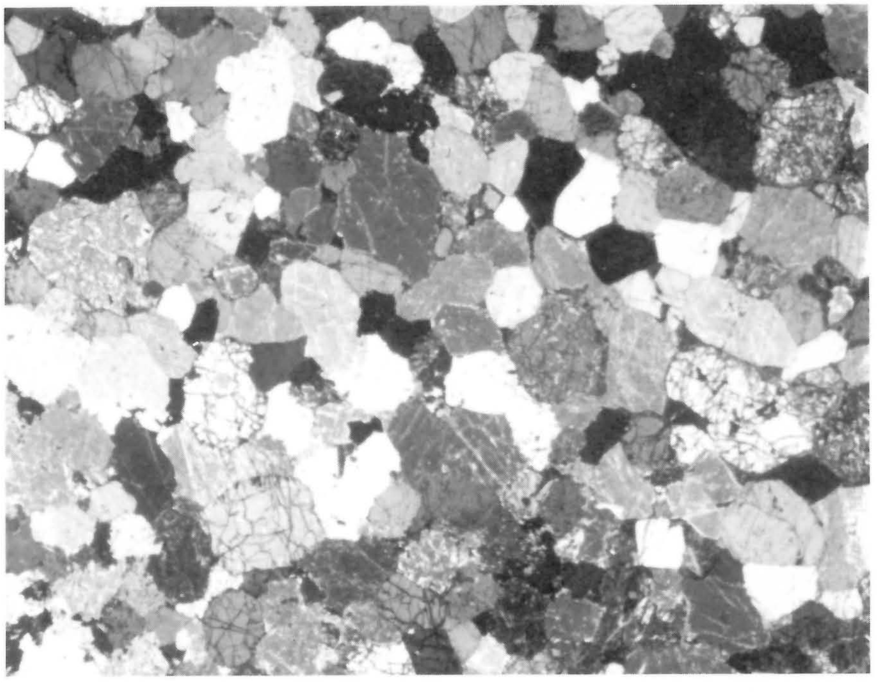


Figure 72: Core axis angles to planar structures, drill hole 13213.

Plate 38: Clinopyroxene + olivine cumulate. Polyhedral clinopyroxene crystals share simple, straight to slightly curving boundaries with adjacent crystals. LCLZ, clinopyroxene cumulate, DDH 13219-980. XN.



Plagioclase cumulate layer

The rocks are granular, massive and grey, and become more highly recrystallized toward the top of the layer. Lath and plate-like plagioclase crystals display a crude preferred orientation (Plate 39) and clinopyroxene occurs as irregular crystals, some with inclusions of plagioclase. Equidimensional rounded olivine crystals contain plagioclase inclusions and likely originated through postcumulus crystallization. Olivine decreases in abundance toward the top of the layer where it is absent.

Plagioclase displays incipient alteration to muscovite + epidote near the base of the layer, is recrystallized to epidote + chlorite in the middle of the layer, and has been completely replaced by an assemblage of garnet + carbonate + chlorite at the top of the layer. A prehnite + chlorite + carbonate veinlet was recognized toward the top of the layer. Tremolite partly replaces clinopyroxene and olivine.

One rock contains irregular masses of interstitial pyrrhotite.

462W SECTION - DRILL HOLES 13237, 13235, 13231 AND 13234

Five of the eight drill holes that compose the section were collared on the section line, and three were collared within 140 m of the line. The drill holes intersect the uppermost LCLZ cyclic units, the LCLZ-UCLZ contact, much of the UCLZ sequence, the HRZ, and the roof contact of the Sill. Four of the drill holes intersect uppermost LCLZ units, of which two holes penetrate the LCLZ-UCLZ contact. Locations for drill holes 13231, 13234, 13235 and 13237 are shown in Figure 73 and a compilation of the geology for the middle part of 462W section is illustrated in Figure 74.

Drill hole 13237

The drill hole intersects a sequence of LCLZ rocks that includes a portion of a three-part cyclic unit, a beheaded or incomplete cyclic unit, and part of the olivine cumulate layer of the next overlying cyclic unit (Fig. 75). The number of cyclic units between the LCLZ-MZ contact and this drill hole in this area is unknown, and the cyclic units intersected by the hole have been arbitrarily numbered 1, 2 and 3 from south to north or stratigraphically upward.

CYCLIC UNIT 1

Olivine cumulate layer

Original olivine cumulate rocks are dark to light apple green and are composed of a dense accumulation of serpentine pseudomorphs after olivine. Curtain-growth serpentine replacing olivine and developed at right angles to the direction of preferred orientation of original olivine crystals is approximately parallel to the core axis. Many of the serpentinites are cut by networks of hair-like fractures.

The rocks were originally medium grained dunite with original olivine crystals averaging 2 mm in size. Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. In one original plagioclase-bearing wehrlite (intercumulus minerals more than 10 percent), the serpentine pseudomorphs after olivine possess rectangular to elongate elliptical shapes. Fine grained, nearly isotropic serpentine replaces original intercumulus clinopyroxene, and chlorite ± phlogopite replaces original intercumulus plagioclase. Disseminated euhedral chromite (up to 0.3 mm in size) makes up 1 to 2 percent of the rock.

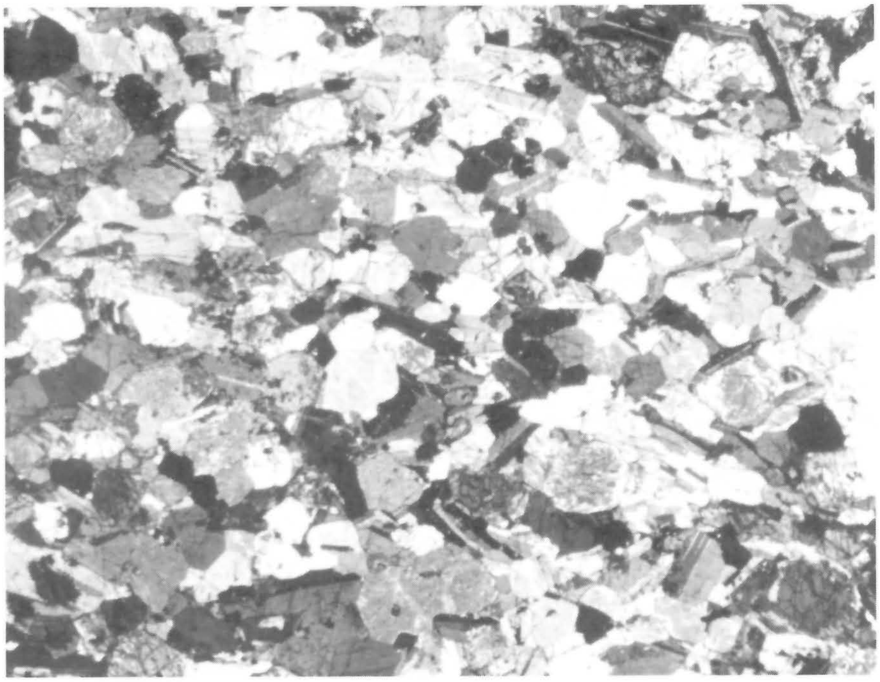


Plate 39: Plagioclase + clinopyroxene cumulate. Plagioclase laths display crude preferred orientation. LCLZ, plagioclase cumulate, DDH 13219-1005, XN.

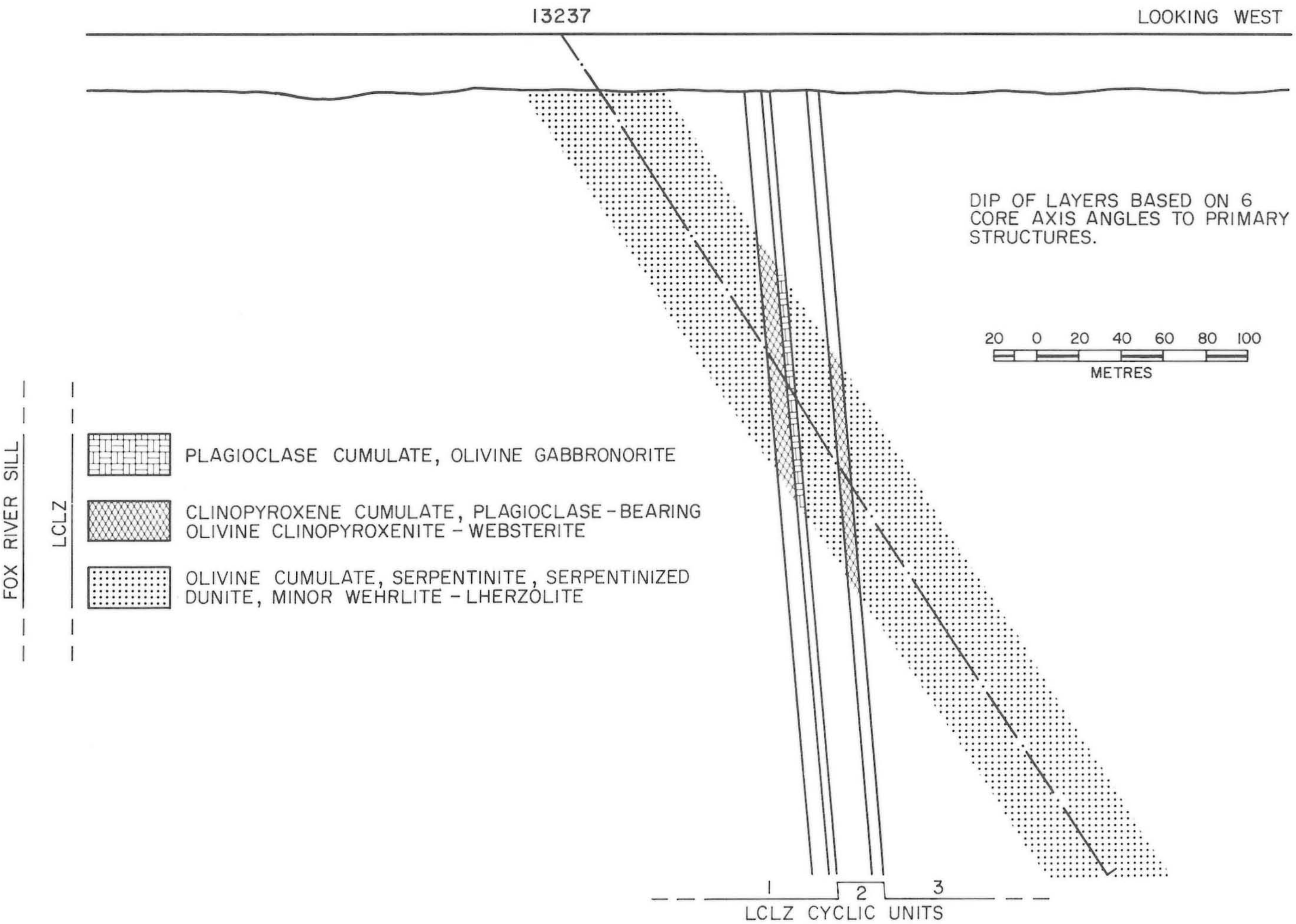


Figure 73: LCLZ geology, drill hole 13237, 462W section.

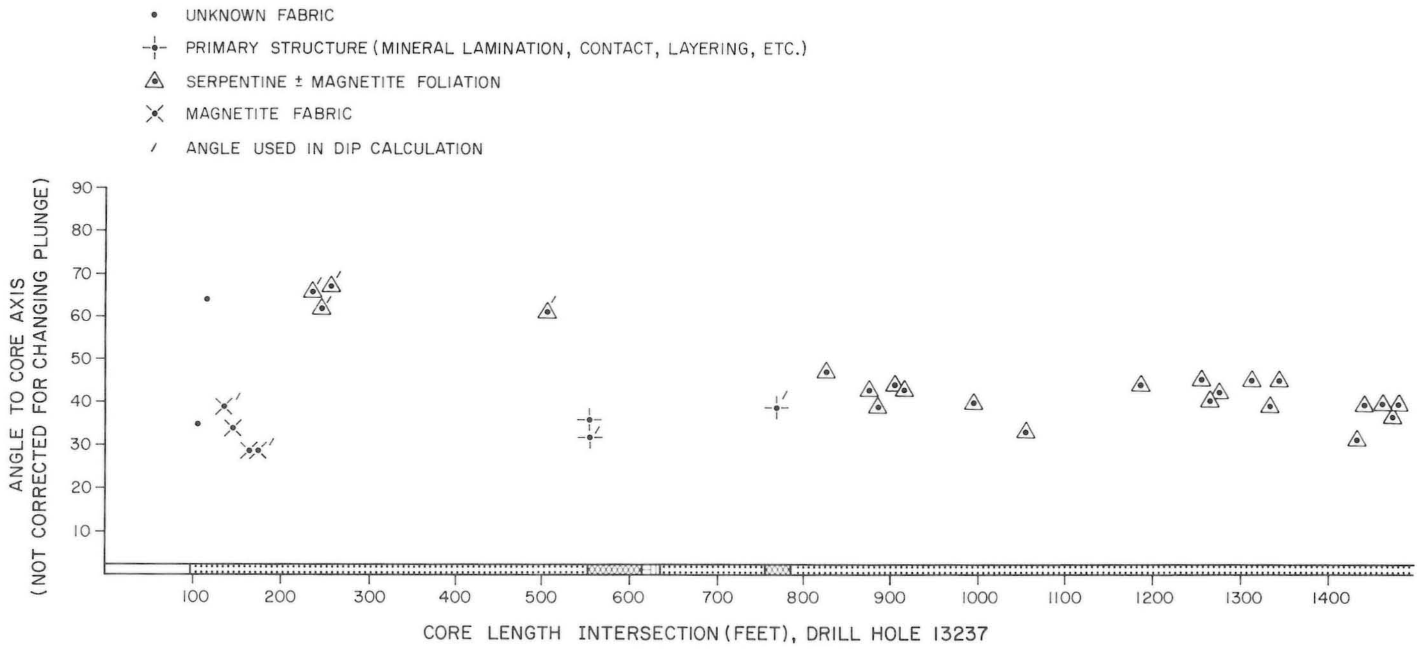


Figure 74: Core axis angles to planar structures, drill hole 13237.

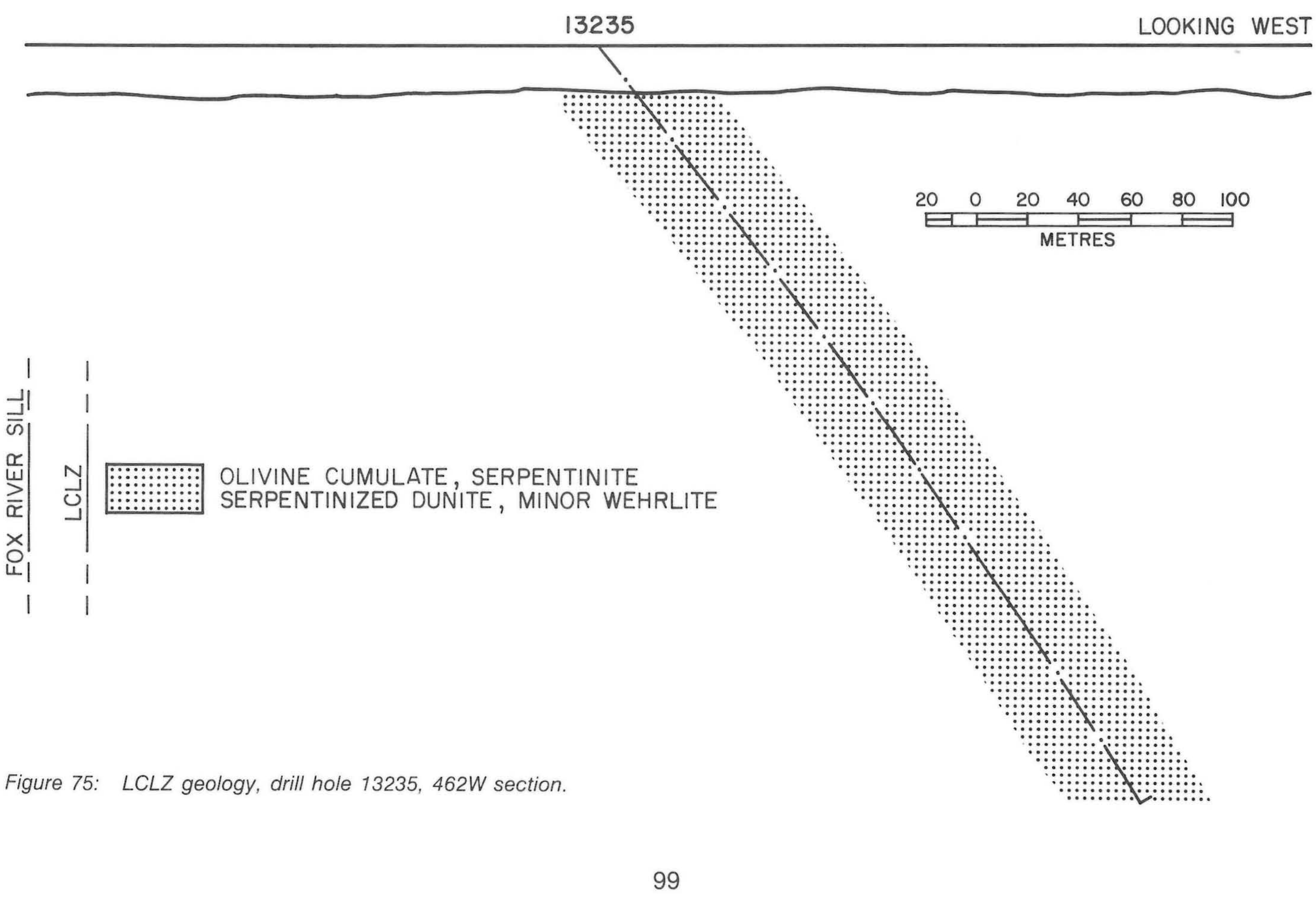


Figure 75: LCLZ geology, drill hole 13235, 462W section.

Clinopyroxene cumulate layer

Clinopyroxene cumulate rocks are massive grey green and granular, and the contact with the underlying olivine cumulate layer is sharp. Near the contact, the rock is composed of a continuous network of clinopyroxene crystals, many possessing irregular shapes with moderately complex mutual boundaries. Irregularly shaped areas composed of serpentine replace original clusters of cumulus olivine. Despite the sharp contact with the underlying olivine cumulate layer, 25 percent of the rock is composed of olivine for several centimetres above the contact.

The bulk of the clinopyroxene cumulate layer is composed of an aggregate of prismatic to somewhat irregularly shaped clinopyroxene crystals that possess uncomplicated mutual contacts. A few complex polycrystalline aggregates possessing highly interdigitated, complex mutual boundaries were noted toward the top of the unit. Poikilitic orthopyroxene crystals with inclusions of clinopyroxene and olivine were also noted near the top of the unit. Postcumulus plagioclase, now altered to chlorite + epidote, was an original constituent of the unit. The original rock ranged from plagioclase-bearing olivine clinopyroxenite at the base of the layer to plagioclase-bearing olivine websterite toward the top.

Plagioclase cumulate layer

Plagioclase cumulate rocks are light grey green and mottled, and the contact with the underlying clinopyroxene cumulate layer is not exposed in the telescoped core. The rocks are composed of plate-like plagioclase crystals, that are partly to completely altered to epidote ± chlorite, and highly irregular clinopyroxene crystals that display incipient alteration to tremolite. Irregular patches of felted tremolite replace original olivine, and original poikilitic orthopyroxene has been replaced by nearly isotropic chlorite. Despite its highly irregular shape, a lack of inclusions suggests that clinopyroxene may have been an original cumulus phase whose crystal shapes have been modified by postcumulus growth. Near the base of the layer, the rock displays a microscopic-scale lamination defined by alternating clinopyroxene-rich and plagioclase-rich lenses and laminae.

CYCLIC UNIT 2

Cyclic unit 2, a beheaded or incomplete cyclic unit, consists of a 16 m (approximate true thickness) olivine cumulate layer overlain by a 5 m thick clinopyroxene cumulate layer.

Olivine cumulate layer

The olivine cumulate is a medium to dark apple-green rock that was originally dunite. The rock is essentially similar to that of the underlying olivine cumulate layer, except that near the base of the layer, sporadically distributed clots of sulphide constitute approximately 1 percent of the rock. The original olivines have been pseudomorphously replaced by mesh-textured serpentine that possesses plate-like, pale grey green, nonfibrous mesh centres. Disseminated chromite constitutes from 1 to 2 percent of the rock near the base of the layer and makes up less than 1 percent of the rock near the top.

Clinopyroxene cumulate layer

The clinopyroxene cumulate layer is composed of a grey-green granular rock that is somewhat mottled and coarser grained than the clinopyroxene cumulate of cyclic unit 1. The contact with the underlying olivine cumulate is gradational over several centimetres.

Near the contact, the rock is composed of a continuous mosaic of interlocking, irregularly shaped clinopyroxene crystals surrounding clusters of serpentine pseudomorphs after original polyhedral to rounded polyhedral cumulus olivine crystals. Clinopyroxene forms an interlocking crystal mosaic throughout the layer, and patches of serpentine ± tremolite ± chlorite form bastite-like pseudomorphs after original poikilitic orthopyroxene. Irregular patches of serpentine replace original individual olivine crystals, and chlorite ± epidote replaces original postcumulus plagioclase. Clots of sulphide are sporadically distributed and constitute less than 1 percent of the rock. The clinopyroxene cumulate is predominantly a plagioclase-bearing olivine websterite.

CYCLIC UNIT 3

Olivine cumulate layer

The relatively thick portion (100 m, estimated true thickness) of the olivine cumulate layer of the next overlying cyclic unit is a dark apple-green rock with networks of hair-like fractures. Much of the unit is characterized by closely spaced (mm-scale), parallel serpentine veinlets that impart a well defined fabric. Several picrolitic serpentine ± carbonate breccia zones were observed.

The rocks are composed of a dense accumulation of serpentine pseudomorphs after original polyhedral- to polygonal-olivine crystals. Portions of the rock are distinguished by clinopyroxene oikocrysts (up to 1 cm in size) that have a sporadic distribution. At thin-section scale, where oikocrysts are absent, the intercumulus area is less than 10 percent and the rock is a dunite. In wehrlites, where clinopyroxene oikocrysts range up to 20 percent, olivine commonly occurred as elongate, rounded polyhedral crystals. A rock estimated to contain less than 3 percent intercumulus area is characterized by a mosaic of serpentine pseudomorphs after original polygonal olivine crystals. Serpentine pseudomorphs after olivine crystals average 2 to 3 mm in size in these medium grained rocks. Original postcumulus plagioclase has been replaced by chlorite ± phlogopite. Chromite occurs as disseminated euhedral crystals (up to 0.3 mm) and clusters of crystals, and constitutes from less than 1 to 3 percent of the rock. Sporadically distributed clots of sulphide make up less than 1 percent of the rock.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. Clinopyroxene, which is partly preserved, has been replaced by clinopyroxene bastite and by fine grained nearly isotropic serpentine. Patches of serpentine resembling orthopyroxene bastite are rare. A fine grained, brownish nonpleochroic fibrous material occupies intercumulus areas and may represent an alteration after clinopyroxene. The rocks were originally dunite with local areas of wehrlite.

Drill holes 13234 and 13235

Drill holes 13234 and 13235, collared approximately 265 m apart (Figs. 73, 74, 75, 76, 77 and 78), are drilled in the same direction, and each intersects a thick sequence of olivine cumulate that was predominantly dunite. At the base of drill hole 13234 a thin clinopyroxenite layer that was intersected (4.5 m estimated true thickness) is interpreted as representing the top of the uppermost LCLZ cyclic unit in this area. The pyroxenite is overlain by mottled wehrlite-lherzolite, interpreted to represent the olivine cumulate of the lowermost UCLZ cyclic unit in this area. Thin sections were not prepared from these drill holes because the holes penetrate the same sequence of dunite-wehrlite intersected by drill hole 13231. The following descriptions are based on megascopic observations.

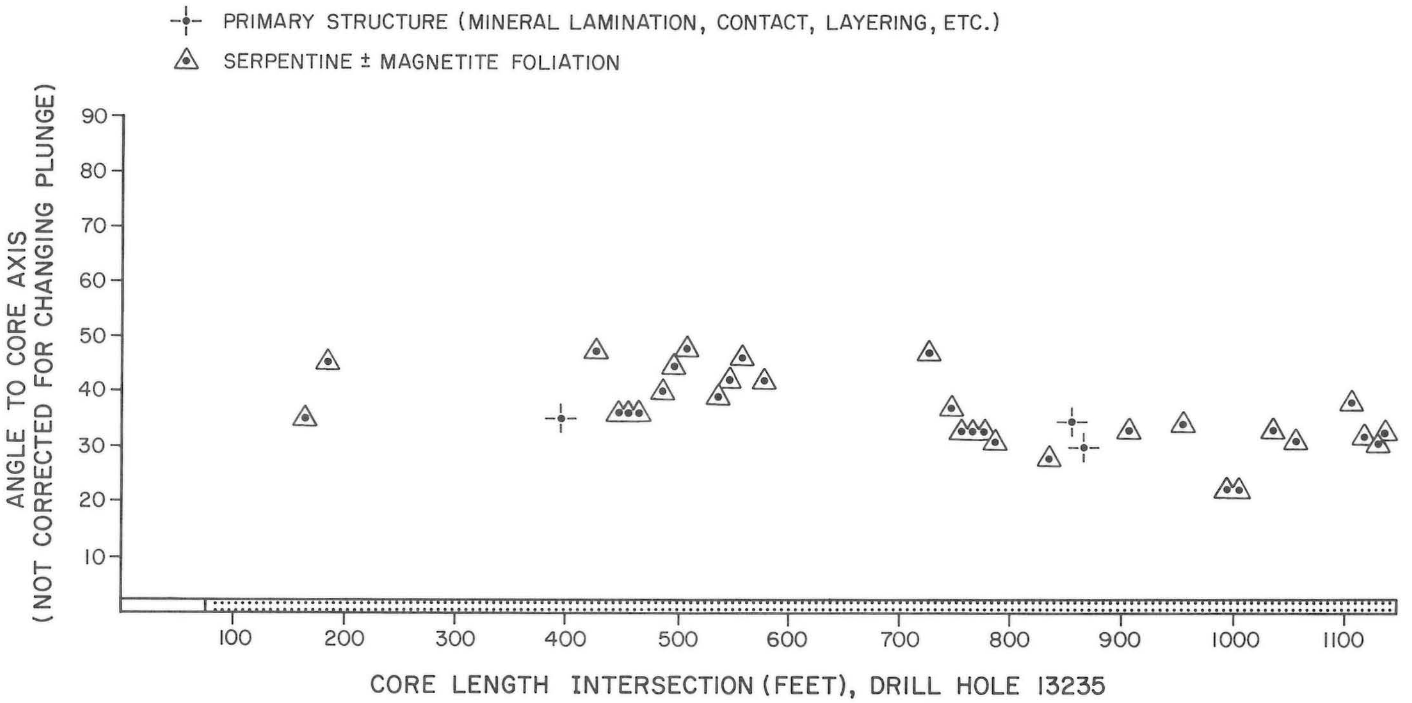


Figure 76: Core axis angles to planar structures, drill hole 13235.

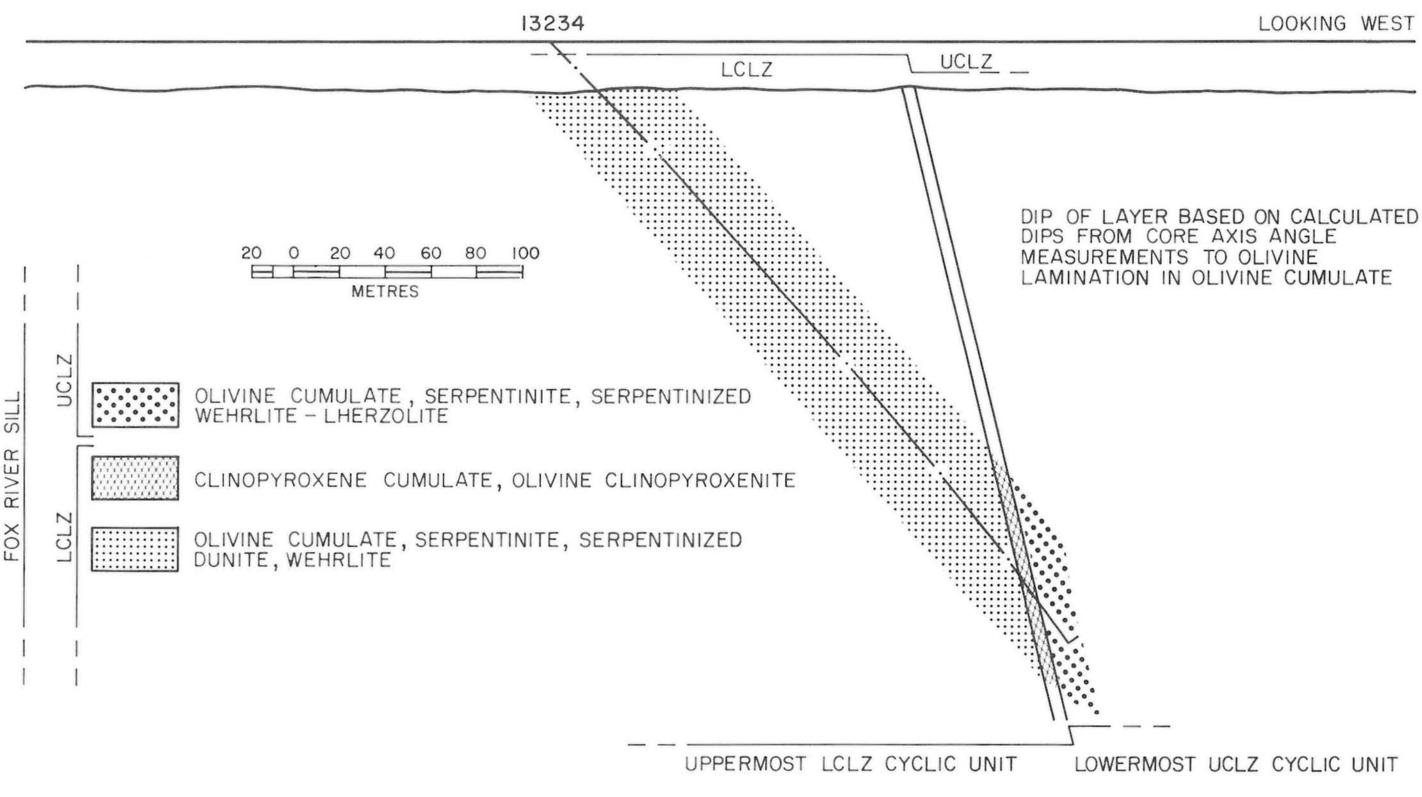


Figure 77: LCLZ-UCLZ geology, drill hole 13234, 462W section.

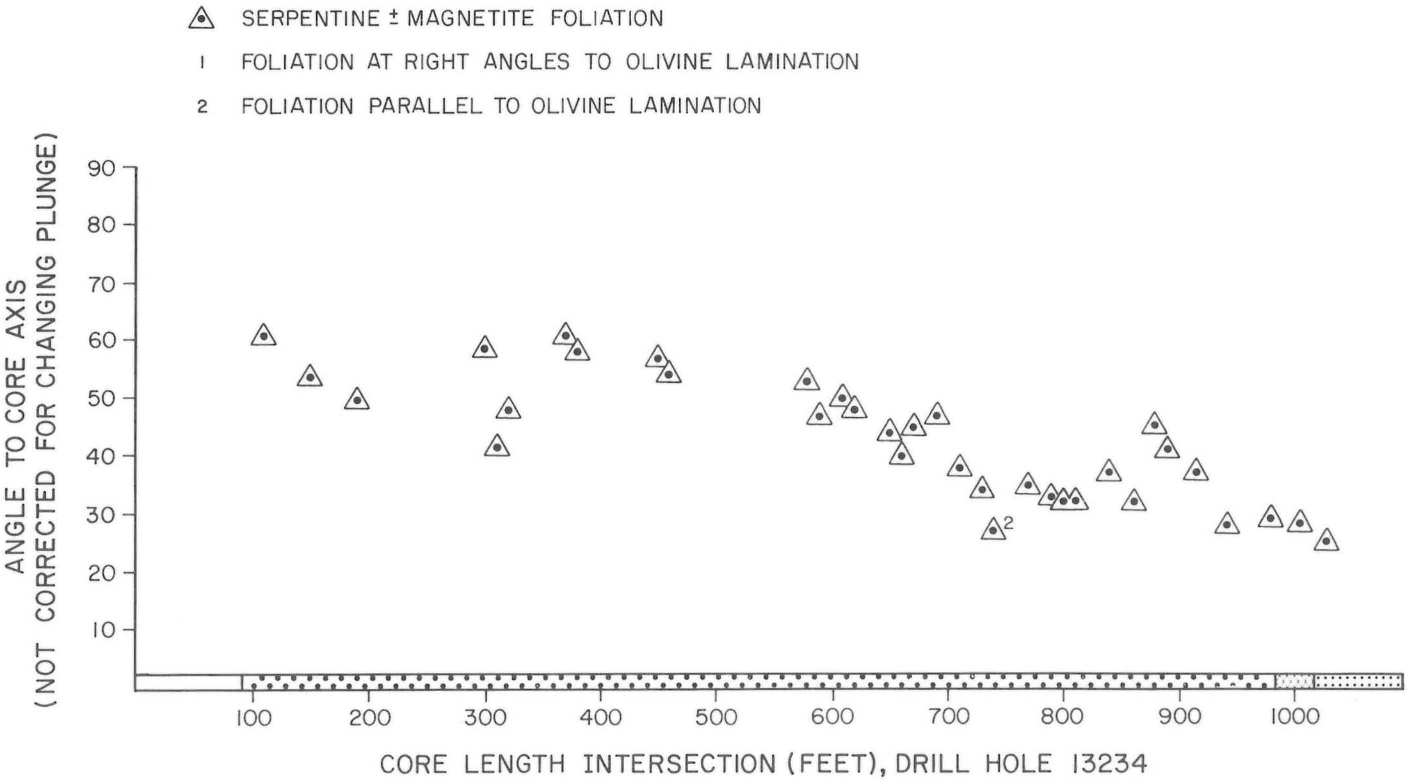


Figure 78: Core axis to planar structures, drill hole 13234.

UPPERMOST LCLZ CYCLIC UNIT

Olivine cumulate layer

The rocks are medium- to dark-apple green to greenish black, the latter displays a waxy lustre, and some display a delicate mottling due to sporadically distributed oikocrysts. Networks of hair-like fractures are well developed, some rocks possessing early serpentine-filled fractures cut by late stage carbonate-filled fractures. A well developed serpentine ± magnetite foliation is at right angles to lamination of original elongate olivine in some rocks, and is parallel to the same primary lamination in other rocks. Portions of the sequence that are peridotitic tend to be coarser grained with original olivine crystals averaging 2 to 3 mm, whereas olivine crystals average 1 to 2 mm in original dunite. A number of picrolitic serpentine zones were observed, as well as several centimetres of gabbroic pegmatite. Sporadically distributed disseminated sulphides constitute 1 to 2 percent of the rock in a number of areas.

Clinopyroxene cumulate layer

The pyroxenite is grey green and granular and is similar to other pyroxenites previously described. It is characterized by local areas of disseminated sulphides that make up 1 to 2 percent of the rock. Neither contact is exposed in the telescoped core.

Drill hole 13231

Drill hole 13231 intersects a portion of the uppermost LCLZ cyclic unit in this area, as well as a substantial portion (approximately 152 m, estimated true thickness) of the lowermost successions of the UCLZ (Figs. 79, 80, 81 and 82).

UPPERMOST LCLZ CYCLIC UNIT

Olivine cumulate layer

The original olivine cumulate consists of a sequence of medium- to dark-apple green rocks that become darker green toward the contact with pyroxenite. Serpentine fabric is well developed in a few rocks where it is clearly at right angles to the direction of elongation of the original olivine crystals. In places, disseminated sulphide constitutes up to 1 percent of the rock.

Original olivine crystals ranged from rounded polyhedral and elongate crystals to clusters of polygonal crystals. Olivine grain size averages 1.5 to 2 mm in original dunite and 2 to 3 mm in original peridotite. Fine grained serpentine replaces original clinopyroxene oikocrysts and in a few rocks orthopyroxene bastite replaces original poikilitic orthopyroxene crystals. Original postcumulus plagioclase has been replaced by chlorite ± epidote. Disseminated euhedral

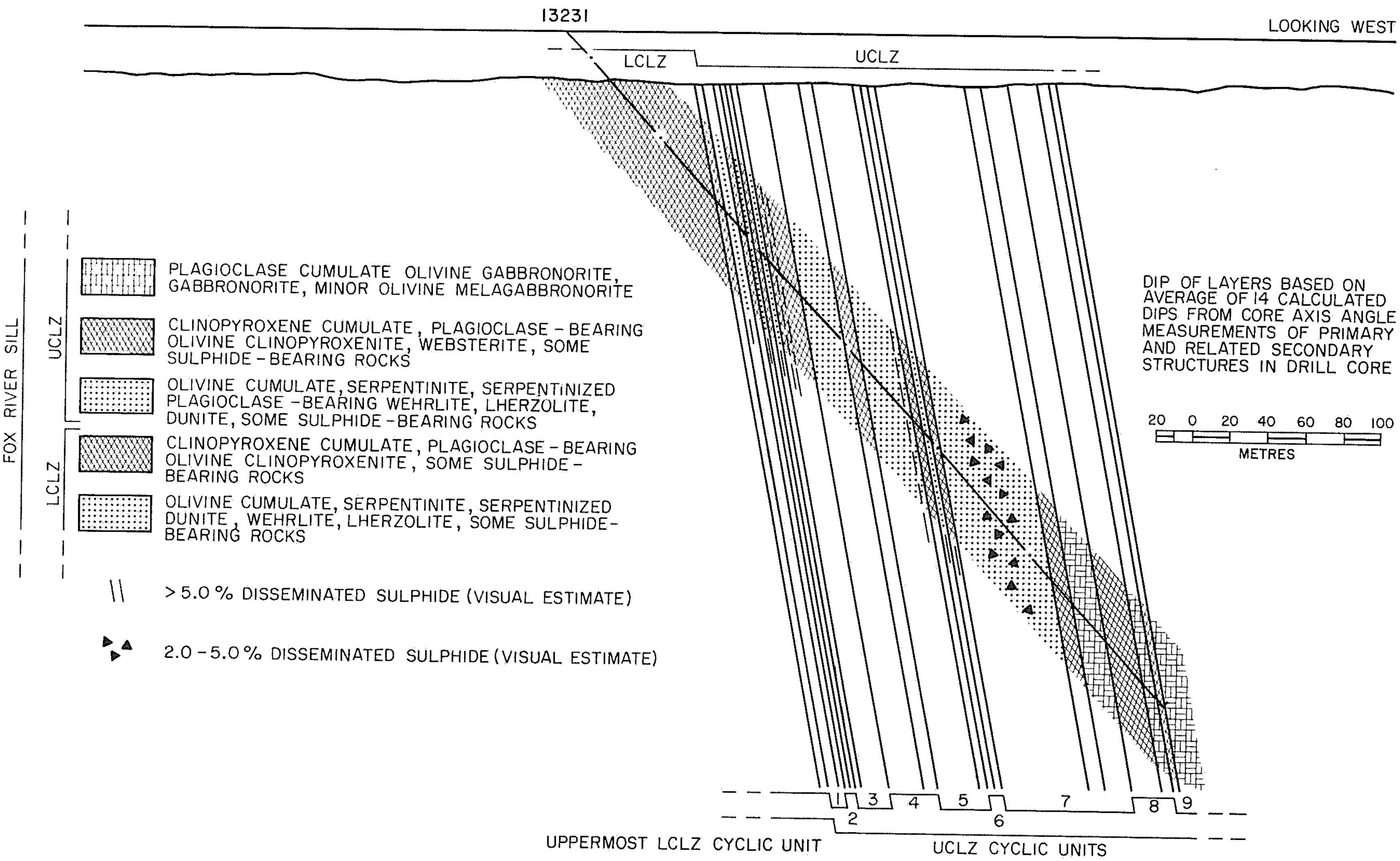


Figure 79: LCLZ-UCLZ geology, drill hole 13231, 462W section.

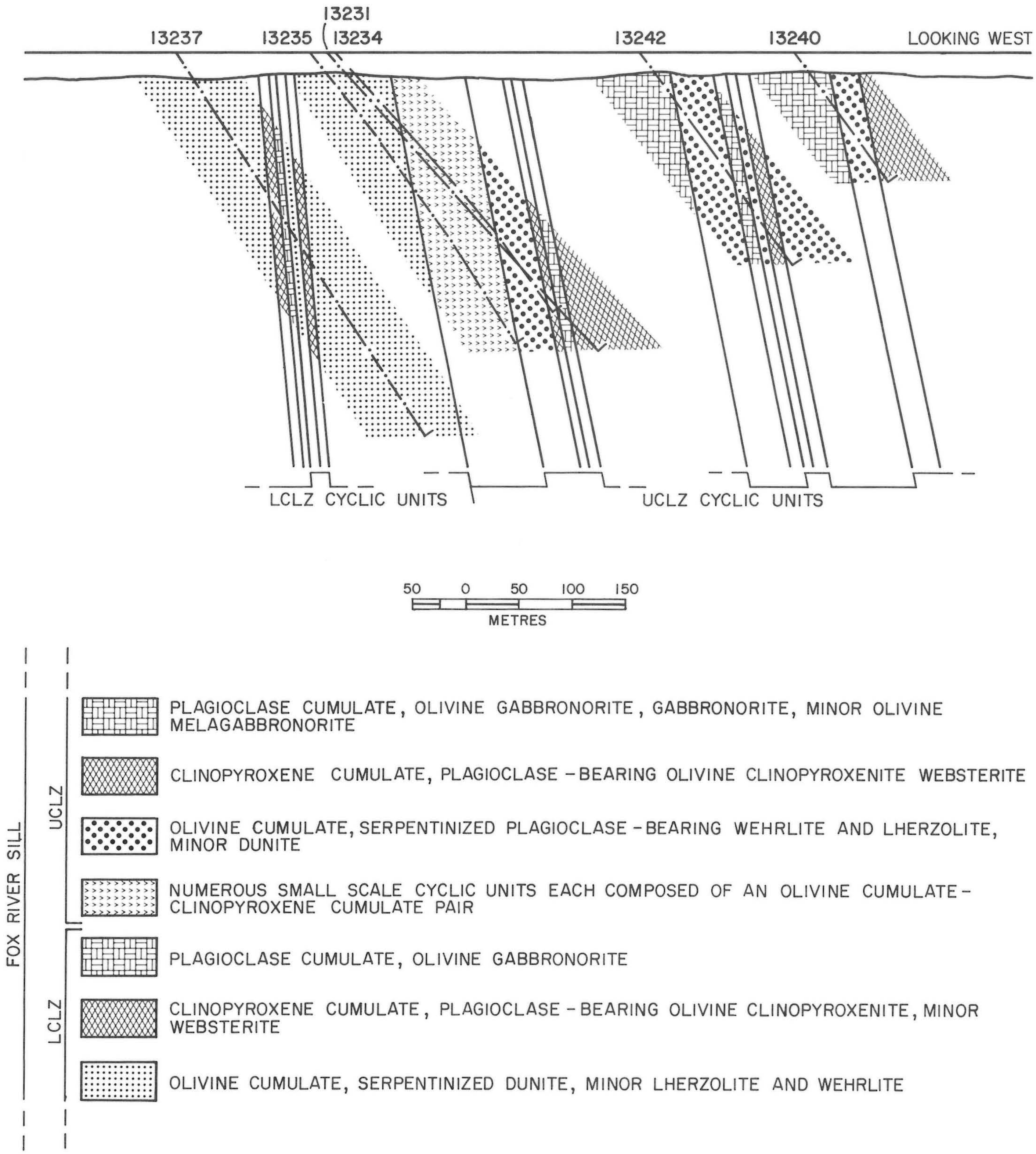


Figure 80: Geological compilation, 462W section.

chromite (up to 0.75 mm) constitutes from less than 1 to 3 percent of the rock.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine, the latter displays parallel growth in many rocks. Secondary magnetite constitutes up to 3 percent of some rocks where it partly outlines original olivine crystal boundaries, forms dust-like concentrations in serpentine after original clinopyroxene, or occurs as intergrowths in talc and chlorite. Talc ± magnetite is sporadically distributed as discrete crystals in intercumulus areas. Sulphide minerals form discrete bleb-like or globular masses in intercumulus areas and occur as inclusions in original poikilitic orthopyroxene crystals.

The original olivine cumulate ranged from plagioclase-wehrlite and lherzolite, to dunite in composition.

Clinopyroxene cumulate layer

The clinopyroxene cumulate is dark greenish black granular, mottled and sulphide-bearing. The rock consists of an interlocking mosaic of clinopyroxene crystals that forms a continuous phase surrounding individual and clusters of olivine crystals, some of which are partly preserved. Nearly isotropic, clay-like material replaces postcumulus plagioclase, and olivine has been replaced by nonfibrous serpentine. The rock is plagioclase-bearing olivine clinopyroxenite and contains up to 10 percent intercumulus sulphide globules.

One olivine determination from the clinopyroxene cumulate ($Fo_{84.4}$) is compatible with olivine determinations from other LCLZ clinopyroxene cumulate rocks (Fig. 83).

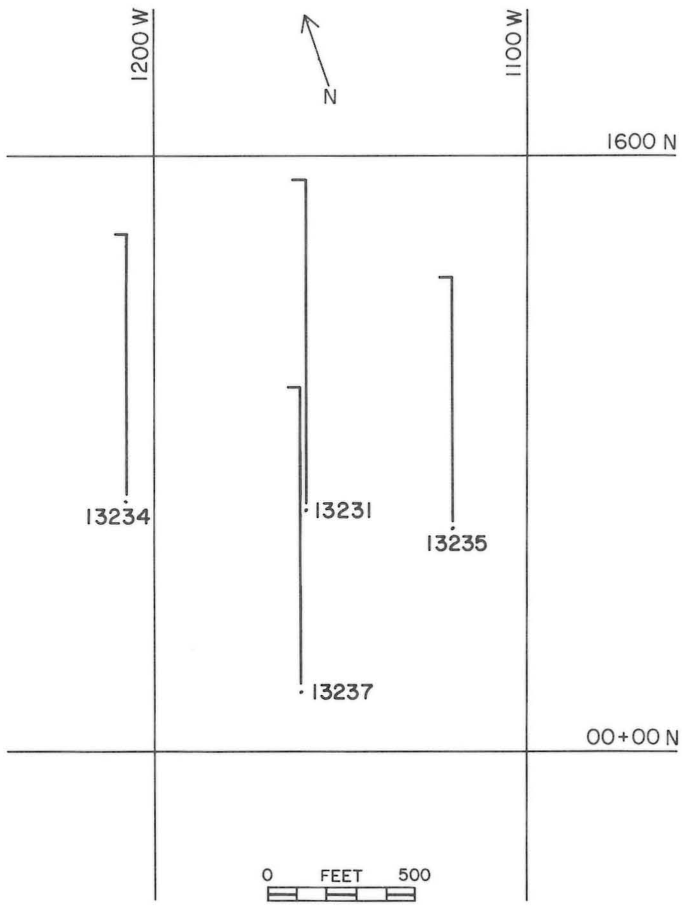


Figure 81: Drill hole locations, central part 462W section.

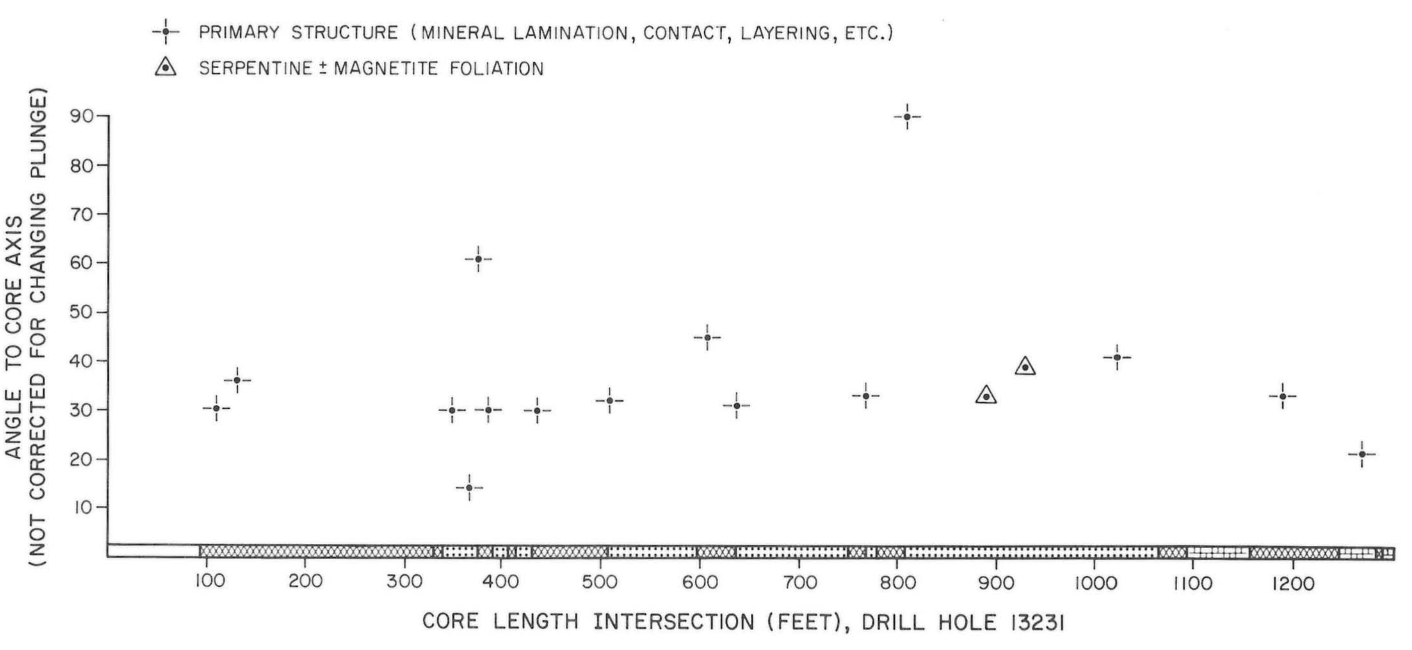


Figure 82: Core axis angles to planar structures, drill hole 13231.

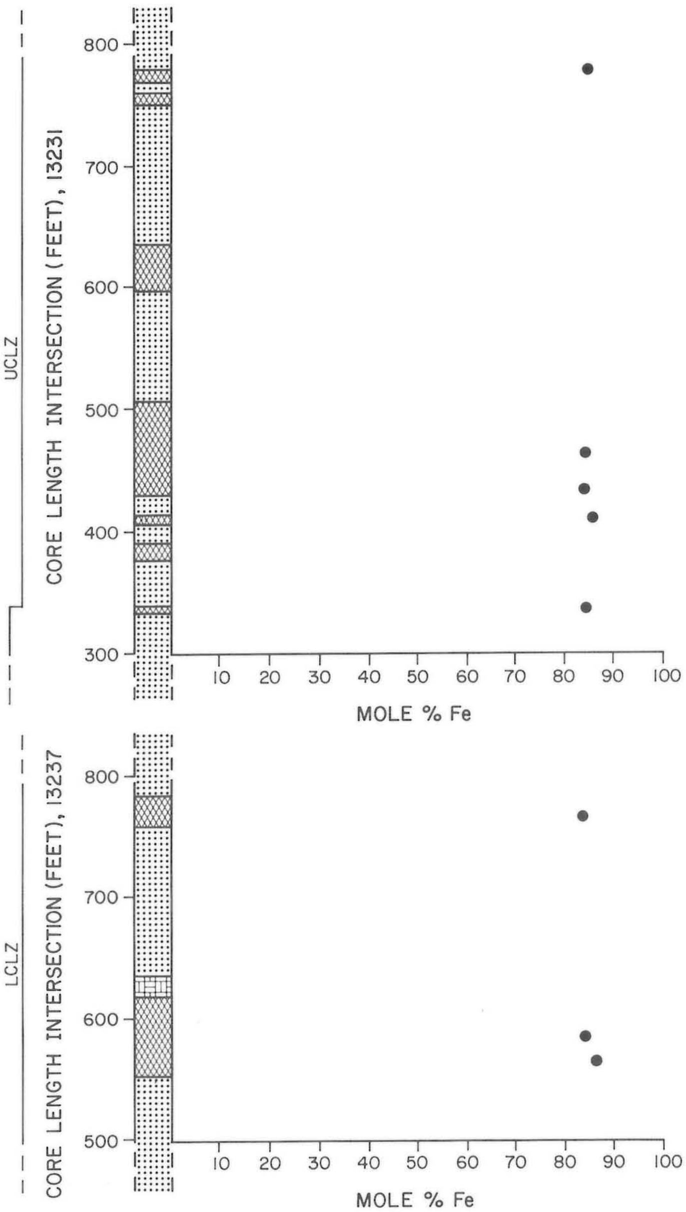


Figure 83: Olivine compositions, drill holes 13237, 13231, 462W section.

DISSEMINATED SULPHIDE

The disseminated sulphides present in the clinopyroxene cumulate layer may have originated in the magma batch that produced the overlying sulphide-bearing, UCLZ cyclic unit. Sulphide minerals are not abundant in LCLZ rocks for the most part, and concentrations in excess of 2 percent are rare. However, disseminated sulphides in abundances of 5 percent and greater, distinguish some of the early-formed UCLZ cyclic units in this area, including the first UCLZ cyclic unit. The disseminated sulphide in the underlying LCLZ clinopyroxene cumulate may have originated as an immiscible sulphide phase in the magma pulse that gave rise to the initial UCLZ cycle. Because of its high density the sulphide would sink rapidly to the crystal/magma interface. Since the material below the interface would have been an unconsolidated mush of crystals (clinopyroxene) and intercumulus magma, the sulphide could have descended below the interface displaying intercumulus magma (± crystals) upward. The sulphide phase would descend until resistance due to consolidation prevented further downward movement.

OTHER DRILL HOLES: DRILL HOLE 13205

Drill hole 13205

Drill hole 13205 intersects what is interpreted to be the contact between LCLZ and UCLZ rocks (Fig. 84). The interpretation is based on a change in character of the original olivine cumulate rocks. The hole, drilled north, cuts serpentinized dunite and minor serpentinized wehrlite and lherzolite before intersecting thin (about 6 m estimated true thickness) clinopyroxene cumulate (plagioclase-bearing olivine clinopyroxenite) and plagioclase cumulate (olivine gabbronorite) layers. The olivine cumulate overlying the plagioclase cumulate is characterized by clinopyroxene bastite after originally large (up to 1 cm) clinopyroxene oikocrysts. Orthopyroxene bastite and chlorite replacing original plagioclase are also present. The rock at the base of the hole contains partly preserved olivine, clinopyroxene, and orthopyroxene and was originally a plagioclase-bearing lherzolite. There is a significant difference in the olivine cumulate that underlies the clinopyroxenite-gabbro pair and the olivine cumulate that overlies it. The latter is similar to UCLZ rocks that are predominantly plagioclase-bearing, wehrlite-lherzolite in composition. For this reason the contact between LCLZ and UCLZ rocks is placed at the upper contact of the plagioclase cumulate. The dunite (± wehrlite) - clinopyroxenite-gabbro suite is thus considered to represent the uppermost LCLZ cycle of fractional crystallization in this area.

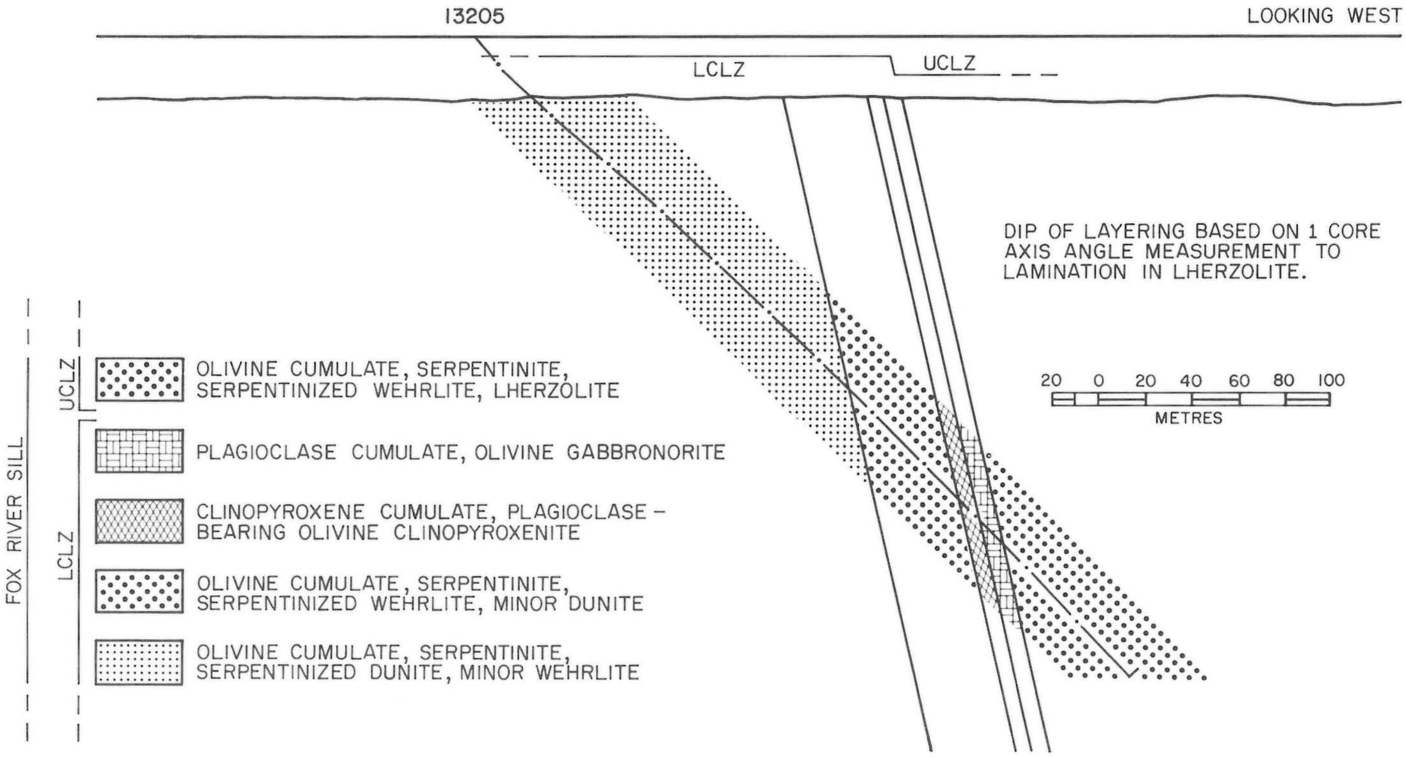


Figure 84: Upper LCLZ geology, drill hole 13205.

UPPERMOST LCLZ CYCLIC UNIT

Olivine cumulate layer

The rocks display a progressive change in colour toward the top of the olivine-rich unit (down the hole), from light- to dark-apple green to greenish black. The light apple-green serpentinites are dull, lustreless and earthy looking and crumble easily; as the rock becomes darker its character changes from earthy and lustreless to waxy. Fracture surfaces are coated with pale-blue carbonate and magnetite, and fracture spacing ranges from 5 to 10 mm. A few rocks possess numerous intersecting carbonate-filled fracture sets that impart a brecciated appearance to the rock. Fractures become less numerous toward the top of the unit. The primary texture is megascopically visible despite the intense serpentinization. These original olivine-rich rocks possess what has been referred to as "fish-eye" texture, caused by densely packed ovoid serpentine pseudomorphs after original olivine crystals.

Serpentinized dunite was originally composed of crudely equidimensional polyhedral to polygonal olivine crystals. Many of the polyhedral crystals have rounded terminations. As with previously described original olivine-rich rocks, these are somewhat heterogeneous in grain shape and size. Olivine crystals averaged 1 to 2 mm in size although crystals up to 5 mm have sporadic distribution. Because the original olivine crystals were crudely equidimensional, the presence of an original preferred orientation for olivine crystals is difficult to determine. However, an example of rare, well developed igneous lamination is illustrated in Plate 40. Chromite ranges from less than 1 to approximately 2 percent and constitutes up to 10 percent over 4 cm in one core sample of serpentinized dunite. The extent of this chromiferous dunite is unknown (telescoped core).

Original peridotites (more than 10 percent intercumulus minerals) tend to be coarser grained than the original dunites with which they are associated. This applies to original olivine crystals (that average 3 to 4 mm with some individuals up to 6 mm in size), to intercumulus minerals, and euhedral chromite crystals. The contact between serpentinized dunite and serpentinized wehrlite is gradational over approximately 30 m. In the peridotite overlying the dunite, intercumulus minerals increase in abundance toward the top of the layer, to such an extent that the intercumulus minerals become the continuous phase of the rock. The original composition of the peridotite changes from wehrlite (possibly plagioclase-bearing) near the base, to plagioclase-bearing lherzolite toward the top of the unit.

The rocks have been completely serpentinized with olivine pseudomorphously replaced by mesh-texture serpentine. The bipartite serpentine component of the mesh-texture serpentine is yellow green to brownish. In some rocks the bipartite veins become so well developed they form curtain-growth serpentine. Late stage, parallel serpentine veinlets are developed in a few rocks. Original clinopyroxene-bearing rocks are recognized by the presence of fine grained serpentine that preserves the well developed parting of the original clinopyroxene oikocryst. Chlorite replaces original postcumulus plagioclase. Orthopyroxene bastite is distinguished from clinopyroxene bastite by being coarser, by lack of inherited parting, and by replacement of more compact poikilitic crystals. Secondary magnetite forms irregular patches in intercumulus areas and discontinuous veinlets ($\pm$ carbonate).

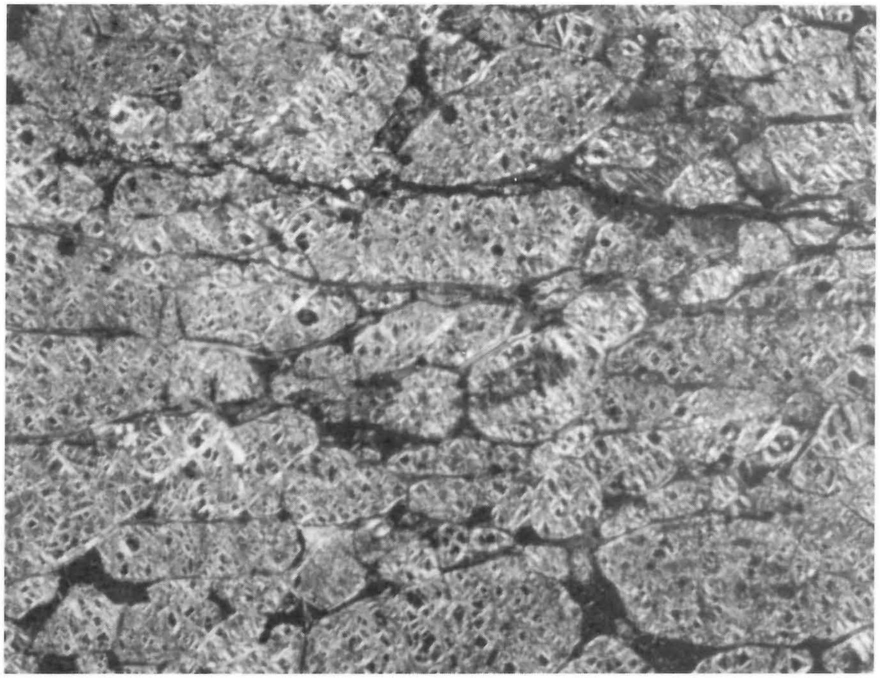
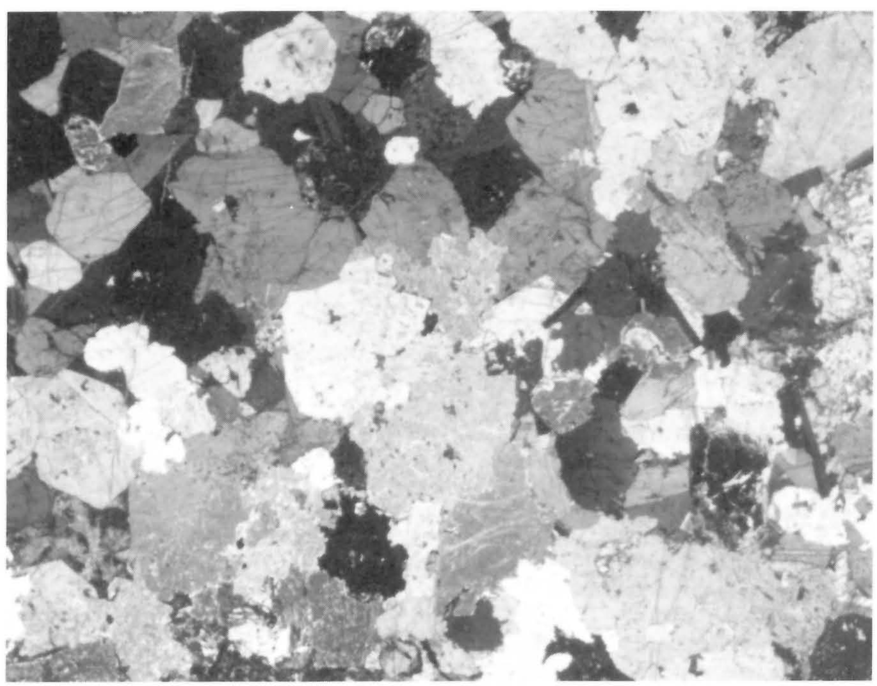


Plate 40: *Serpentine pseudomorphs after original elongate olivine crystals. Parallel orientation of olivines reflects original igneous lamination. LCLZ, olivine cumulate, DDH 13205-530, XN.*

Plate 41: *Clinopyroxene + olivine cumulate. Clinopyroxenes display complex, interdigitated mutual contacts (lower half of plate) and occur as regularly shaped crystals (upper left). LCLZ, clinopyroxene cumulate, DDH 13205-940, XN.*



Clinopyroxene cumulate layer

The clinopyroxene cumulate is medium grained, massive, granular and light- to dark-greyish green. The rock is well preserved and clinopyroxene forms small, regularly shaped prismatic crystals separated from each other by intercumulus plagioclase. In other areas clinopyroxene forms polycrystalline aggregates displaying complex, interdigitated mutual contacts (Plate 41). Olivine crystals (Fo_{82}), an original cumulus phase, are locally replaced by intermeshed tremolite laths ± plate-like tremolite. Plagioclase (An_{86}) displays incipient alteration to microcrystalline nearly isotropic chlorite. The rock was originally plagioclase-bearing olivine clinopyroxenite.

Plagioclase cumulate layer

The plagioclase cumulate is a medium grained, massive, granular light grey mottled or spotted rock. The randomly disposed, dark-green spots are talc + serpentine pseudomorphs after olivine. The rock is dominated by aggregates of lath plagioclase (An_{92}, Fig. 85) displaying a well developed lamination. The lamination is locally disrupted where plagioclase laths wrap around nearly equidimensional olivine crystals. Clinopyroxene crystals, possessing highly irregular shapes, occupy the intercumulus areas and many contain plagioclase inclusions. Patches of chlorite replace original plate-like orthopyroxene. The rock is an olivine gabbronorite.

WESTERN AND EASTERN EXTREMITIES

380W SECTION - DRILL HOLES 13206, 13202 and 13201

The drill holes of 380W section were collared within approximately 300 m of the western termination of the Sill. Here the Sill is estimated to be slightly in excess of 300 m thick. Drill holes 13206, 13202 and 13201 intersect approximately 200 m (estimated true thickness) of LCLZ rocks that consist of one cyclic unit composed of a thick (170 m) olivine cumulate, a thin (7 m) clinopyroxene cumulate and a plagioclase cumulate layer (21 m) (Fig. 27). The contact between LCLZ and UCLZ rocks has been placed at the top of the first or southernmost plagioclase cumulate layer where it separates different olivine cumulate rocks; UCLZ varieties are coarser grained and possess a greater volume of postcumulus phases than their LCLZ equivalents.

CYCLIC UNIT 1

Olivine cumulate layer

The rocks range from medium grey green and dark greenish black to apple green and dark apple green, and are somewhat waxy in appearance. Lherzolite occurs at the top of the layer, possesses a granular texture and is mottled. The shapes of the original olivine crystals are in part related to the abundance of intercumulus minerals. In rocks where intercumulus minerals are 10 percent or more, the original olivine crystals tend to have polyhedral or granular shapes. On the other hand, original dunites in this suite are characterized by clusters of mosaic-like polygonal olivine crystals. Original olivine crystals average 1 to 1.5 mm in size, although crystals up to 4 mm are not uncommon and one elongate crystal is 6 x 1.5 mm. Original elongate olivines display a crude preferred elongation in some rocks giving rise to a poorly defined lamination. Clinopyroxene bastite is the predominant intercumulus mineral, although areas of nearly isotropic chlorite and phlogopite ± magnetite also are present. Large clinopyroxene oikocrysts (up to 2 cm) are preserved in some rocks. Euhedral to slightly rounded chromite is disseminated as clusters of crystals in intercumulus areas, and constitutes from 1- to approximately 4 percent of the rock.

Olivine crystals have been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. The cores of some serpentine pseudomorphs after olivine are occupied by randomly disposed amphibole laths. Secondary magnetite constitutes from 2 to 4 percent of the rock as irregular patches and discontinuous veinlets (± serpentine), and is associated with phlogopite in intercumulus areas. Sparsely disseminated pinpoint sulphide is associated with magnetite in some rocks.

Clinopyroxene cumulate layer

The rocks are grey green and granular and near the base of the layer they have been cut by carbonate ± sulphide veinlets. They are composed of an aggregation of equidimensional, prismatic clinopyroxene crystals, and irregular complex polycrystalline aggregates that display incipient recrystallization to tremolite. Original postcumulus plagioclase has been completely converted to epidote + chlorite, and olivine has been replaced by chlorite + tremolite. Rare poikilitic orthopyroxene with clinopyroxene inclusions has been replaced by chlorite. The rocks are plagioclase-bearing clinopyroxenite to websterite in composition.

Plagioclase cumulate layer

The rocks are grey, granular and spotted or finely mottled and some rocks possess a crude lamination. They consist of an accumulation of plagioclase laths, and irregularly shaped

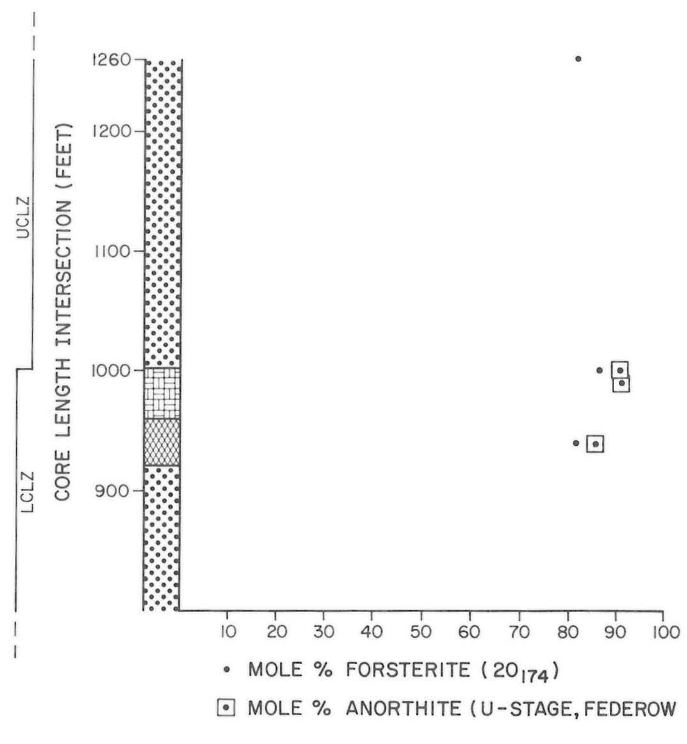


Figure 85: Olivine and plagioclase compositions, drill hole 13205.

clinopyroxene, the latter possibly being cumulus. Plagioclase has been completely converted to epidote + chlorite + muscovite, and tremolite + chlorite replace original poikilitic orthopyroxene and intercumulus olivine. The rocks are olivine gabbronorite in composition.

64W SECTION - DRILL HOLES 38527 and 38526

Near the east end of the west lobe of the Sill (Map GR81-1-1), three drill holes, on the same section line (64W), provide intersections of Fox River Belt rocks over approximately 1 km (Fig. 86). The southernmost drill hole (38527) intersects the south Sill contact between Middle sedimentary formation and MZ rocks, and the northernmost drill hole (38525) intersects approximately 130 m (core length) of Middle sedimentary formation rocks that represent the roof of the Sill. Drill hole 38526, collared between 38527 and 38525, intersects an estimated 230 m (approximate true thickness) of LCLZ serpentinite and serpentinized dunite.

The Sill is estimated to be approximately 850 m thick in this area, based on the apparently steep dips of layering in serpentinized dunite and Middle sedimentary formation rocks. There appears to be little space for UCLZ and HRZ rocks and the Sill is composed almost entirely of LCLZ serpentinite-serpentinized dunite in this area.

Attempts to produce thin sections from these highly serpentinized rocks were unsuccessful, and consequently the following description of the rocks is based on megascopic examination of drill core.

Drill hole 38527

Drill hole 38527 intersects approximately 17 m (estimated true thickness) of LCLZ serpentinite-serpentinized dunite (Fig. 39). The serpentinites overlie MZ gabbronorite, range from light- to dark-apple green, and are characterized by numerous silver-grey to beige serpentine ± magnetite zones. Original olivine crystals ranged from granular, to equidimensional polygonal, to elongate in shape and averaged 1.5 mm in size with elongate crystals up to 4 mm long. Intercumulus minerals make up less than 10 percent of the rocks.

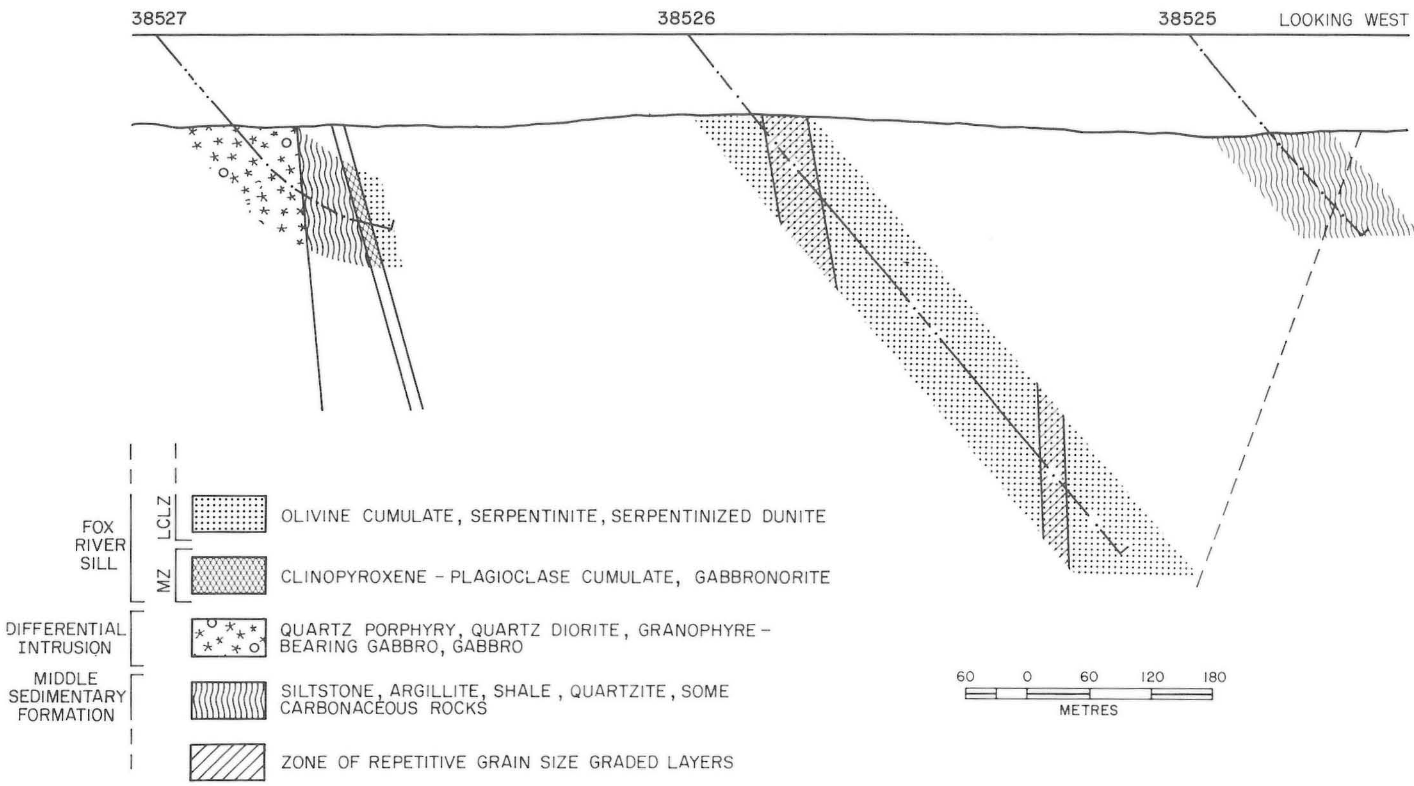


Figure 86: 64W section geology.

Drill hole 38526

NON-CYCLIC UNIT (?)

Olivine cumulate rocks

Drill hole 38526 intersects approximately 556 m (core length) of serpentinite-serpentinized dunite that represents an estimated 230 m of true thickness (Fig. 87). The rocks range from medium- to light-apple green, to medium and dark grey, to grey green and dark greenish black. The range in colour seems to be directly related to the distribution of magnetite. In apple-green rocks magnetite forms discrete hair-like veinlets, whereas in darker rocks it seems to form a more even, dust-like dissemination. Some rocks have a shiny or waxy lustre, others are dull and lustreless, and many are slippery or soapy to touch. The middle section of the drill hole is characterized by rocks that are spotted or finely mottled. The fine whitish mottling is caused by cross-fibre serpentine that partly outlines original olivine grain boundaries. The development of this serpentine tends to obliterate textural relationships.

Numerous soft-fibre asbestiform serpentine ± magnetite zones, as well as numerous brittle serpentine zones, contribute to broken and blocky drill core and intervals of lost core. Fibre length in excess of 3 cm has been noted in a few soft-fibre zones.

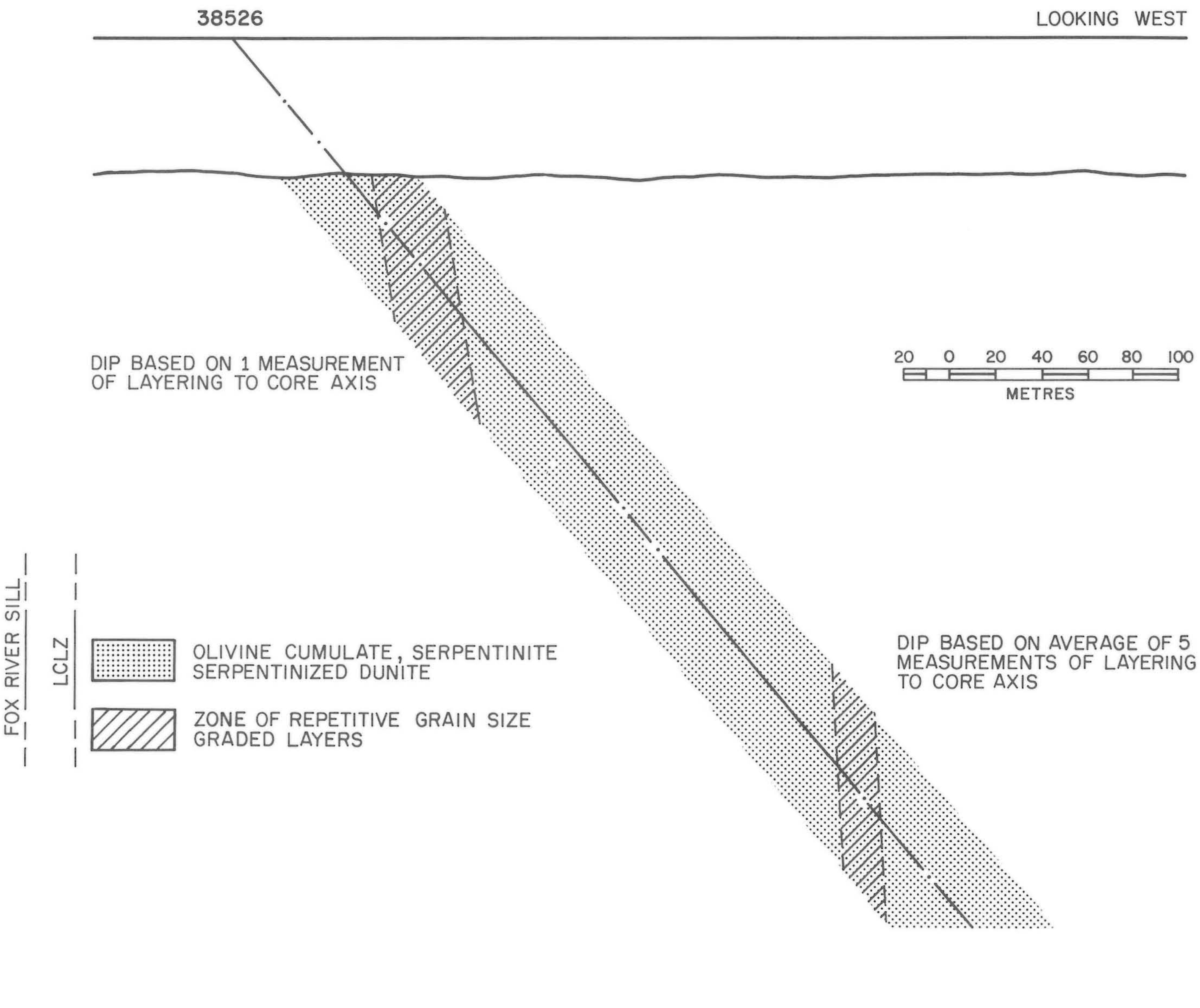


Figure 87: LCLZ geology, drill hole 38526, 64W section.

Size Graded Layers

Two well defined intervals, characterized by grain size graded layers, have been intersected; one from 398.0 to 676.2, the other from 1785.6 to 1910.0 (core length interval in feet) (Fig. 88). Other individual size graded layers occur in a random fashion and the high degree of serpentinization in some parts of the hole precludes serious evaluation for the presence of size graded layers. Macro-size graded layers range from 1 m to 16 m thick. Centimetre-scale layers are common, and groups of size graded layers occur where individual layers are less than 25 cm thick (estimated true thickness) (Fig. 88). Contact relationships are variable; in many examples the change from fine- or medium-grained to coarse grained dunite is abrupt and contacts are sharp (Plate 42 and Fig. 89), whereas the change from coarse- to fine-grained dunite is gradational. However, examples of a progressive increase in grain size from fine- to coarse-grained dunite over several centimetres have been observed.

In some rocks the abundance of disseminated chromite increases in association with changes in olivine grain size. In one example, the abundance of disseminated chromite increases immediately below an abrupt contact between fine grained and coarse grained dunite. In another example, a concentration of disseminated chromite forms a 2 mm diffuse layer 1 cm below an abrupt contact between fine grained and coarse grained dunite.

These grain size graded layers may represent cyclic units similar to the olivine cumulate (dunite) - clinopyroxene cumulate (olivine clinopyroxenite) cyclic units described from the Great Falls area. The base (south contact) of each coarse grained dunite could be interpreted to represent the base of an olivine cumulate cyclic unit. On the basis of a lack of structure suggestive of current sorting, Page *et al.* (1972) suggested that size graded layers in certain olivine cumulate rocks of the Stillwater Complex represent an oscillatory or cyclic process within a single magma batch. On the other hand Irvine (1979) has stated that layers in which minerals appear to have been sorted by grain size or density are commonly small local features for which an origin of deposition from local, rapid density currents or suspension currents seems reasonable. Whatever the origin of the grain size graded layers it is clear that crystal sorting according to size was accomplished. Analogous olivine cumulate cyclic units have been described from the Stillwater Complex (Jackson, 1970; Page *et al.* 1972), and the Muskox Intrusion (Irvine and Smith, 1967; Irvine, 1970a).

Textural Relationships

The original rocks in this sequence were composed almost entirely of crudely equidimensional, polygonal olivine crystals that shared simple, straight to slightly curving grain boundaries and the resultant texture has a distinct mosaic-like quality. Fine grained rocks (original olivine less than 3 mm) are relatively homogeneous, whereas coarse grained rocks (original olivine more than 3 mm) are heterogeneous in grain size, grain shape and percentage of intercumulus space (Plate 43). Coarse grained rocks contain patches of polygonal olivine crystals that are similar to, but larger than, those of fine grained dunite. In addition, many coarse grained dunites are characterized by up to 10 percent intercumulus dark green translucent serpentine. Thus some coarse grained rocks approach peridotite in composition. Original olivine crystals in these coarse grained rocks tend to possess highly irregular shapes. Chromite crystals in coarse grained rocks are several times larger (up to 1 mm in size) than those in fine grained dunite. Sparsely disseminated, brassy, pinpoint sulphide has been identified by X-ray as mixtures of pentlandite + heazlewoodite.

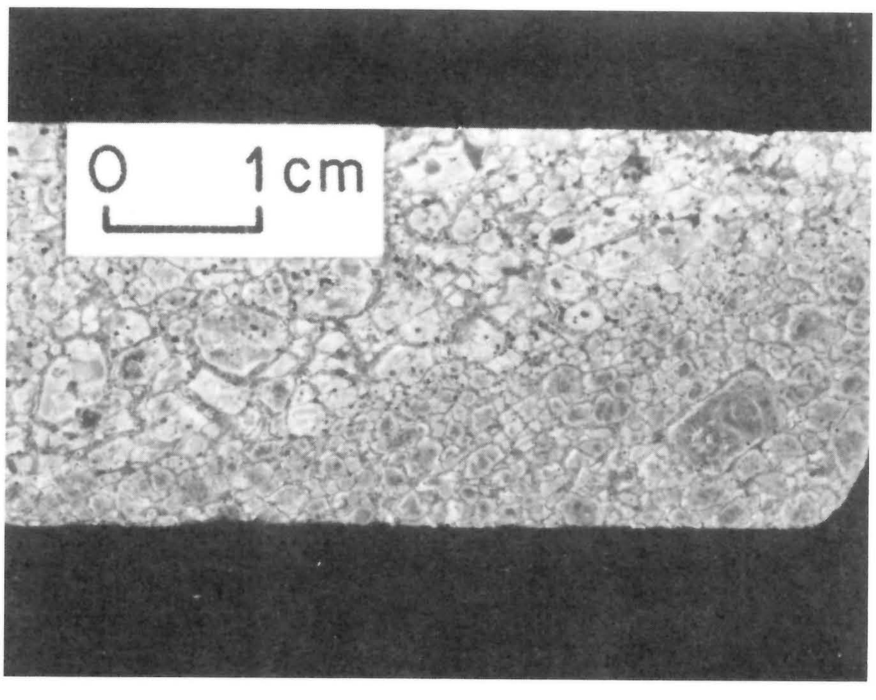


Plate 42: Contact between grain size graded layers, olivine cumulate. Note sharp nature of contact that is outlined by fine grained chromite crystals, and dimensional orientation of original elongate fine grained olivine crysals that are parallel with and below the contact. Olivine crystals have been completely serpentinized. LCLZ, olivine cumulate (original dunite), 64 W section, DDH 38526-414.0.

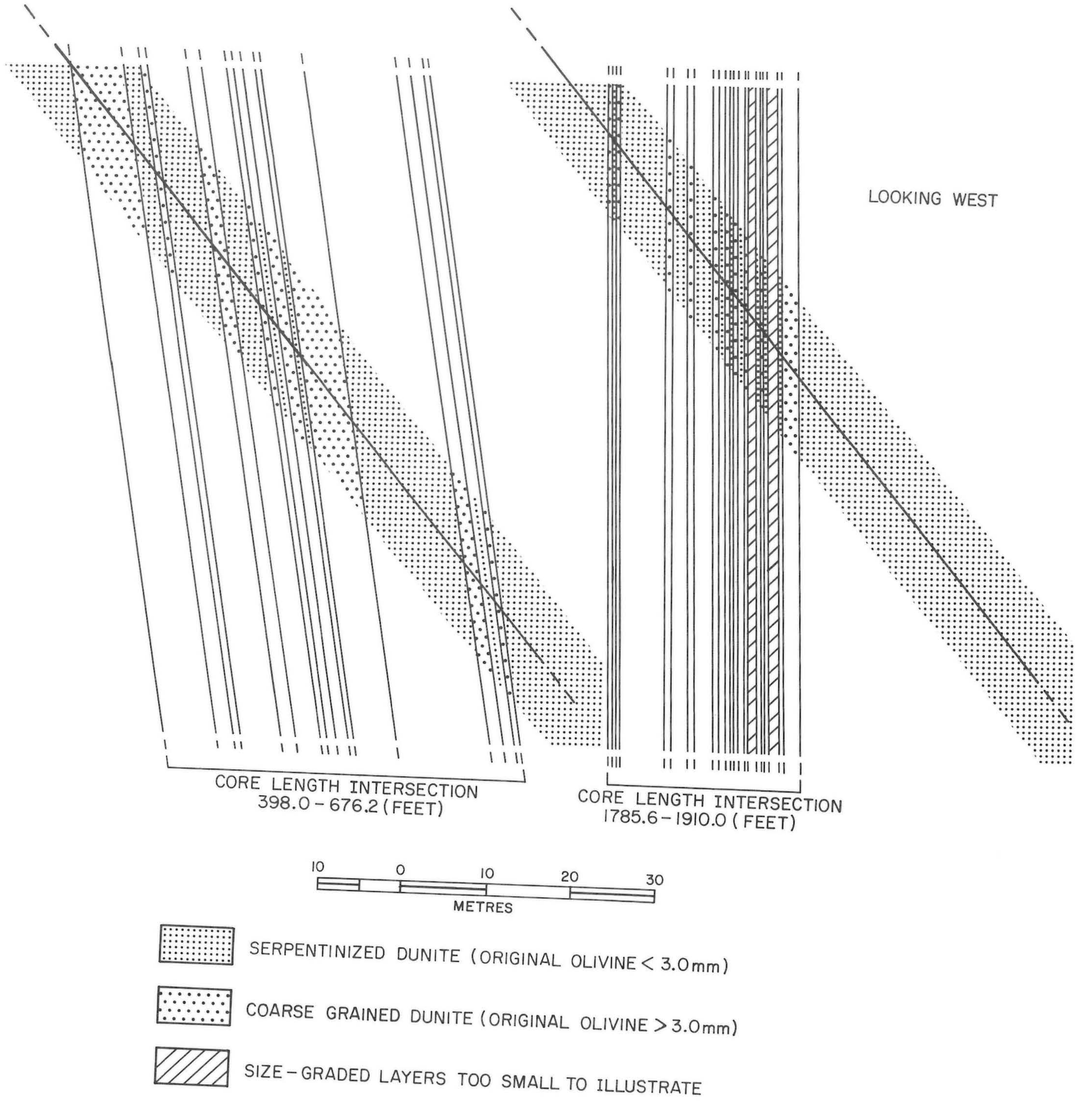


Figure 88: Size graded layers, drill hole 38526.

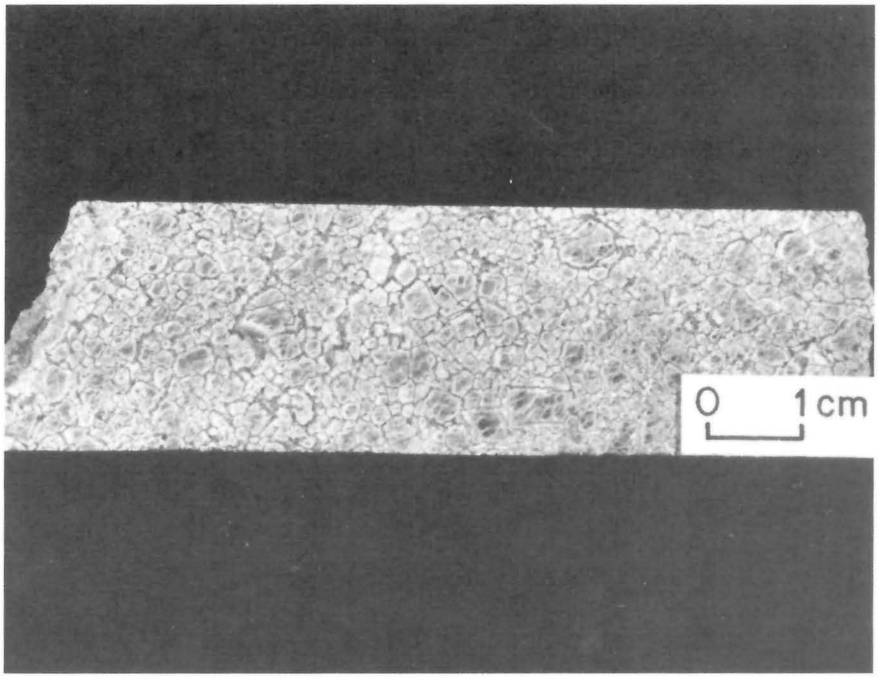


Plate 43: *Olivine cumulate displaying well developed heterogeneous character of original olivine crystals in terms of grain size and grain shape. Highly irregular shapes and the great range in size of individual olivine crystals produce a continuous mosaic of olivine crystals with a total lack of intercumulus area. Large irregular crystals represent extensive adcumulus growth. LCLZ, olivine cumulate (original dunite), 64W section, DDH 38526-415.3.*

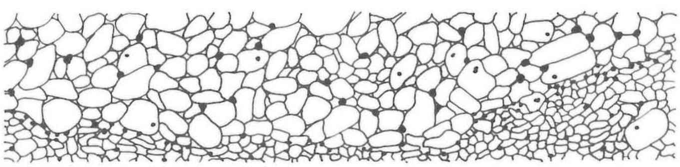


Figure 89: Sketch of contact between size-graded layers, drill hole 38526.

OTHER DRILL HOLES

Drill hole 38521

Drill hole 38521, collared west of 64W section (Map GR81-1-1), intersects 107 m (core length interval) of serpentinite-serpentinized dunite (Fig. 90).

NON-CYCLIC UNIT (?)

Olivine cumulate rocks

The rocks are medium- to light-apple green, possess a waxy lustre and are characterized by moderately well developed serpentine ± magnetite fabric (Fig. 91). Disseminated chromite composes 2 to 3 percent of the rock and silver-grey metallic mineral that occurs as widely disseminated fine grained masses has been identified by X-ray as awaruite (Ni_3Fe). The rocks were originally dunite.

Olivine has been pseudomorphously replaced by mesh-texture, nearly isotropic serpentine. Mesh-texture serpentine has been cut by late-stage serpentine bipartite veinlets that partly outline former olivine grain boundaries and produce a foliation. Talc veins cut all serpentine varieties and appear to represent the last alteration event.

Drill hole 38528

Drill hole 38528, collared within approximately 600 m of the east end of the west lobe of the Sill (Map GR81-1-1), intersects laminated Middle sedimentary formation rocks (carbonaceous shale) that are in contact with LCLZ olivine cumulate rocks (Fig. 41). MZ rocks are absent.

Middle sedimentary formation rocks, comprise of finely laminated siltstone, argillite and shale, with interlaminated carbonate-rich, quartz-rich and carbonaceous laminae; they become increasingly graphitic toward the Sill contact, where they are cut by a number of cross-fibre serpentine veinlets. They have been partly converted to hornfels. The sediments have been intruded by a body of gabbro (Fig. 41). The presence of granophyre-bearing rocks on the north side of the body suggests that the gabbro faces north like the Sill, and is interpreted as being sill-like.

NON-CYCLIC UNIT (?)

Olivine cumulate (serpentinite, serpentinized dunite)

The rock at the contact is a dark greenish-black, foliated serpentinite that contains numerous picrolite zones and cross-fibre serpentine veinlets. The primary texture, although poorly preserved, has not been completely obliterated, and originally the rock was dunite. Progressing north from the contact, the rock becomes a medium grained, apple-green, serpentinized dunite, that contains numerous magnetite stringers, and picrolite and cross-fibre serpentine veinlets. South of the lherzolite (Fig. 41) the rock is a serpentinite breccia. There is much lost core through this zone, and the core that remains is cut by numerous serpentine veinlets.

The rocks are totally serpentinized and the bulk of the serpentine

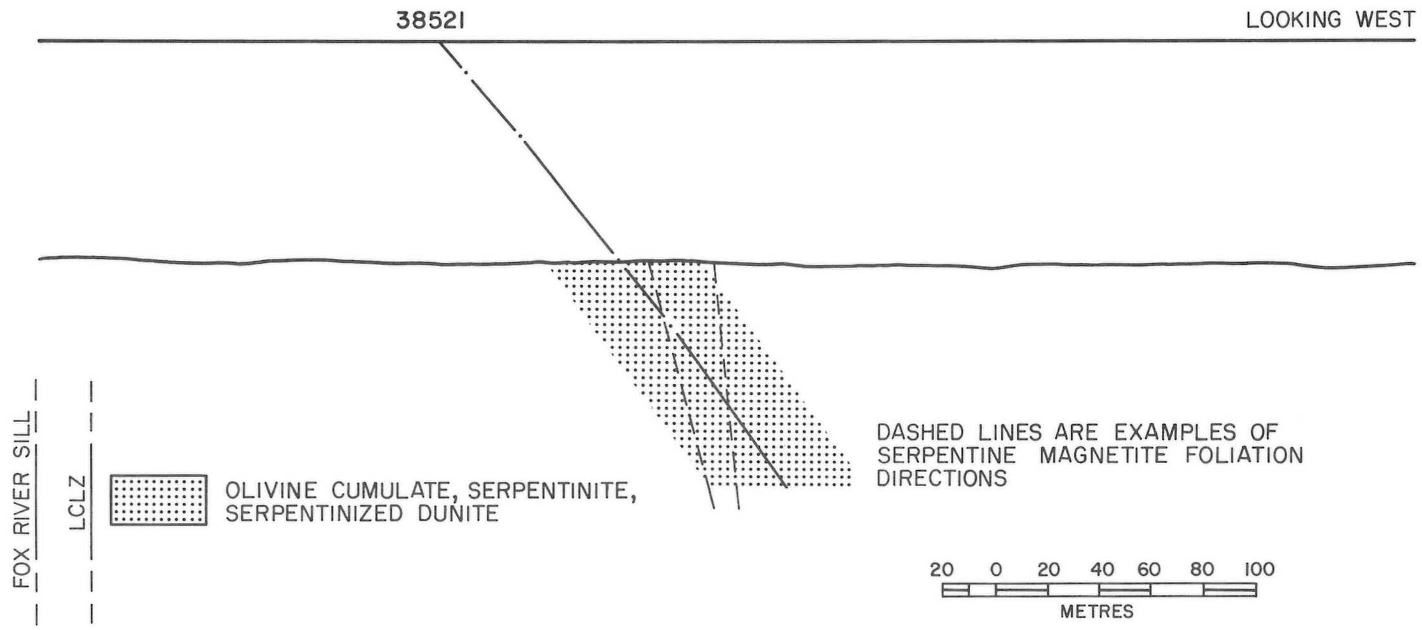


Figure 90: LCLZ geology, drill hole 38521.

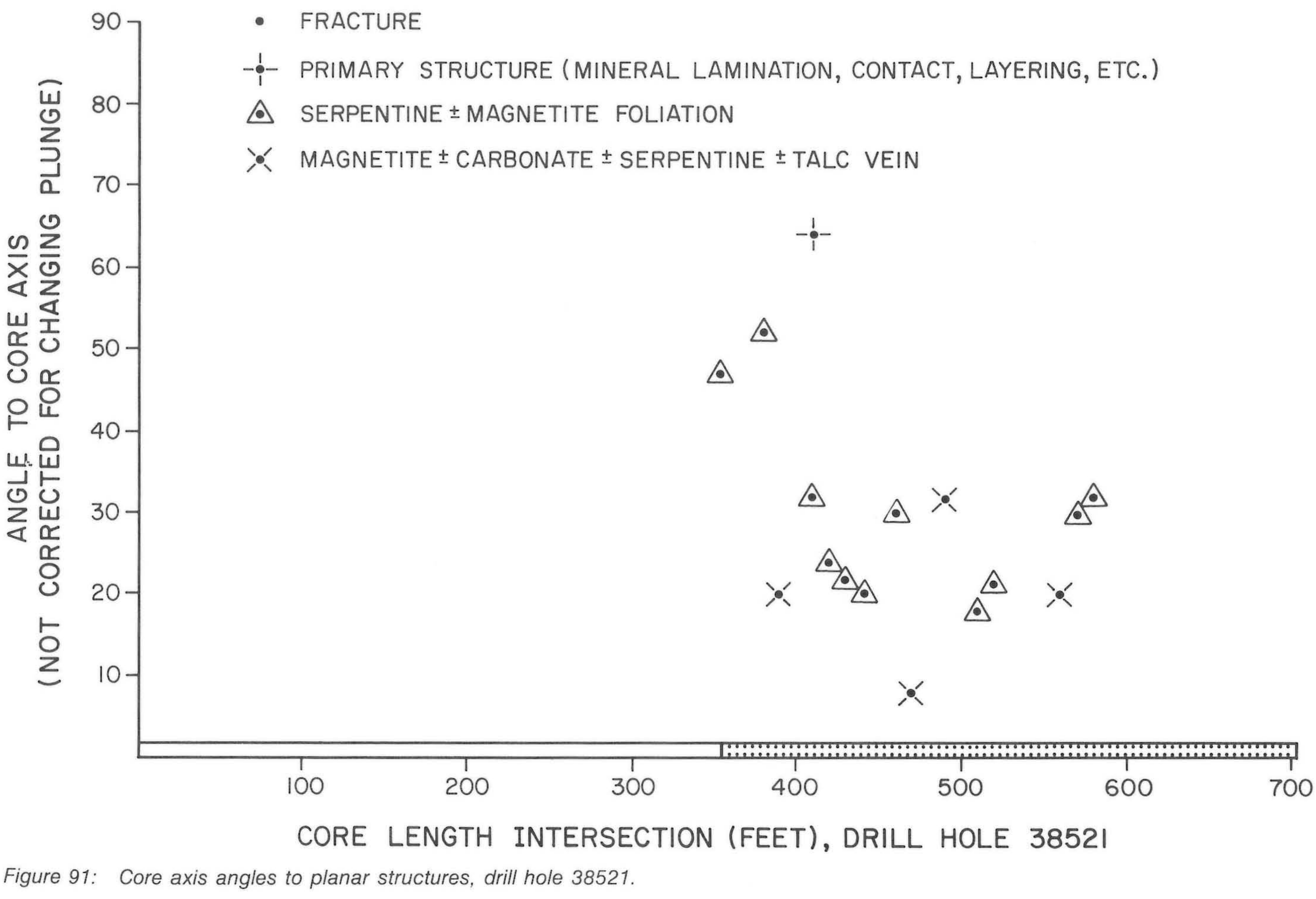


Figure 91: Core axis angles to planar structures, drill hole 38521.

forms an extremely fine grained mat of nonfibrous material. Consequently, the primary texture is more readily discernible megascopically than microscopically. Euhedral to slightly rounded chromite crystals are evenly distributed throughout and constitute from 1 to 3 percent of the rock.

Olivine cumulate (mottled plagioclase-bearing lherzolite)

The rocks are medium- to coarse-grained, dark greyish black and mottled. The mottled, heterogeneous character of the rock is due to the sporadic distribution of large (up to 1 cm) poikilitic orthopyroxene crystals, and clinopyroxene and plagioclase oikocrysts.

Olivine and chromite were original cumulus phases. Olivine is granular to polyhedral and chromite forms clusters of euhedral crystals. Clinopyroxene is preserved and forms large oikocrysts (up to 1 cm) with numerous inclusions of olivine and chromite. Orthopyroxene originally formed large (up to 1 cm) poikilitic crystals. Plagioclase formed oikocrysts that were originally finer grained and much less abundant than clinopyroxene.

Olivine has been completely converted to fine grained, nonfibrous serpentine, that has been cut by late-stage veins of faintly pleochroic serpentine ($\pm$ magnetite) that possess anomalous birefringence. Secondary diopside, some as radially disposed sprays, replaces serpentine. Some olivine enclosed by clinopyroxene has been converted to tremolite. Orthopyroxene has been replaced by tremolite $\pm$ serpentine $\pm$ chlorite that form bastite-like pseudomorphs, and plagioclase has been completely converted to chlorite $\pm$ epidote $\pm$ serpentine.

Chromite averages 1 to 3 percent and displays a slight increase in abundance toward the base of the hole.

SUMMARY

LCLZ rocks form a continuous zone along the entire 70 km length of the west lobe of the intrusion, and they range from 600 to 900 m thick throughout most of the length. However, in the vicinity of the pinch-and-swell structure at the midpoint of the west lobe of the intrusion, LCLZ rocks are less than 150 m thick. LCLZ rocks overlie MZ rocks and the contact between these zones may be sharp, gradational, or a fault. LCLZ rocks are predominantly serpentinites derived from original olivine cumulate rocks that were mainly dunite in composition. Thin clinopyroxene cumulate (olivine clinopyroxenite) layers separate much thicker olivine cumulate layers and much of the LCLZ succession can be grouped into repetitive sequences of olivine cumulate-clinopyroxene cumulate cyclic units. A lack of outcrop and/or drill hole continuity precludes determining with any certainty the number of these cyclic units in any given area of the intrusion; however, five complete units and a part of a sixth are exposed in the Great Falls outcrop area. Cyclic units are not present at the western and eastern extremities of the west lobe of the intrusion. However, LCLZ olivine cumulate rocks in the easternmost part of the intrusion are characterized by well defined intervals composed of successive size graded layers. These layers may represent smaller scale cyclic units, similar to the olivine cumulate-clinopyroxene cumulate units that characterize the rest of the LCLZ succession. Plagioclase cumulate rocks (olivine gabbro, olivine gabbronorite) are rare, and form the uppermost layers of cyclic units at or toward the top of the LCLZ succession.

The LCLZ repetitive sequence, olivine cumulate-clinopyroxene cumulate, is identical to the repetitive sequence in the lower part of the Muskox Intrusion (Irvine and Smith, 1967; Jackson, 1970). These cyclic units are interpreted as being incomplete or beheaded units (Jackson, 1970) on the basis that several cycles in the upper part of the LCLZ possess an uppermost plagioclase cumulate layer. The implication is that plagioclase cumulate would have occurred throughout the LCLZ succession, but was prevented from developing. It has been suggested that the reason for this was the influx of new magma into the chamber and the removal of old magma prior to plagioclase becoming a liquidus phase. These beheaded cyclic units are thus considered to represent interruptions in the fractional crystallization process. Thus LCLZ cyclic units are unlike MZ cyclic units that are interpreted as representing complete fractional crystallization of magma. The process of repeated magma influx is interpreted to have a bearing on the origin of Upper volcanic formation rocks in the Fox River Belt through some of the replaced magma breaching the intrusion roof and reaching the surface to form lava flows (Scoates, 1981 and 1984).

The LCLZ succession is composed of rocks that were originally mineralogically simple; olivine + clinopyroxene are the predominant phases, plagioclase is much less common, and orthopyroxene is rare. It is this simple mineralogical character that distinguishes LCLZ rocks from MZ and UCLZ rocks. The abundance of dunite, lack of plagioclase cumulate rocks (gabbro), lack of orthopyroxene, and lack of sulphide minerals, distinguish LCLZ from UCLZ rocks.

Chromite is a ubiquitous phase in olivine cumulate rocks, ranging from less than 1 to 3 percent in most rocks. Concentrations of chromite that form thin chromitite layers (up to 5 mm thick) are rare, whereas zones of heavily disseminated chromite (more than 3 percent, up to 10 percent) are somewhat more common. Sulphide minerals are rare, and occur as sparsely disseminated pinpoint grains; pyrrhotite, pentlandite and heazelwoodite were identified by X-ray. Awaruite, a nickel-iron alloy (Ni_3Fe), was identified in one sample.

The almost complete serpentinization of olivine in olivine cumulates precludes an examination of orientation of olivine c-axes; however, the preferred orientation of original elongate olivine crystals is a relatively common observation. This suggests that magmatic currents may have been operative from time to time during accumulation of LCLZ rocks. The intervals of size graded layers in olivine cumulate rocks, observed at the extreme eastern end of the west lobe of the intrusion, may be interpreted to have originated through deposition from rapid density currents or suspension currents.

The LCLZ succession represents accumulation of an enormous volume of olivine derived through fractional crystallization of magma. Each olivine cumulate-clinopyroxene cumulate cyclic unit is interpreted to represent accumulation of fractional crystallization products from a new or fresh magma batch. This explains the apparent resetting or starting over that each cyclic unit seems to represent.

LCLZ olivine cumulate rocks commonly contain less than 10 percent intercumulus material and many contain less than 5 percent. This contrasts with MZ olivine cumulate rocks that commonly contain in excess of 40 percent intercumulus minerals. It was previously noted that the intercumulus minerals in MZ olivine cumulate rocks represent crystallization of intercumulus magma, and that the minerals that resulted and their order of crystallization were dependent, to a large extent, on composition of the intercumulus magma and composition of the cumulus phase(s) with which the intercumulus magma was in contact. The polygonal shapes of individual olivine crystals in LCLZ olivine cumulates and the simple, straight to slightly curving mutual grain boundaries suggest adcumulus growth. This implies that the intercumulus magma possessed a composition that enabled crystallization of additional olivine. Thus, the conditions under which accumulation and postcumulus crystallization took place in LCLZ olivine cumulates was dramatically different from the conditions under which MZ olivine cumulate rocks accumulated and crystallized. This also suggests that the magma pulses that gave rise to MZ cyclic units and those that gave rise to LCLZ cyclic units were of different composition, with the latter being more primitive.

UPPER CENTRAL LAYERED ZONE

UCLZ rocks are distinguished from LCLZ rocks by the presence of orthopyroxene in olivine, clinopyroxene and plagioclase cumulate rocks, and by the presence of plagioclase cumulate rocks that form the uppermost layers of many UCLZ cyclic units. Sulphide minerals that are rare in LCLZ rocks are common though not abundant constituents of the UCLZ succession. Olivine crystals are not densely packed in olivine cumulate rocks, and consequently dunite is rare. UCLZ rocks are widespread, although they appear to be absent in the easternmost part of the west lobe of the intrusion (Fig. 92).

462W SECTION - DRILL HOLES 13231, 13234, 13240, 13242, 38524 AND 38523

Rocks of the UCLZ succession have been intersected in 6 of the 8 drill holes that compose 462W section. Both the LCLZ-UCLZ and UCLZ-HRZ contacts have been penetrated, in addition to a substantial portion of the UCLZ succession.

Drill hole 13231

Drill hole 13231 intersects the uppermost LCLZ cyclic unit in this area, as well as a substantial portion (approximately 152 m, estimated true thickness) of the lowermost part of the UCLZ. The contact between the zones has been placed so as to separate rock successions of substantially different character. Here, the lowermost part of the UCLZ is composed of six olivine cumulate-clinopyroxene cumulate cyclic units, succeeded by one olivine cumulate-clinopyroxene cumulate-plagioclase cumulate cycle, and two clinopyroxene cumulate-plagioclase cumulate cyclic units. This succession contrasts markedly with underlying LCLZ units, in this area, that are composed of relatively thick olivine cumulate (dunite) and thin clinopyroxene cumulate layers (see drill holes 13237, 13235 and 13234). In addition, although orthopyroxene is not abundant, it is more common in the UCLZ succession than in the underlying LCLZ sequence where it is rare. Some UCLZ cyclic units are sulphide-bearing (up to 10 percent in some rocks) whereas disseminated sulphide minerals, in LCLZ rocks in this area, seldom form more than 2 percent of the rock. (An exception has been noted in the upper part of the clinopyroxene cumulate layer of the uppermost LCLZ cyclic unit in drill hole 13231). The greater abundance of plagioclase cumulate in the UCLZ sequence (Fig. 79) further distinguishes this suite of rocks from the underlying LCLZ succession where plagioclase cumulate rocks are rare.

CYCLIC UNITS 1 TO 6

Olivine cumulate layers

The original olivine cumulate part of these cyclic units ranges from medium- to dark-apple green to dark grey, and dark greenish black; some rocks are mottled and some possess a waxy lustre. The mottling is caused by network-like postcumulus phases or oikocrysts whose diameter is larger than the width of the diamond drill core (more than 3 cm). The upper part of the cycle 1 olivine cumulate layer is characterized by interlayered, centimetre-scale, clinopyroxene cumulate-olivine cumulate layers. Disseminated sulphides make up in excess of 5 percent of all or part of five of the six olivine cumulate layers.

The rocks were originally composed dominantly of olivine, as rounded polyhedral crystals, many of which were elongate, and polygonal crystals. As previously noted, olivine in original dunite is somewhat finer grained (1 mm) than olivine in original peridotite (1.5 to 3 mm). Elongate crystals display preferred orientation in a few rocks, and some olivine originally possessed circular inclusions of the kind previously described. Clinopyroxene, some of which is partly preserved, commonly occurred as oikocrysts; however, in some rocks, networks of clinopyroxene are composed of a continuous interlocking mosaic of irregular clinopyroxene crystals. Thus, some olivine cumulate rocks in this area were originally composed of an aggregation of cumulus olivine and cumulus clinopyroxene. Both varieties of clinopyroxene occur together in a few rocks. Original postcumulus plagioclase has been replaced by chlorite $\pm$ epidote and by amorphous clay-like material. Orthopyroxene bastite has replaced original, sporadically distributed orthopyroxene oikocrysts.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. In a few rocks, olivine has been replaced by nonpseudomorphous serpentine that produces poorly preserved original textures. Clinopyroxene has been replaced by clinopyroxene bastite, in which magnetite outlines an original parting. Talc $\pm$ magnetite occupies former intercumulus areas.

Disseminated euhedral chromite crystals make up from less than 1 to 3 percent of the rock. Many of the rocks are sulphide bearing, the sulphide minerals occurring as globular inclusions in original clinopyroxene or orthopyroxene crystals or as crescent- or cusp-shaped masses in intercumulus areas surrounding cumulus olivine crystals. Sulphide minerals constituting in excess of 5 percent of some rocks are not uncommon.

The olivine cumulate rock ranged from dunite to lherzolite in composition, with plagioclase-bearing wehrlite being the predominant rock type.

Clinopyroxene cumulate layers

The clinopyroxene cumulate layers of cyclic units 1 to 6 are similar to other clinopyroxene cumulate rocks previously described. The rocks are grey to grey green and granular, and many are spotted or mottled. Many rocks in this area are sulphide bearing, some estimated to contain in excess of 10 percent sulphide minerals. A few zones of picrolitic serpentine breccia have been observed.

The rocks are composed of a continuous interlocking mosaic of irregularly shaped clinopyroxene crystals that forms a network mass surrounding individual and clusters of individual olivine crystals. The ratio of clinopyroxene to olivine is variable; olivine constitutes from 5 to 40 percent of the rock. Where olivine is abundant, clinopyroxene commonly occurs as individual or clusters of individual prismatic crystals. Orthopyroxene occurs as sporadically distributed poikilitic crystals with numerous inclusions. Some preserved orthopyroxene displays incipient alteration to talc. Orthopyroxene has been replaced by orthopyroxene bastite and by tremolite forming bastite-like pseudomorphs. Former postcumulus plagioclase has been replaced by an amorphous, clay-like material.

As in the olivine cumulate layers, sulphide minerals occur as globular inclusions in orthopyroxene, and as intercumulus phases whose shapes are controlled by the shapes of the surrounding cumulus minerals (Plate 44).

The clinopyroxene cumulate rocks are predominantly plagioclase-bearing olivine websterite.

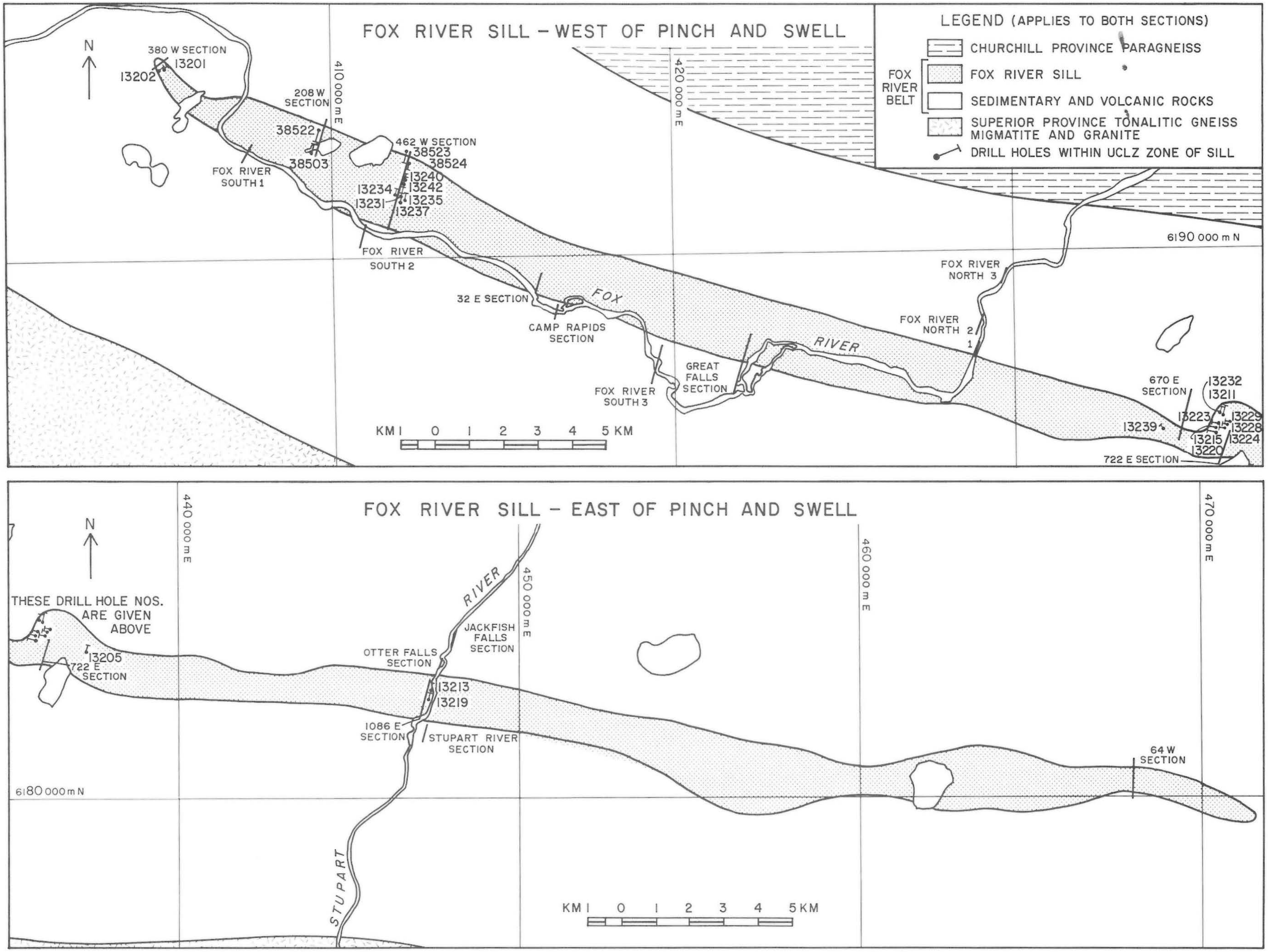


Figure 92: Drill hole and outcrop locations, UCLZ.

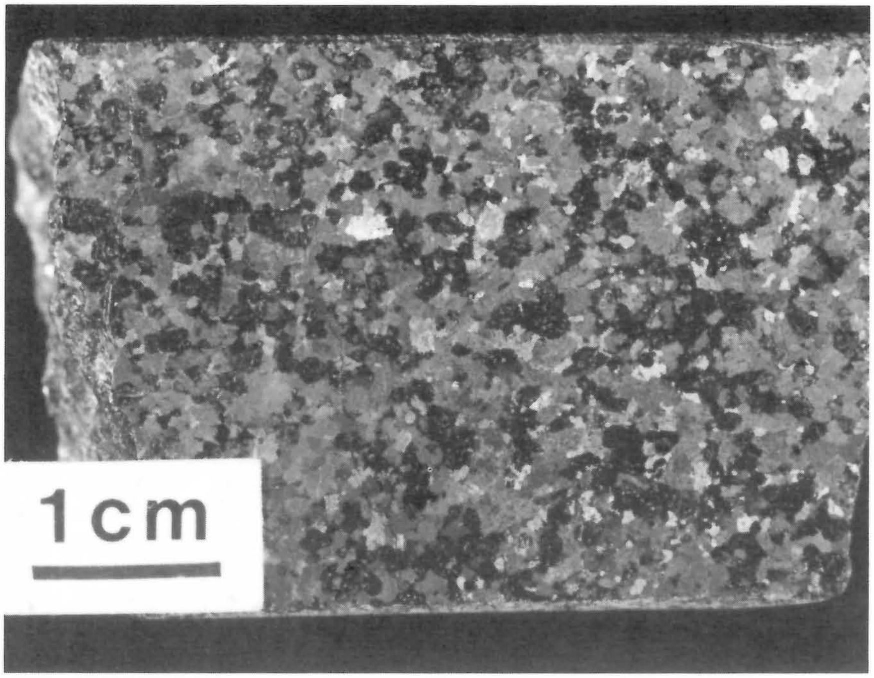


Plate 44: Sulphide-bearing clinopyroxene + olivine cumulate. Light grey to whitish grey patches are intercumulus sulphide. Mid-grey is a continuous mosaic of cumulus clinopyroxene crystals. Dark grey patches are clusters of cumulus olivine. UCLZ, clinopyroxene + olivine cumulate, DDH 13231-780.

CYCLIC UNIT 7

Cyclic unit 7 (Fig. 79) is composed of an olivine cumulate layer, clinopyroxene cumulate layer and plagioclase cumulate layer. The olivine cumulate is similar in colour, texture, alteration and composition to the olivine cumulate rocks of cyclic units 1 to 6, the rock being plagioclase-bearing wehrlite in original composition. The rock is distinguished, however, by a slightly higher content of disseminated chromite that constitutes up to 5 percent of the rock. Sulphide globules make up to 3 percent of the rock.

The clinopyroxene cumulate layer is grey green to slightly brownish green and sulphide bearing. The rocks are similar in composition and texture to the clinopyroxene cumulate rocks of cyclic units 1 to 6, being plagioclase-bearing olivine websterite in composition.

The plagioclase cumulate layer is grey to beige, and vaguely mottled. The rock contains up to 3 percent sulphide near its contact with the underlying websterite. The rock possesses a well developed lamination due to the preferred orientation of pseudomorphs after original lath plagioclase, and to alternating plagioclase-rich and clinopyroxene-rich laminae. Parallel orientation of elongate clinopyroxene crystals also contributes to the lamination. Plagioclase occurs as laths and clusters of laths that have been completely converted to epidote + chlorite. Clinopyroxene occurs as groups of irregular crystals, some of which are elongate, that represent an original cumulus phase. Original intercumulus olivine has been replaced by chlorite $\pm$ tremolite, and original poikilitic orthopyroxene crystals, that contained clinopyroxene and plagioclase inclusions, have been replaced by chlorite that forms bastite-like pseudomorphs. The rock is olivine gabbronorite in composition.

CYCLIC UNITS 8 AND 9

Cyclic units 8 and 9 are each composed of a clinopyroxene cumulate layer and a plagioclase cumulate layer. The clinopyroxene cumulates are similar in texture and composition to the clinopyroxene cumulates of the underlying cyclic units and in addition originally contained red-brown hornblende as a primary postcumulus phase. The rocks, some of which are sulphide bearing (up to 5 percent), are hornblende- and plagioclase-bearing olivine websterite.

The plagioclase cumulate rocks are similar to cyclic unit 7 plagioclase cumulate in possessing a strong lamination, the lamination is caused by alternating plagioclase-rich and clinopyroxene-rich laminae and by parallel orientation of elongate clinopyroxene crystals. Strong linear alignment of clinopyroxene c-axes is demonstrated by a near perfect bull's-eye fabric diagram (Fig. 93). This is strong evidence of magmatic current activity during accumulation of these crystals. The rocks contain ilmenite and rare sulphide minerals, and are gabbronorite in composition.

OLIVINE COMPOSITIONS

Four olivine compositions determined on olivine from clinopyroxene cumulate rocks range from $Fo_{83.6}$ to $Fo_{85.1}$, and two olivines from the same layer possess identical compositions ($Fo_{83.6}$, Fig. 80).

Drill hole 13234

The lower part of the drill hole penetrated the LCLZ-UCLZ contact and intersected 21 m (core length interval) of the lowermost UCLZ olivine cumulate layer in this area. The following description is based on megascopic observations of drill core.

Red-brown hornblende is a rare postcumulus phase. Sulphides in sulphide-bearing rocks occur as globular inclusions in postcumulus silicates or as larger, cusp-shaped intercumulus masses. Originally these rocks were plagioclase-bearing olivine websterite in composition.

CYCLIC UNIT 1

Olivine cumulate layer

The rocks are grey to grey green and mottled, the mottling being caused by numerous, 1 cm, equidimensional to circular oikocrysts. The presence of orthopyroxene is implied by patches of honey coloured material on broken core surfaces. Disseminated sulphides occur throughout the exposed portion of the unit and constitute up to 3 percent of the rock.

Drill holes 13240 and 13242

CYCLIC UNITS

The drill holes drilled in a northerly direction on 462W section, intersected a succession of UCLZ cyclic units (Fig. 94). Altogether, two complete cyclic units and portions of three others have been penetrated by the drill holes. The complete cyclic units are each composed of two layers, an olivine cumulate-plagioclase cumulate unit, overlain by an olivine cumulate-clinopyroxene cumulate unit. The olivine cumulate at the base of 13242 and the plagioclase cumulate at the top of 13240 are likely parts of the same cyclic unit.

Olivine cumulate layers

Olivine cumulate rocks are dark greenish black and mottled to dark apple green, the mottling being caused by the distribution of 0.5 to 1 cm oikocrysts. They were originally composed of granular to rounded polyhedral olivine crystals, some of which were elongate. The abundance of intercumulus minerals is highly variable in these rocks, and where they constitute less than 5 percent of the rock, the olivine crystals occur as a mosaic of polygonal crystals. Clinopyroxene, which is partly preserved in some rocks, has been replaced by clinopyroxene bastite. It originally formed large (0.5 to 1 cm) spherical oikocrysts. Chlorite replaces original postcumulus plagioclase and orthopyroxene bastite replaces original poikilitic orthopyroxene crystals.

Chromite content ranges from less than 1 to 3 percent, but makes up approximately 10 percent of one rock. Because of the telescoped nature of the drill core the extent of this chromiferous rock is unknown. One rock contains chromite with circular inclusions. The inclusions are commonly filled with red-brown hornblende, some are nearly isotropic and others are composed of the same material that surrounds the crystal. In a few examples, the circular inclusion is larger than the chromite and breaches one side of the grain, giving rise to C-shaped crystals. Coarser grained (up to 1 mm) chromite crystals constitute 2 percent of one particular rock. Intercumulus sulphide is present in a few rocks where it ranges from 1 to 5 percent. In rocks where the primary texture is poorly preserved, the original shape of the intercumulus sulphide has been modified. Sulphide $\pm$ magnetite $\pm$ serpentine veinlets are common in such rocks.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. In a few rocks that had an original preferred orientation of elongate olivine crystals, curtain-growth serpentine forms parallel veins at right angles to the direction of olivine elongation. The presence of nonpseudomorphous serpentine in some rocks seems to relate to the extent of clinopyroxene oikocrysts; olivine within oikocrysts has been replaced by pseudomorphous serpentine, and olivine in the groundmass has been replaced by nonpseudomorphous serpentine. In the chromiferous rock (chromite about 10 percent), relict olivine ($Fo_{81.6}$) is preserved in a sea of nonpseudomorphous serpentine. Here, it appears that olivine has been replaced by nonpseudomorphous serpentine, consisting of interlocking blades and plates of nonfibrous serpentine. The replacement seems to represent a single step process. A few rocks that are entirely replaced by nonpseudomorphous serpentine are true serpentinites. The majority of rocks were originally plagioclase-bearing lherzolite to wehrlite in composition.

Clinopyroxene cumulate layers

The rocks are grey to grey green and brownish green and granular, and are composed predominantly of cumulus clinopyroxene as stubby prismatic crystals. In some rocks, original prismatic crystals have been modified by adcumulus growth that results in a mosaic of irregularly shaped clinopyroxene crystals with simple to slightly irregular mutual grain boundaries. Complex polycrystalline aggregates, some with blebby exsolution of the type previously described from MZ and some LCLZ rocks, have been observed. Large (up to 1 cm) poikilitic orthopyroxene crystals have been replaced by tremolite $\pm$ chlorite, commonly forming bastite-like pseudomorphs. Chlorite replaces postcumulus plagioclase, and chlorite $\pm$ tremolite $\pm$ serpentine replace original olivine crystals. Opaque minerals are rare, although one rock contains 30 percent intercumulus sulphide. The rocks are predominantly plagioclase-bearing olivine websterite.

Plagioclase cumulate layers

The rocks range from grey to grey green and bluish grey to slightly brownish grey, the range in colour reflecting the large range of original composition and of alteration that these rocks display.

The plagioclase cumulate in the upper part of drill hole 13242 (cyclic unit 1) is a medium grained rock that was originally composed of large (up to 5 mm) plate-like plagioclase, now replaced by albite + chlorite, and irregularly shaped clinopyroxene, now almost entirely converted to tremolite. Large patches of skeletal ilmenite (up to 3 mm) are widely disseminated through the rock. Much of this unit is highly altered to a mass of prehnite + chlorite + tremolite + epidote + sphene that completely obliterates the original texture. The original rock was an ilmenite-bearing gabbro.

In the other two plagioclase cumulate layers, the rocks are finer grained and many were originally pyroxene-rich and orthopyroxene-bearing. Large skeletal ilmenite crystals have not been observed in these layers. The rocks were originally composed of fine grained plagioclase laths (0.5 to 1 mm long), and cumulus clinopyroxene. Plagioclase has been converted to a fine grained felted mat of secondary minerals including epidote + chlorite + tremolite. Clinopyroxene forms stubby prismatic crystals to elongate crystals (up to 2 mm long) and is the most abundant mineral in some plagioclase cumulates. Well developed microscopic lamination, caused by alternating mm-scale, plagioclase-rich and clinopyroxene-rich laminae, and enhanced by parallel orientation of elongate clinopyroxene, distinguishes some rocks. Original poikilitic orthopyroxene has been replaced by tremolite $\pm$ chlorite that forms bastite-like pseudomorphs (up to 7 mm). Oval areas of chlorite $\pm$ tremolite replace original olivine crystals.

The rocks were originally gabbronorite to melagabbronorite in composition.

Drill hole 38524

Drill hole 38524 intersects portions of two relatively thick olivine cumulate sequences (61 and 73 m, respectively, approximate minimum true thickness) that are separated by a short interval (5.5 m, approximate true thickness) composed of alternating orthopyroxene cumulate and olivine cumulate layers. The orthopyroxene cumulate layers represent the first noteworthy concentration of cumulus orthopyroxene in the Sill although minor amounts of cumulus orthopyroxene were noted in a few MZ plagioclase cumulate rocks. Each orthopyroxene cumulate layer is interpreted as representing the top of a two-layer cyclic unit.

CYCLIC UNIT 1

Olivine cumulate layer

The olivine cumulate layer is composed of medium- to dark-apple green to dark greenish-black, mottled rocks, the mottling being caused by large (up to 3 cm) clinopyroxene oikocrysts that form reflecting patches in the drill core. The rocks become sulphide bearing toward the contact with the first of the orthopyroxene cumulate layers.

The rocks were originally composed of rounded polyhedral to stubby and rectangular olivine crystals, that possess well defined crystal shapes. There is a substantial range in olivine grain size (from 0.5 to 3 mm), as well as in distribution of postcumulus minerals. Small patches of close-packed olivine display polygonal shapes and share mutually simple grain boundaries. The original olivine crystals have been pseudomorphously replaced by mesh-texture and curtain-growth serpentine, much of which displays parallel growth. Nearly isotropic serpentine ± magnetite replaces large clinopyroxene oikocrysts. Large (1 cm) poikilitic orthopyroxene crystals, now orthopyroxene bastite, occur in the uppermost part of the layer. Patches of chlorite, occupying intercumulus areas, replace original postcumulus plagioclase. The ratio of cumulus to postcumulus minerals decreases at the top of the layer where postcumulus minerals constitute approximately 25 percent of the rock. Disseminated chromite, as clusters of euhedral crystals, makes up from 1 to 3 percent of the rock, and secondary magnetite is relatively common (up to 5 percent) and is associated with secondary minerals in intercumulus areas. Sulphide minerals are rare throughout the layer, but constitute 2 to 3 percent of the rock near the top of the layer. The original rocks were predominantly plagioclase-bearing wehrlite, with plagioclase-bearing lherzolite occurring at the top of the layer, adjacent to the first of the orthopyroxene cumulate layers.

Orthopyroxene cumulate layer

The relatively thick olivine cumulate layers are separated by a short interval (5.5 m approximate true thickness) composed of alternating orthopyroxene cumulate and olivine cumulate layers. The orthopyroxene cumulate rocks are grey to greenish grey and brownish green, medium- to coarse-grained and granular. Each of the four orthopyroxene cumulate layers is sulphide bearing; disseminated sulphides range from 2 to 10 percent of the rock (visual estimates) (Plate 45).

The rocks consist of an accumulation of stubby prismatic orthopyroxene crystals that display incipient to complete recrystallization to talc ± tremolite. Postcumulus plagioclase is partly altered to an amorphous-like secondary mineral. Large, irregularly shaped, postcumulus clinopyroxene oikocrysts contain inclusions of corroded orthopyroxene, as well as globular sulphides, and olivine is a postcumulus mineral in one orthopyroxene cumulate layer. Intercumulus sulphide possesses distinct cusp-like shapes. The rocks

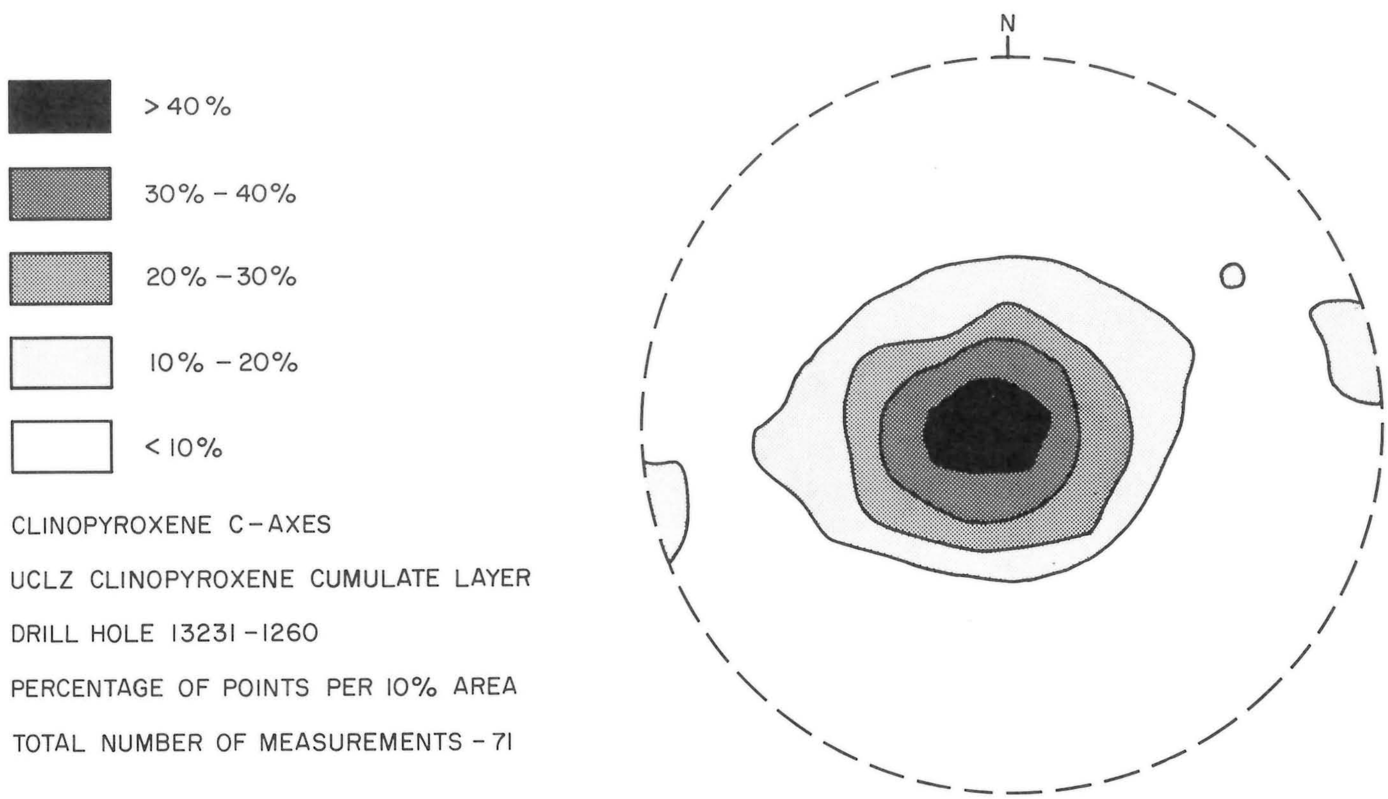


Figure 93: Fabric diagrams, clinopyroxene c-axis, UCLZ plagioclase + clinopyroxene cumulate layer, drill hole 13231.

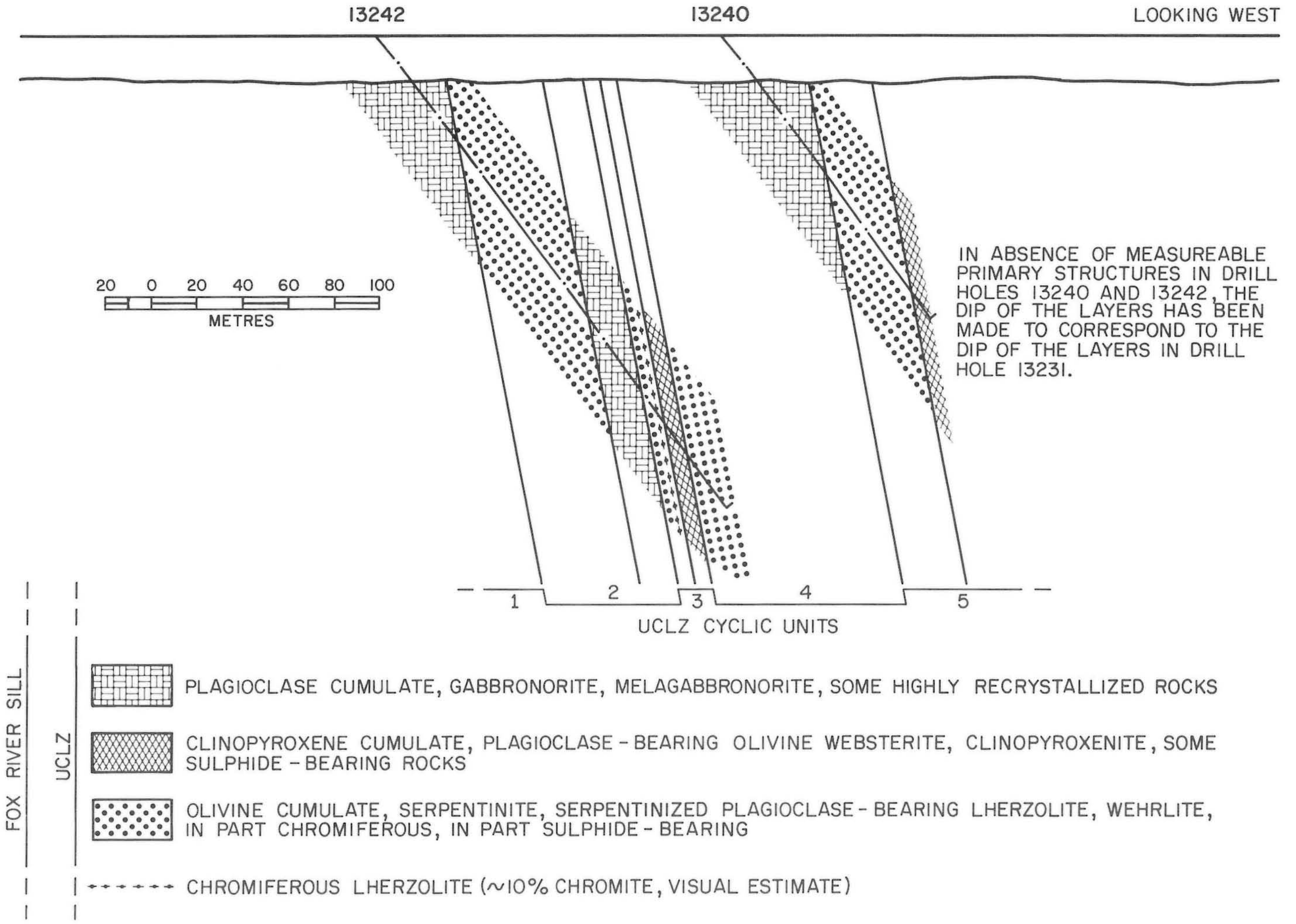


Figure 94: UCLZ geology, drill holes 13242, 13240, 462W section.

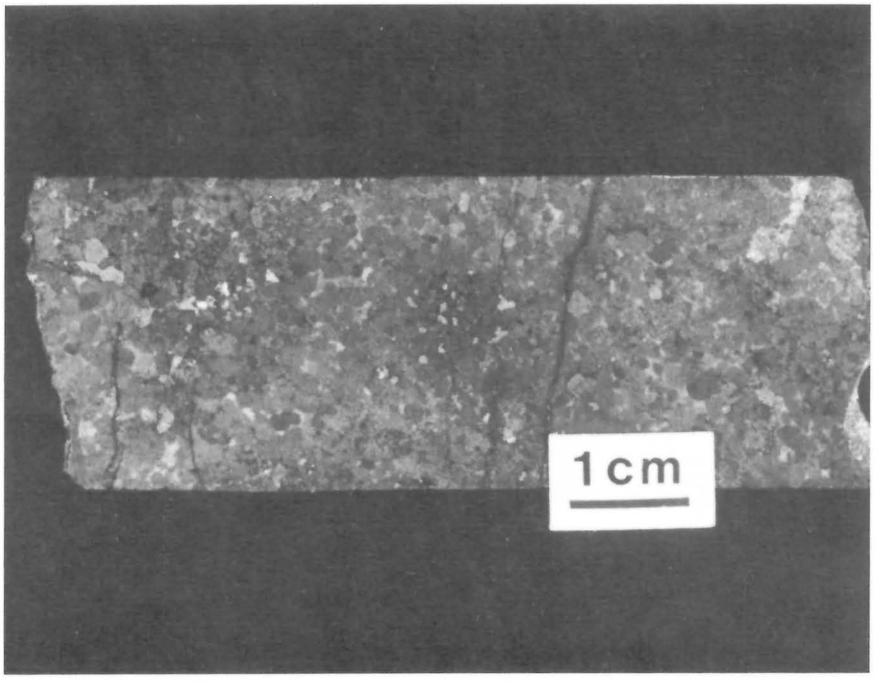


Plate 45: Sulphide-bearing orthopyroxene + olivine cumulate. Rock consists of cumulus tabular orthopyroxene crystals (mid-grey), cumulus olivine (mid- to dark grey) and postcumulus plagioclase (mid- to light grey). Light grey to whitish grey patches are intercumulus sulphide. UCLZ, orthopyroxene + olivine cumulate, DDH 38524-460.

are predominantly sulphide- and plagioclase-bearing websterite.

The olivine cumulate rocks that separate successive orthopyroxene cumulate layers contain abundant poikilitic orthopyroxene crystals that, in turn, contain numerous olivine inclusions, the inclusions being characterized by smoothly irregular, corroded outlines. Postcumulus clinopyroxene and plagioclase, now altered to amorphous-like secondary products, are the other common silicate minerals, and some of the rocks are sulphide bearing. The thin olivine cumulate layers are composed of rocks that were originally plagioclase-bearing lherzolite.

The presence of orthopyroxene cumulate illustrates the problem of terminology and naming rocks of layered intrusions. These particular orthopyroxene cumulates range from plagioclase-bearing orthopyroxenite to plagioclase-bearing websterite in composition (total modal mineralogy after Streckeisen, 1976). However, the field representing plagioclase-bearing websterite accommodates clinopyroxene-rich cumulates and orthopyroxene-rich cumulates. These orthopyroxene cumulates are websterites only by virtue of the fact that they contain postcumulus clinopyroxene that crystallized by reaction of orthopyroxene with intercumulus magma. Thus, naming the rocks on the basis of total modal mineralogy does not necessarily indicate the essential character of the rock.

The presence of orthopyroxene cumulates also illustrates that the sequence or order of crystallization of liquidus minerals in the main magma has changed from ol;cpx;pl to ol;opx. The cyclic repetition, olivine cumulate-orthopyroxene cumulate, suggests an incomplete or beheaded sequence of the kind noted in the LCLZ succession. In this case cpx and pl may have been prevented from becoming liquidus minerals in the main magma (both minerals are present as postcumulus phases). Irvine (1970) has pointed out that similar cyclic units in the Muskox Intrusion that lack a gabbro layer resulted from the crystallization path of the magma probably being terminated by an influx of fresh magma, the influx preventing plagioclase from becoming a liquidus phase.

CYCLIC UNIT 2

Olivine cumulate layer

The olivine cumulate layer is sulphide bearing at its base and is composed of medium- to dark-apple green, to greenish-back, mottled rocks. The mottling is caused by a white to cream-white alteration product that replaces partly continuous, postcumulus plagioclase. The rocks have been cut by a number of whitish-green picrolitic serpentine veinlets. The lower part was originally composed of plagioclase-bearing wehrlite, and the upper part of the layer was originally plagioclase-bearing lherzolite, orthopyroxene bastite replacing original orthopyroxene oikocrysts (up to 1.5 cm). Parallel, curtain-growth serpentine veinlets are developed at right angles to the direction of preferred orientation of original elongate olivine crystals in some rocks.

Drill hole 38523

Drill hole 38523 penetrated the uppermost part of the UCLZ succession, a complex Hybrid Roof Zone (HRZ) section, the roof contact of the Sill, and the siltstone-argillite sequence and derived hornfels of the overlying Middle sedimentary formation (Fig. 95). The plagioclase cumulate at the base of the drill hole is interpreted as representing the uppermost layer of the cyclic unit (cyclic unit 2, Fig. 95) that contains the olivine cumulate intersected in the upper part of drill hole 38524. The plagioclase cumulate contains some coarse grained quartz- and granophyre-bearing gabbro, similar to that associated with HRZ assemblages. The olivine cumulate, overlying the plagioclase cumulate, represents the uppermost UCLZ layer in this area, and is characterized by numerous, thin plagioclase cumulate layers, that range from 1 cm to 1 m thick, in addition to being intersected by a number of coarser grained gabbro dykes.

CYCLIC UNIT 2

Plagioclase cumulate layer

The rocks range from light to dark grey green and are medium grained. The lower third of the layer is composed of coarse grained, quartz-bearing rocks, characterized in part by graphic-like textures caused by intersecting randomly oriented hornblende blades, and locally by slender, curving hornblende crystals up to 5 cm long.

The rocks of the upper two-thirds of the layer were originally composed of lath-like plagioclase, irregularly shaped, commonly elongate clinopyroxene crystals, and poikilitic plate-like orthopyroxene crystals. Some rocks originally contained rare postcumulus olivine crystals. Crude lamination is preserved in a few rocks, and is caused by a rough parallel orientation of plagioclase laths and elongate clinopyroxene, and an imperfect segregation of the rock into mm-scale plagioclase-rich and clinopyroxene-rich lenses and laminae.

The rocks are highly recrystallized, plagioclase being replaced by a fine grained mat of epidote + chlorite, clinopyroxene being partly to completely altered to pale green actinolite, orthopyroxene being replaced by tremolite + chlorite intergrowths that produce bastite-like pseudomorphs, and olivine being replaced by tremolite ± chlorite. Prehnite veinlets were observed in one sample.

The coarse grained rocks are characterized by large (3 to 4 mm) skeletal ilmenite crystals, now largely replaced by sphene and other alteration products. Original plagioclase has been replaced by albite ± muscovite ± epidote ± chlorite ± carbonate ± sphene. Pale green actinolite replaces original twinned clinopyroxene, some of which contained plagioclase inclusions. Some actinolite forms dense stellate radiating masses. Clinopyroxene crystals up to 5 mm in size are common. Coarse patches of granophyre characterize some of these coarse grained gabbros. The fine grained rocks were originally laminated gabbronorites; the coarse grained rocks ranged from gabbro and quartz-bearing gabbro to granophyre-bearing gabbro in original composition.

UPPERMOST UNIT

Olivine cumulate

The rocks are grey green to dark greenish black and some are mottled due to sporadic distribution of 0.5 to 1 cm oikocrysts. The rocks are somewhat granular in appearance, although some greenish-black rocks possess a waxy lustre on the core surface. The rocks are cut by numerous 1 to 2 mm thick cross-fibre serpentine veinlets. Disseminated sulphides are rare, some sulphides being associated with magnetite in serpentine veins.

The sequence of olivine cumulate rocks has been interrupted by numerous mm-scale (up to 1 m thick) plagioclase cumulate layers, most of which possess sharp contacts with olivine cumulate rocks. The contact between the upper part of one individual plagioclase cumulate layer (23 cm thick, core length interval) is sharp, although in detail it is seen to be irregular in a cuspate manner, with individual olivine crystals or clusters of olivine crystals extending for several mm into the underlying plagioclase cumulate layer (Plate 46). The grain size of the cumulus olivine in the overlying olivine cumulate layer decreases (from 1 mm to 0.5 mm) over a distance of 6 cm (core length interval) from the contact (Plate 46).

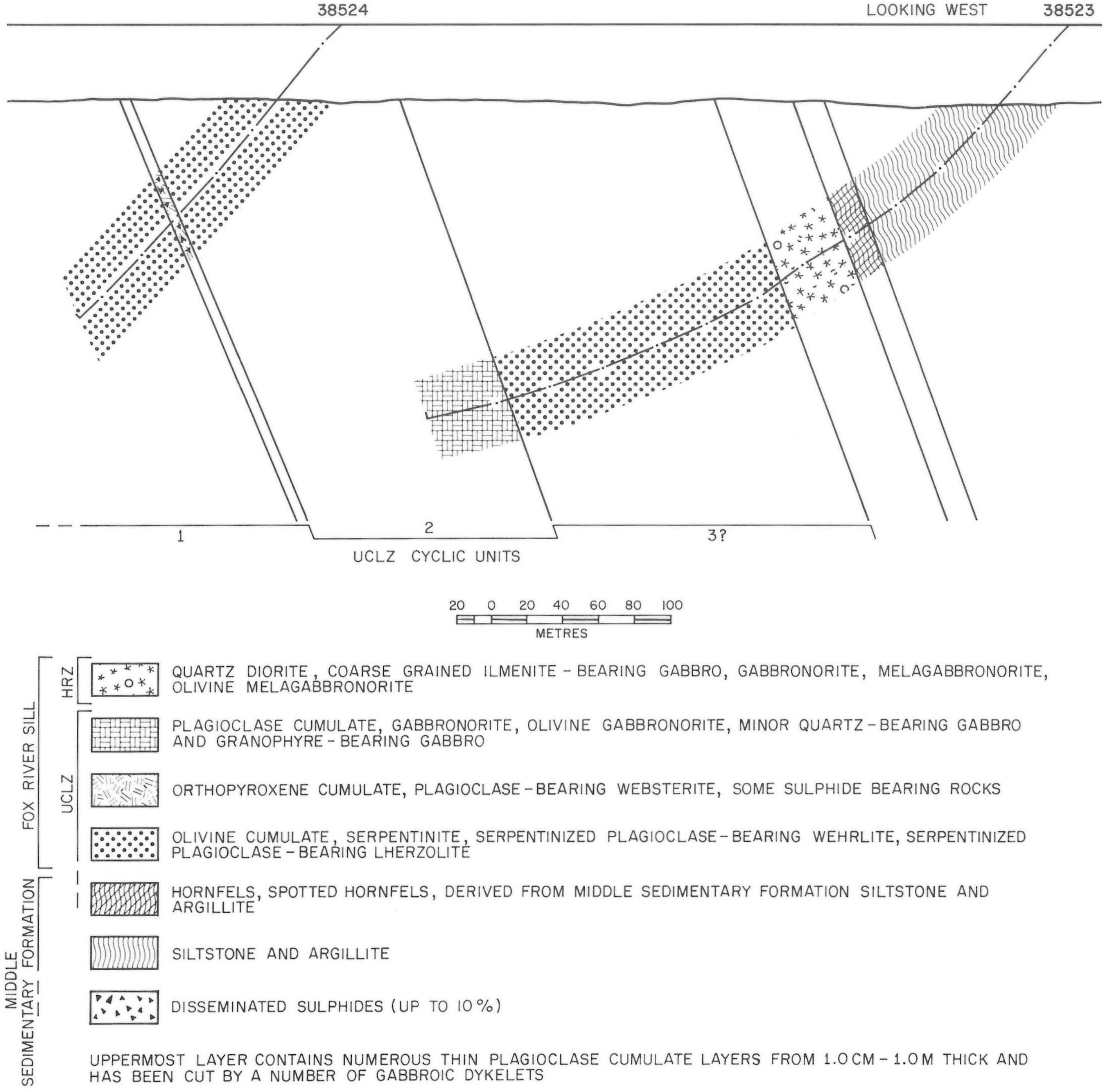


Figure 95: UCLZ-HRZ geology, drill holes 38524, 38523, 462W section.

A number of gabbro dykes cut the olivine cumulate sequence. These are distinguished from plagioclase cumulate rocks on the basis of their coarser grain size (plagioclase laths up to 3 cm long), and sharp, regular contacts with olivine cumulate rocks (Plate 47).

The olivine cumulate rocks were originally composed of rounded polyhedral olivine crystals, that have been replaced by mesh-texture and curtain-growth serpentine. Olivine is partly preserved toward the base of the layer ($Fo_{80.2-85.1}$). Parallel orientation of original elongate olivine crystals gives rise to laminated rocks in a few areas. Disseminated euhedral chromite crystals, the other cumulus phase, constitute from 1 to 3 percent of the rock. The postcumulus phases that originally made up from 10 to 25 percent of the rock, are dominated by clinopyroxene that originally formed large (0.5 to 1 cm) sporadically distributed oikocrysts. Clinopyroxene, which is partly preserved in many rocks, has been altered to fine grained, nearly isotropic serpentine ($\pm$ magnetite), clinopyroxene bastite and colourless tremolite. Orthopyroxene has been partly to completely altered to talc $\pm$ tremolite or orthopyroxene bastite; it originally formed large (0.5 to 1 cm) poikilitic crystals, some of which were similar to clinopyroxene oikocrysts in character. Original postcumulus plagioclase has been totally replaced by chlorite $\pm$ phlogopite, and postcumulus red-brown hornblende has been partly replaced by colourless tremolite. Numerous discontinuous magnetite $\pm$ serpentine veinlets distinguish many of these rocks.

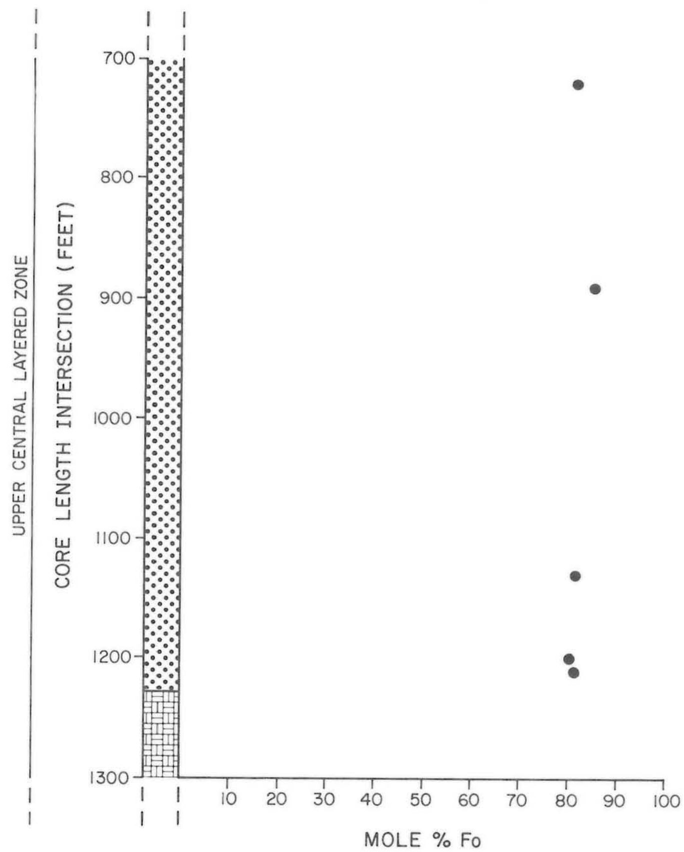


Figure 96: Olivine compositions, drill hole 38523.

There does not appear to be any progressive change in grain size, abundance of intercumulus material or distribution of laminated rocks from base to top of the layer. The layer has been treated as a single entity; however, as noted, it has been interrupted by a number of cm-scale plagioclase cumulate layers, the significance of which is not clear. They may represent the end of a cycle of fractional crystallization, in which case the sequence of liquidus minerals giving rise to these rocks would have been ol;pl, a sequence previously noted only in drill hole 13242.

Olivine compositions

Olivine compositions range from $Fo_{80.2}$ to $Fo_{85.1}$, although 4 of the 5 determinations display a much more limited range from $Fo_{80.2}$ to $Fo_{81.8}$, suggesting that UCLZ olivines are less Fo-rich than their LCLZ equivalents (Fig. 96). The apparent lack of a distinct decrease in Fo-content of olivines, from base to top of the layer, may suggest that the layer is composed of a number of small-scale cyclic units defined by the cyclic repetition olivine cumulate-plagioclase cumulate.

LAYER ATTITUDES

Correlation of layers between drill holes 38503 and 38522, collared on a section line approximately 2800 m west of 464W section line, produces layer dips of 69°N (Fig. 97). Calculation of layer dips based on means of observed layer contacts over fixed core length intervals of drill hole 38523 produces two possible solutions, steep dips to the south or intermediate to shallow dips to the north. The fact that the plunge of the drill hole changes from nearly 50°S (grid S) at the top of the hole to 13°S at the bottom of the hole, suggests that the drill hole may have deviated in azimuth direction as well as plunge. Given these uncertainties the layers are given a dip of 70°N that is in keeping with the sense and approximate dip estimated for drill hole 13231, and from correlation of layers in drill holes 38503 and 38522.

208W SECTION - DRILL HOLES 38503, 38522 AND 38510

Drill holes 38503 and 38522, collared on the same section line (208W), 636 m apart, were drilled in opposite directions so that the lower parts of the drill holes overlapped (Fig. 98). Drill hole 38510, collared on a section line 1091 m east of 208W, and projected onto 208W penetrated the roof contact of the Sill and 52 m (approximate true thickness) of HRZ rocks. Drill holes 38503 and 38522 intersected 565 m (approximate true thickness) of UCLZ rocks.

Drill holes 38503 and 38522

Because of their overlap, drill holes 38503 and 38522 intersected a continuous succession of UCLZ rocks. The fact that the lower portions of the drill holes intersect the same sequence of rocks allows for correlation between holes. Fortunately, a number of distinctive units occur in this area, and this provides for excellent correlation (Fig. 99). A layer dip of 70°N results from this correlation. Calculation of dips on the basis of measured primary structures to the core axis does not reproduce the dip obtained by correlation (Figs. 100 and 101). This may result from the holes not being drilled exactly at right angles to the direction of strike of the layers, so that the angle determined by correlation may be an apparent angle. The indicated northerly direction of dips is supported by the asymmetrical shape of ground magnetic anomaly profiles.

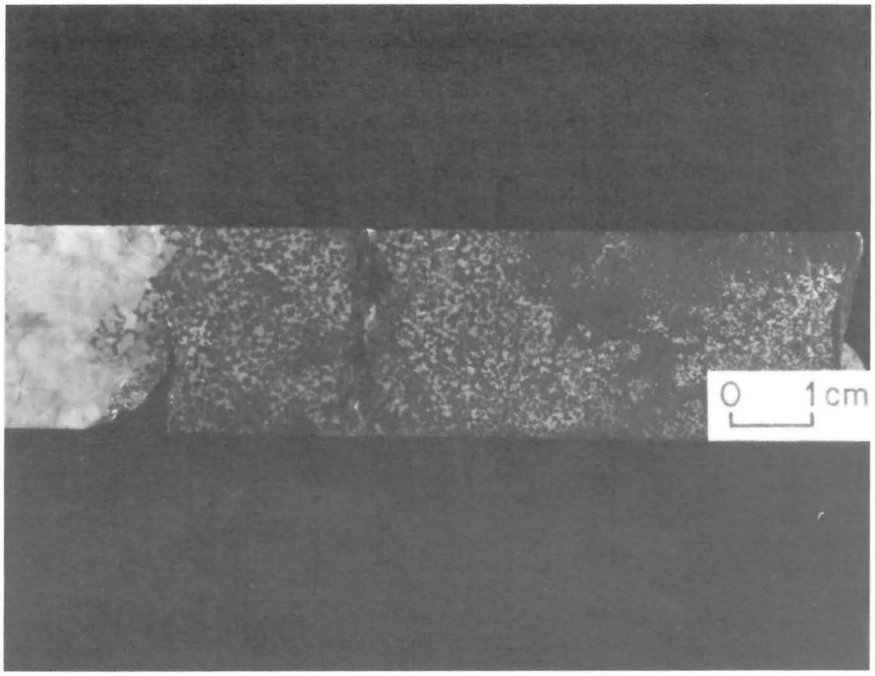


Plate 46: *Irregular contact between plagioclase cumulate and olivine cumulate layers. Note decrease in grain size of olivine away from the contact. Clinopyroxene oikocrysts are mid to light grey. The plagioclase cumulate has been extensively altered to secondary products. UCLZ, DDH 38523-772.0.*

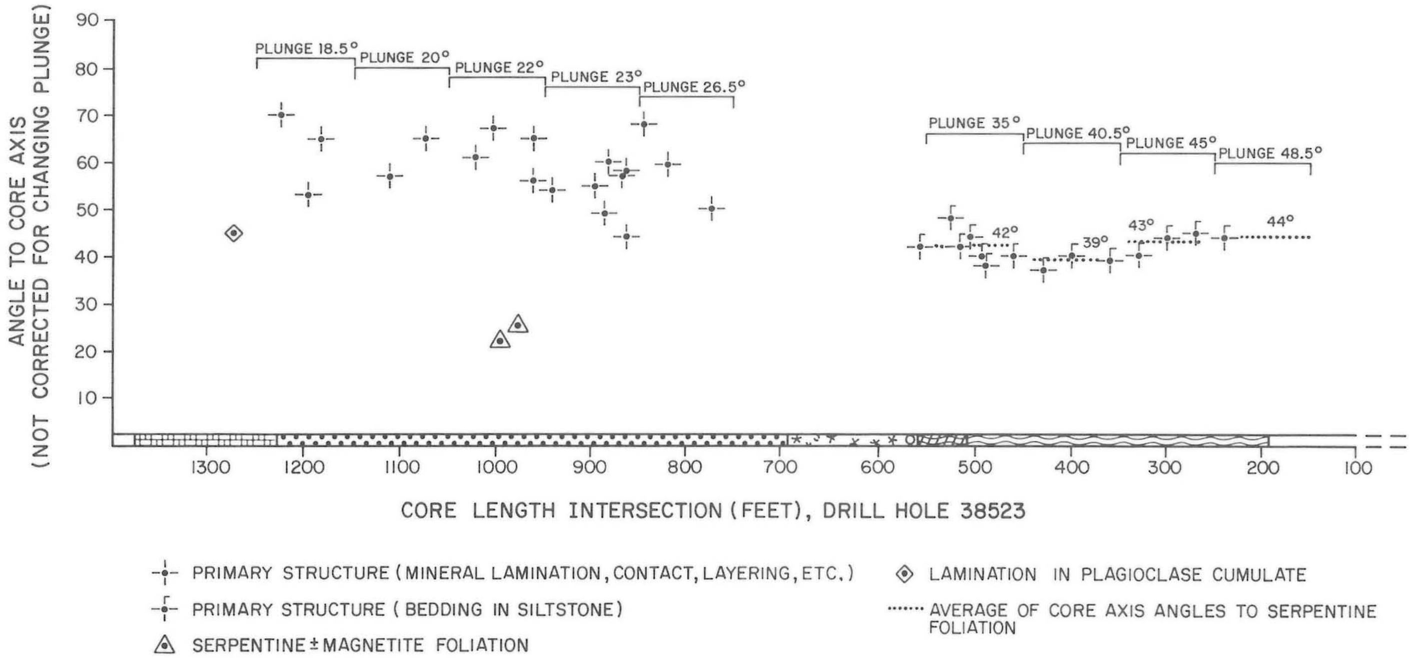


Figure 97: *Core axis angles to planar structures, drill hole 38523.*

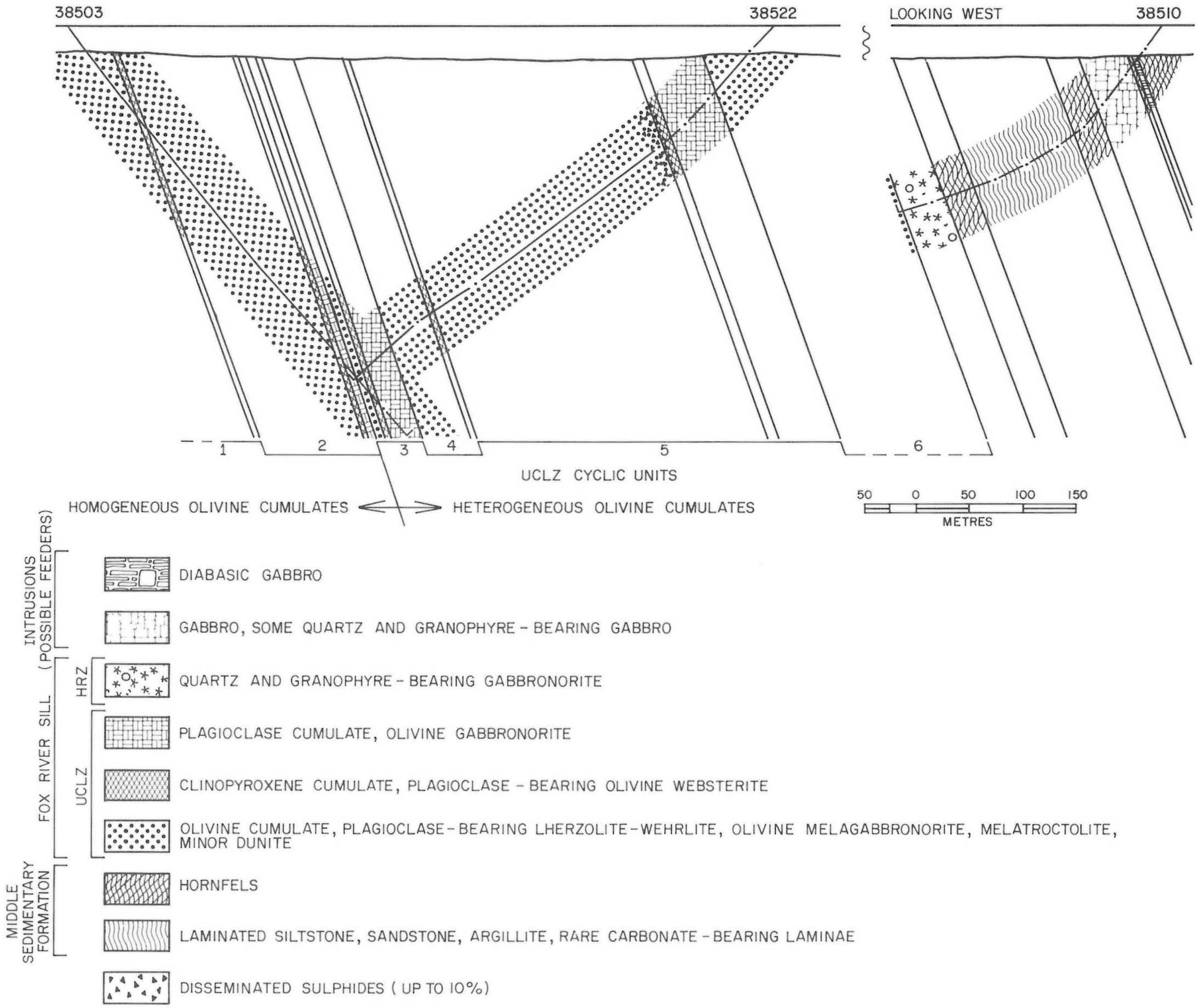


Figure 98: UCLZ-HRZ geology, drill holes 38503, 38522, and 38510, 208W section.

CYCLIC UNITS

Four complete cyclic units and portions of two other cyclic units are intersected by the holes. The cyclic units are arbitrarily numbered from 1 to 6, beginning with the stratigraphically lowest units. Three of the complete units are composed of olivine cumulate, clinopyroxene cumulate and plagioclase cumulate layers (cyclic units 2, 3 and 5). The other complete unit, (cyclic unit 4), as well as one of the incompletely exposed units (cyclic unit 1), are composed of olivine cumulate-clinopyroxene cumulate layers only. The cyclic units range from approximately 40 m to 307 m thick, and the proportion of olivine cumulate to plagioclase cumulate in the different units is extremely variable. By contrast, individual clinopyroxene cumulate layers are thin and display a relatively constant thickness. The plagioclase cumulate layer of cyclic unit 3 contains a narrow, 1 m thick olivine cumulate layer (Fig. 99), the significance of which, in terms of cyclic units, is not clear. Grain size grading of olivine crystals in the thickest olivine cumulate layer (cyclic unit 5) can be seen in a number of samples, individual graded layers ranging from 1 to 4 cm thick. Thus, it is possible that this 246 m thick layer may be constructed of numerous cm-scale beds or layers. The dynamic character of deposition of olivine in these olivine cumulate layers is demonstrated by the bull's-eye patterns produced by olivine c-axes from the olivine cumulate layer of cyclic unit 1 (Fig. 102). Plagioclase cumulate rocks are commonly well laminated, and poles perpendicular to plagioclase 010 produce a well defined bull's-eye pattern indicating that these lath-like crystals are oriented so that 010 is perfectly parallel to the layering plane (Fig. 103).

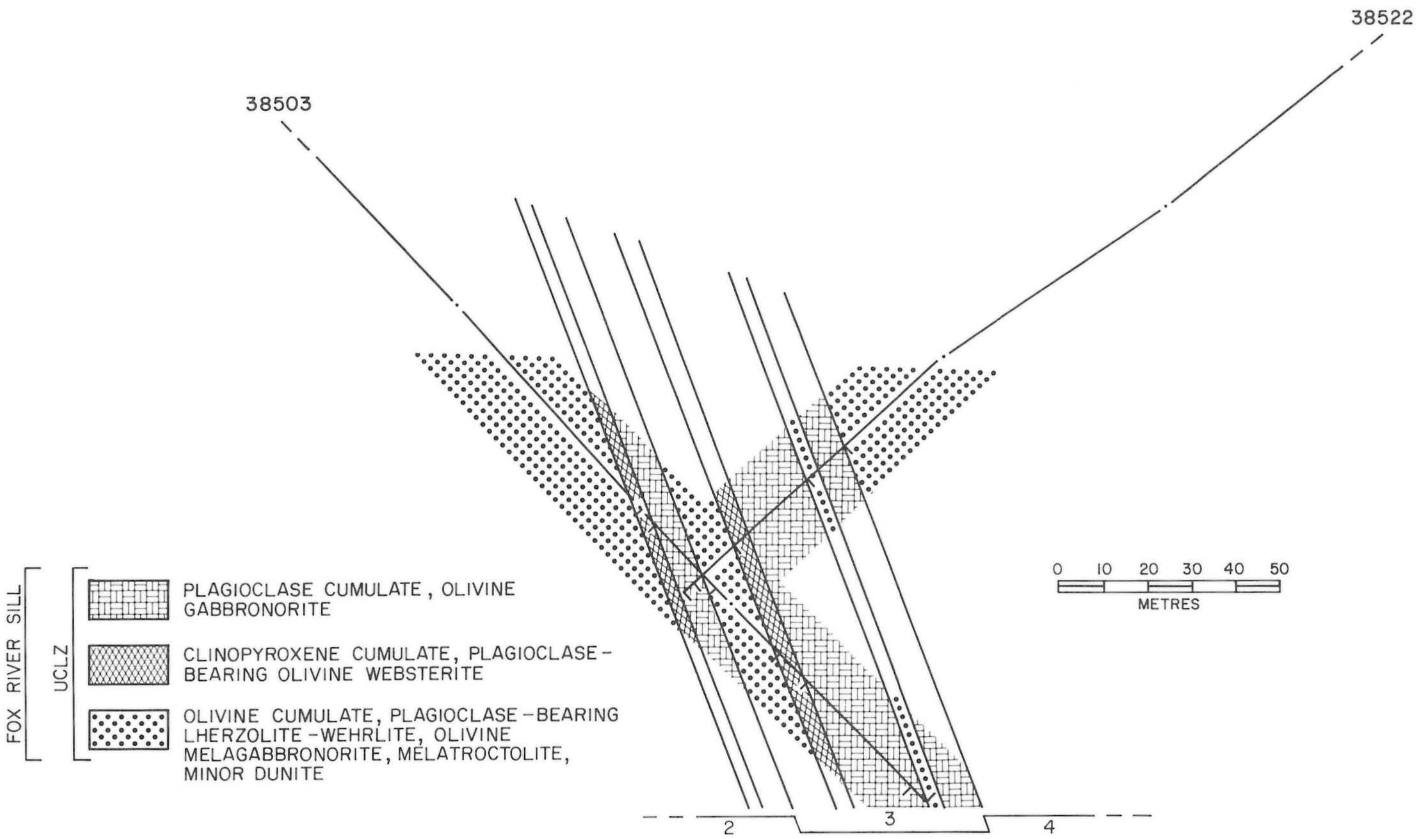


Figure 99: Detail of correlation between drill holes 38503 and 38522.

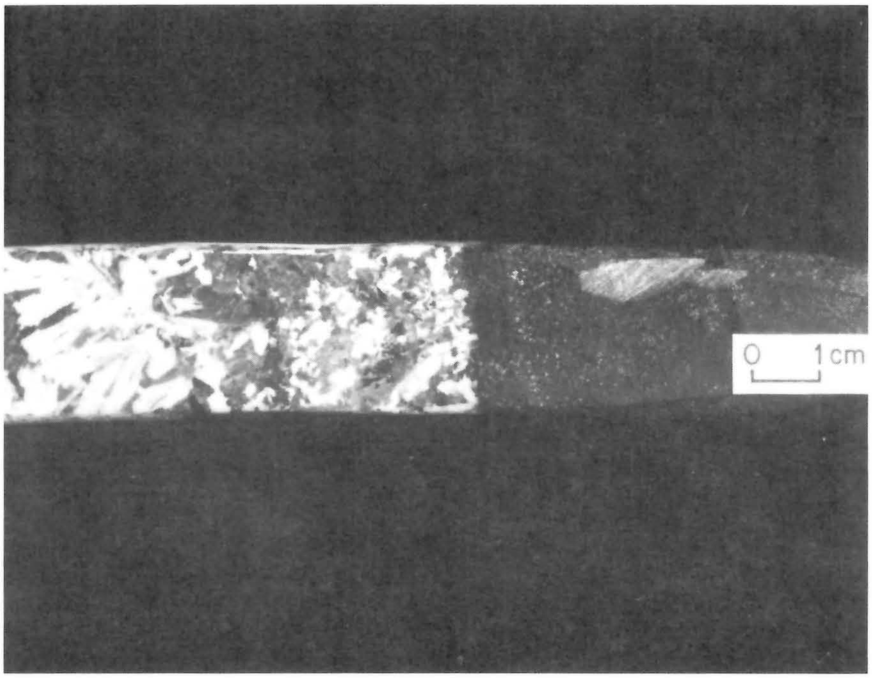


Plate 47: Contact between 12.0 cm thick gabbroic pegmatite dyke and olivine cumulate. Note increase in grain size from margin to centre of dyke. UCLZ, DDH 38523-1075.2.

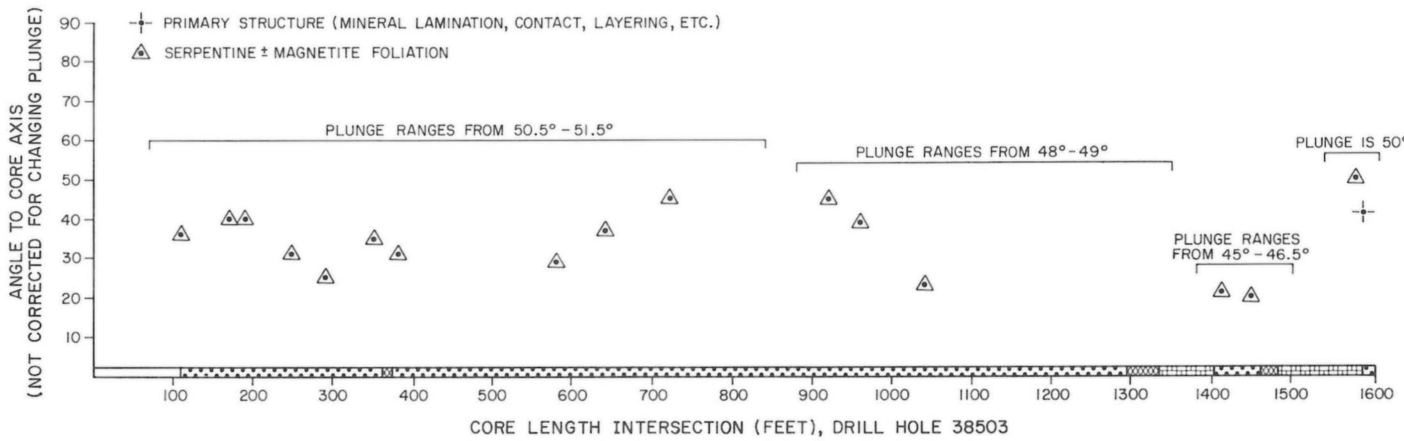


Figure 100: Core axis angles to planar structures, drill hole 38503.

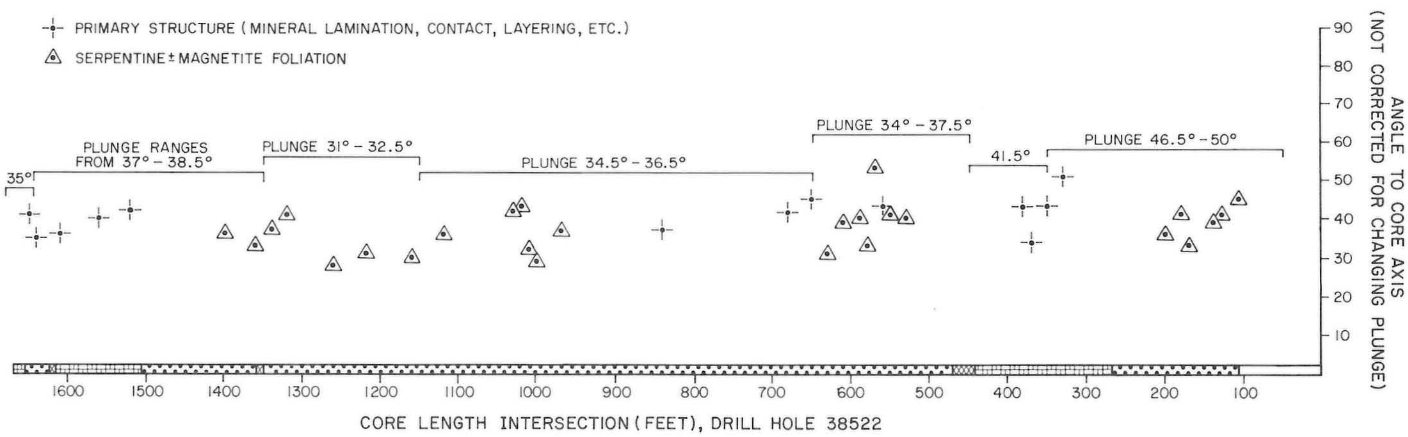


Figure 101: Core axis angles to planar structures, drill hole 38522.

Olivine cumulate layers

The olivine cumulate layers of cyclic units 1 and 2 are similar, being relatively homogeneous in character. The rocks range from medium- to dark-apple green to greenish black and a few rocks are finely mottled or spotted due to a whitish alteration product after original postcumulus plagioclase. Strong lamination in some rocks is caused by original elongate olivine crystals displaying near-perfect, parallel orientation. Serpentine $\pm$ magnetite veinlets are widely spaced and one picrolite-carbonate breccia zone was observed.

Olivine cumulate rocks of cyclic unit 1 were originally composed of rounded polyhedral olivine crystals and clusters of polygonal crystals in areas where the intercumulus phases constituted less than 10 percent of the rock (Plate 48). Original elongate olivine crystals commonly display parallel orientation that is particularly well developed toward the top of the layer. This is illustrated in Figure 102 where an irregular bull's-eye pattern and partial girdle demonstrate the lineate lamination (Jackson *et al.*, 1975) of olivine c-axes in one of these laminated rocks. Chromite, the other cumulus phase, occurs as disseminated individuals and clusters of crystals and constitutes from 1 to 3 percent of the rock. A few crystals possess central circular inclusions of the type previously described. Olivine, which is partly preserved in one sample, has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. Clinopyroxene and orthopyroxene, that originally formed large oikocrysts, have been replaced by clinopyroxene bastite and orthopyroxene bastite, respectively. Original postcumulus plagioclase has been replaced by chlorite. The rocks ranged from plagioclase-bearing wehrlite to plagioclase-bearing lherzolite to dunite in original composition.

Olivine cumulate rocks of cyclic unit 2 are similar to cyclic unit 1 olivine cumulate rocks. They possess heterogeneous olivine grain size in a few areas, original olivine crystals ranging from 0.3 to 5 mm in one thin section. In addition the ratio of postcumulus phases to cumulus olivine increases from 10 to 25 percent (visual estimates) over the last 60 m (approximate true thickness) toward the contact with the underlying clinopyroxene cumulate.

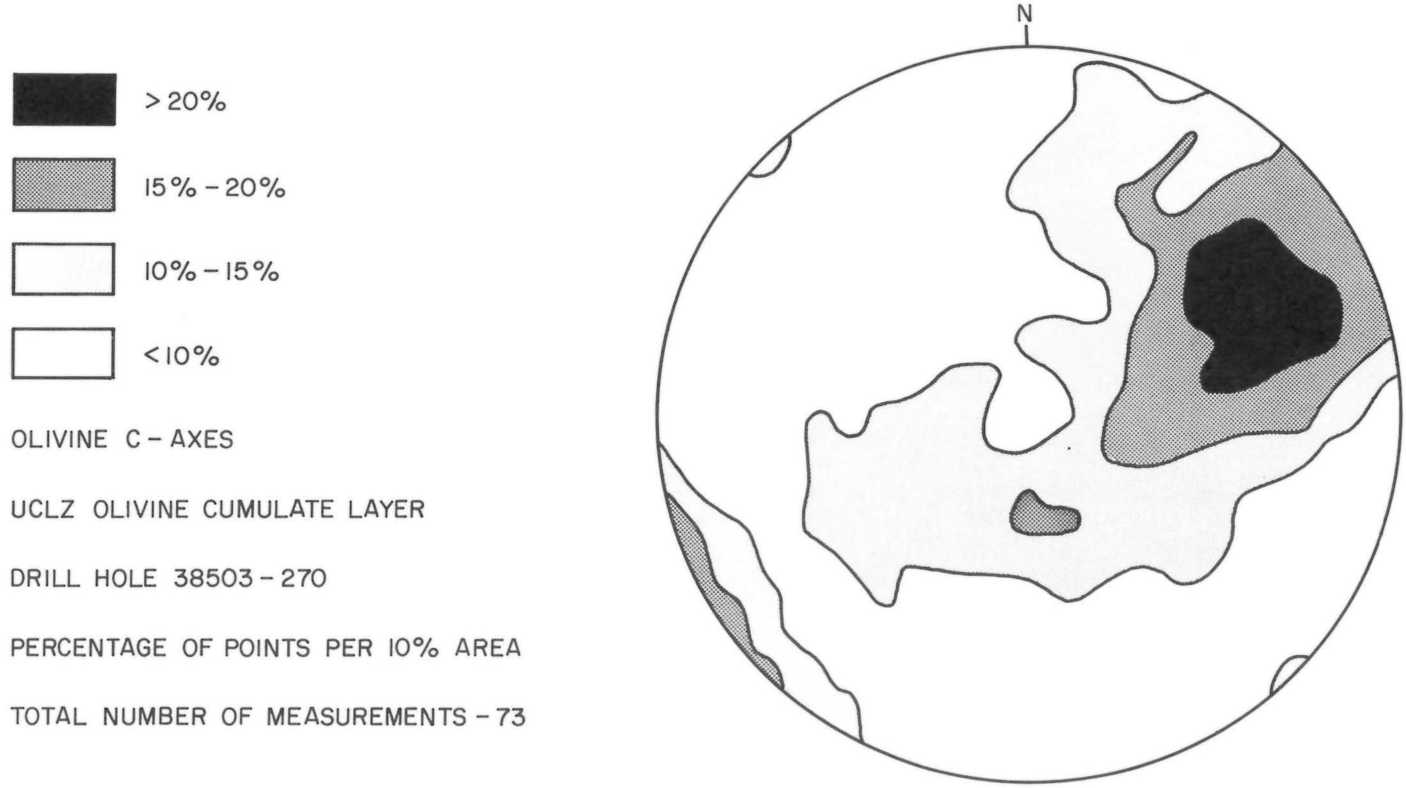


Figure 102: Fabric diagram, olivine c-axis, UCLZ olivine cumulate layer, drill hole 38503.

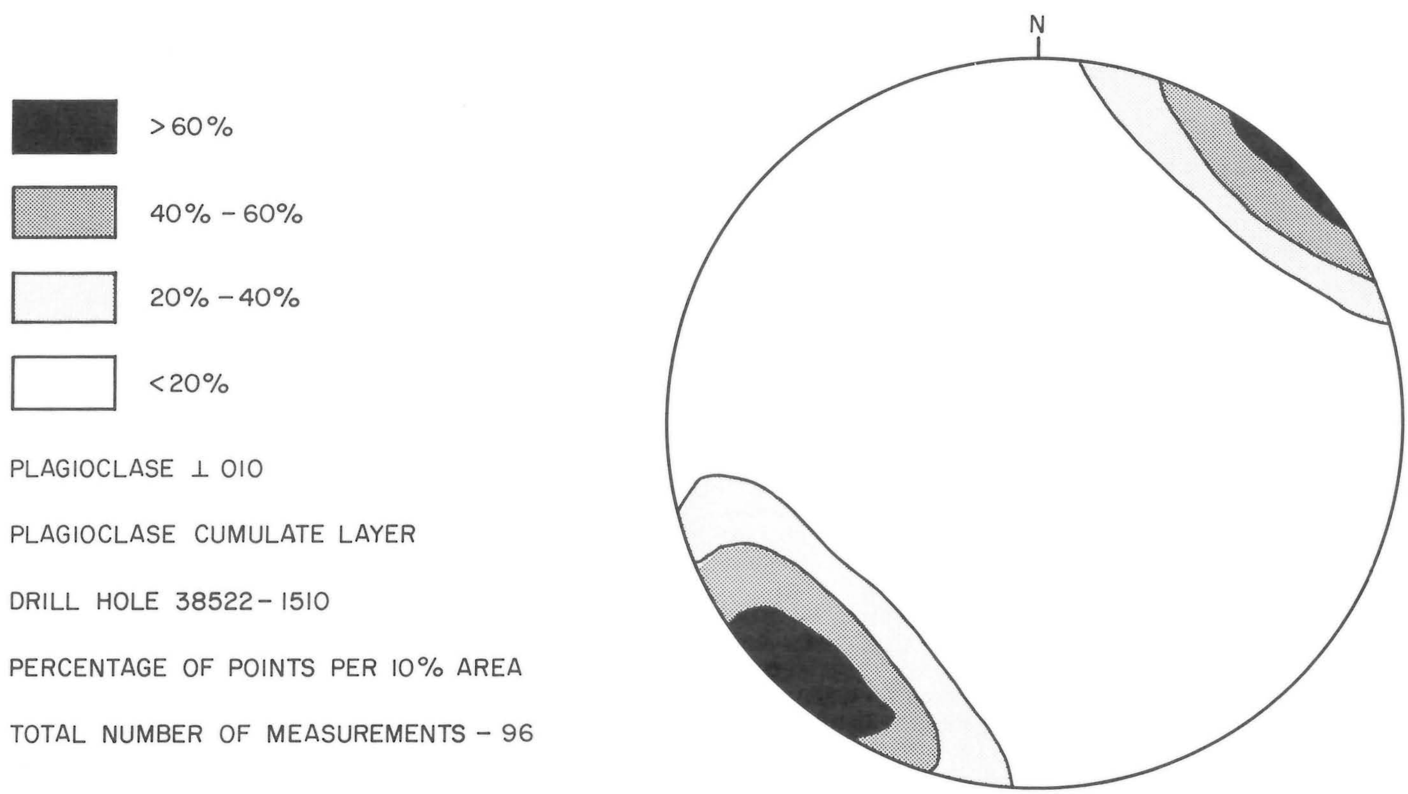


Figure 103: Fabric diagram, pole 010 in plagioclase, UCLZ plagioclase cumulate, drill hole 38522.

Cyclic unit 3, which contains the thinnest olivine cumulate layer (8.8 m thick, approximate true thickness), is the first of the heterogeneous olivine cumulate layers of this sequence. The rocks are grey to brownish green to greenish black and strongly mottled, the mottling being caused by original clinopyroxene and plagioclase oikocrysts and abundantly distributed poikilitic orthopyroxene crystals (Plate 49).

The rocks are characterized by abundant postcumulus phases that constitute from 25 to 35 percent (visual estimate) of the rock, and by being somewhat coarser grained with original cumulus olivine crystals averaging approximately 2 mm in size. The postcumulus phases are composed of large (2 to 3 cm), partly preserved, poikilitic orthopyroxene crystals, large (1 to 2 cm), partly preserved, clinopyroxene oikocrysts and fine grained mixtures of alteration products after original plagioclase oikocrysts. Red-brown hornblende forms smaller oikocrysts. Orthopyroxene is the most abundant postcumulus phase and contributes greatly to the rock's mottled, heterogeneous character (Plate 49). Disseminated chromite is rare, and sulphides occur as discontinuous veinlets (+ magnetite + serpentine) and as rare globular masses enclosed in postcumulus phases. The original rock was olivine melagabbronorite in composition.

Olivine cumulate rocks of cyclic unit 4 are also characterized by a heterogeneous character, the mottled rocks ranging from dark apple green to dark greenish black. The mottling is caused by the widespread distribution of pyroxene and plagioclase oikocrysts, the latter now occurring as whitish alteration products. The rocks are laminated near the upper contact with the overlying clinopyroxene cumulate layer.

The rocks are similar to those previously described, consisting of original rounded polyhedral cumulus olivine crystals and relatively abundant (15 to 25 percent) postcumulus phases. The postcumulus phases consist of clinopyroxene, partly preserved and partly as clinopyroxene bastite, orthopyroxene as orthopyroxene bastite, and plagioclase, now as a fine grained mixture of alteration products including garnet. Chromite is rare (about 1 percent), secondary magnetite composes up to 3 percent of some rocks and sulphide is rare (less than 1 percent). The original rocks ranged in composition from plagioclase-bearing wehrlite to melatroctolite and olivine melagabbronorite.

Cyclic unit 5 contains the thickest of the heterogeneous olivine cumulate layers of this UCLZ sequence. The layer, 246 m thick (approximate true thickness), is composed of rocks that range from grey green to medium and dark apple green, and that in places are strongly mottled by abundant oikocrysts (Plate 50). The sporadic distribution of poikilitic orthopyroxene crystals contributes to the heterogeneous character of the rocks as does a substantial range in grain size of the original cumulus olivine crystals (from 0.5 to 5 mm). Centimetre-scale grain size graded layers have been observed (Plate 51). Strong serpentine fabric is well developed locally, and sulphide-bearing rocks (up to 5 percent sulphide) occur near the top of the layer (Plate 52).

The rocks are characterized by serpentine pseudomorphs after rounded polyhedral, polygonal and prismatic olivine crystals. Parallel orientation of original elongate olivine crystals is well developed at the top of the layer and at the top of some individual, centimetre-scale grain size graded layers. Mesh-texture and curtain-growth serpentine replace original olivine crystals, with secondary fibrous diopside occurring in the cores of serpentine pseudomorphs in some rocks. Disseminated euhedral chromite crystals constitute approximately 1 percent of the rock and are slightly more abundant (2 to 3 percent) toward the top of the layer. Postcumulus phases constitute from 10 to 20 percent of the rocks and are composed of clinopyroxene oikocrysts, partly preserved and partly as clinopyroxene bastite, and plagioclase oikocrysts, now as fine grained mixtures of secondary products including garnet and chlorite. Sulphide minerals of the sulphide-bearing assemblage occur as cusp-shaped intercumulus phases. Talc $\pm$ magnetite and phlogopite $\pm$ magnetite occur as widely distributed secondary assemblages in intercumulus areas. The original rocks ranged in composition from plagioclase-bearing lherzolite and plagioclase-bearing wehrlite, to melatroctolite and olivine melagabbronorite.

The portion of the olivine cumulate layer of cyclic unit 6 intersected at the top of drill hole 38522 is similar to cyclic unit 5 olivine cumulate

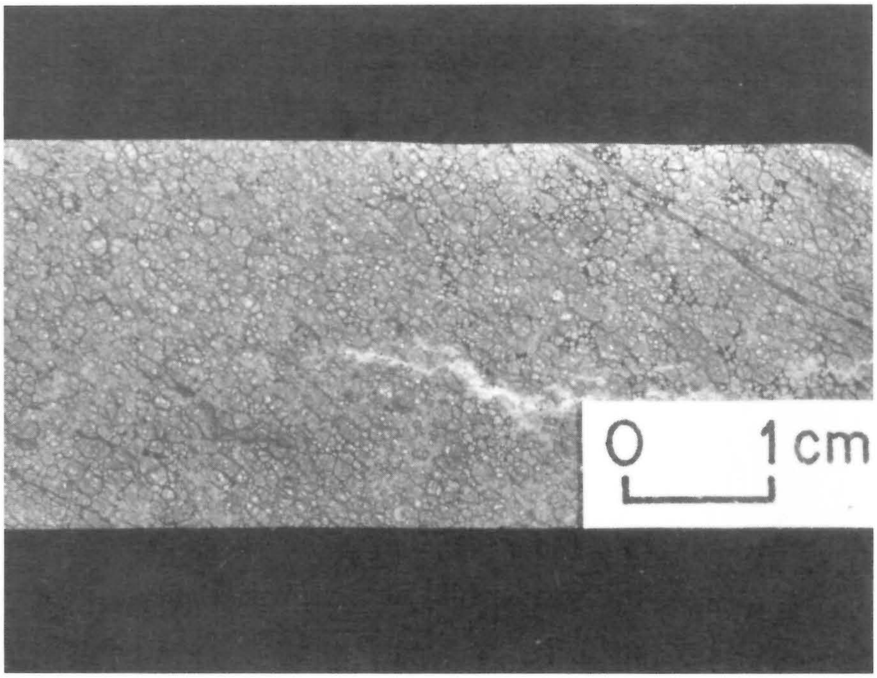


Plate 48: Mosaic-like network of densely packed olivine crystals (now serpentinized). Lamination diagonal to core axis is caused by parallel orientation of elongate olivine and is enhanced by parallel serpentine veinlets. Whitish material is carbonate. UCLZ, serpentinized dunite, DDH 38503-240.

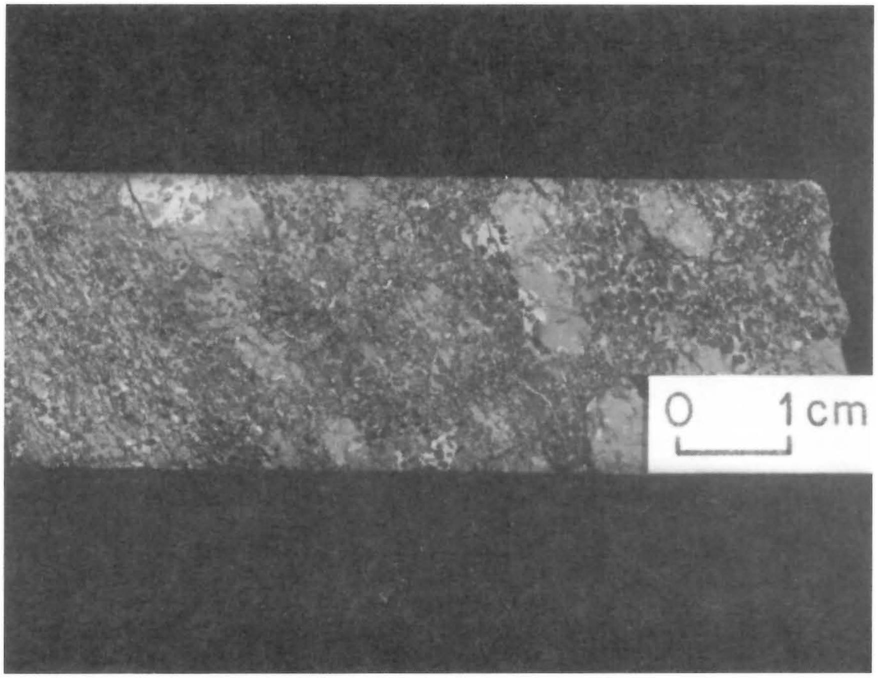


Plate 49: *Heterogeneous olivine cumulate. Elongate, mid-grey patches displaying parallel orientation are aggregates and single poikilitic crystals of orthopyroxene. Light grey intercumulus material is alteration after postcumulus plagioclase, mid-grey intercumulus material is postcumulus clinopyroxene. Dark grey, kernel-shaped crystals are partly serpentinized olivine. UCLZ, olivine cumulate, DDH 38522-1640.*

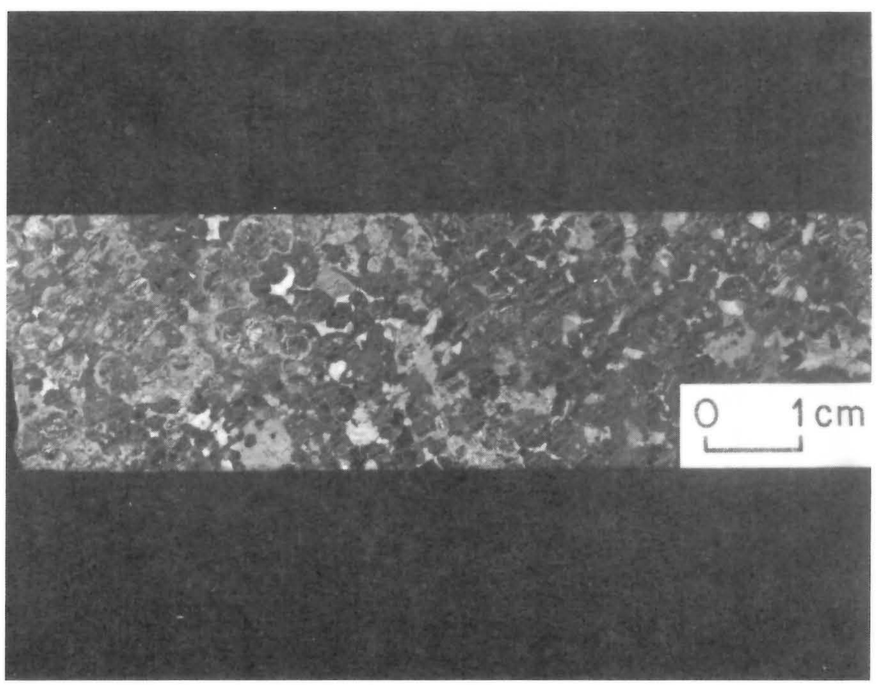


Plate 50: *Medium grained olivine cumulate. Whitish material is alteration after postcumulus plagioclase. Mid-grey intercumulus areas are clino- and orthopyroxene and dark grey crystals are serpentinized olivine. Rock is slightly more even textured than heterogeneous varieties. UCLZ, olivine cumulate, DDH 38522-580.*

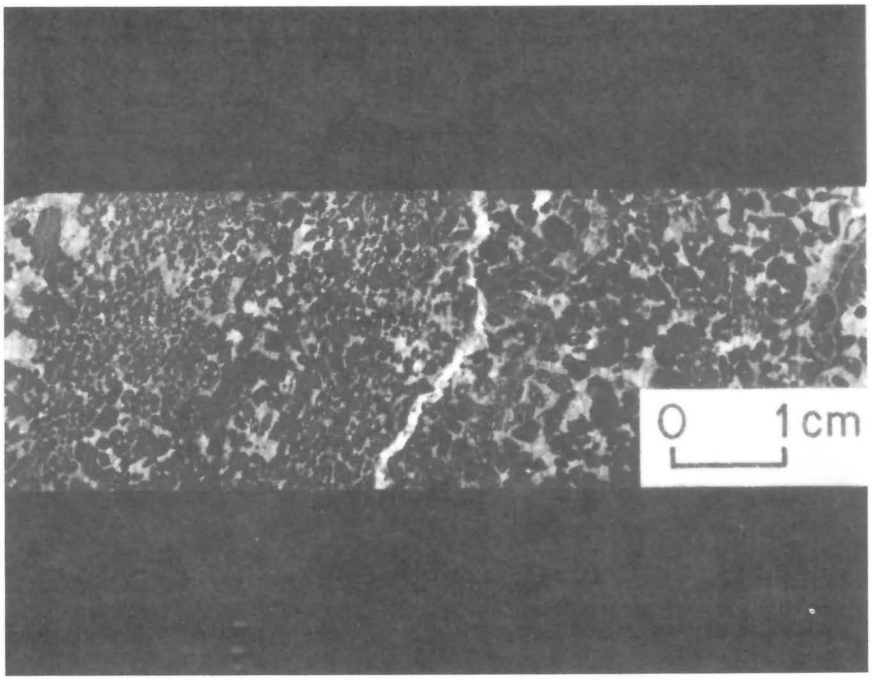


Plate 51: *Cm-scale grain size graded layers in olivine cumulate. Whitish material is alteration after postcumulus plagioclase oikocrysts, mid-grey are pyroxene oikocrysts and dark grey to black is serpentinized olivine. Progressing from right to left, contacts between fine grained and coarse grained olivine are abrupt suggesting tops to the left. Note parallel orientation of elongate fine grained olivine parallel with layering. UCLZ, olivine cumulate, DDH 38522-920.*

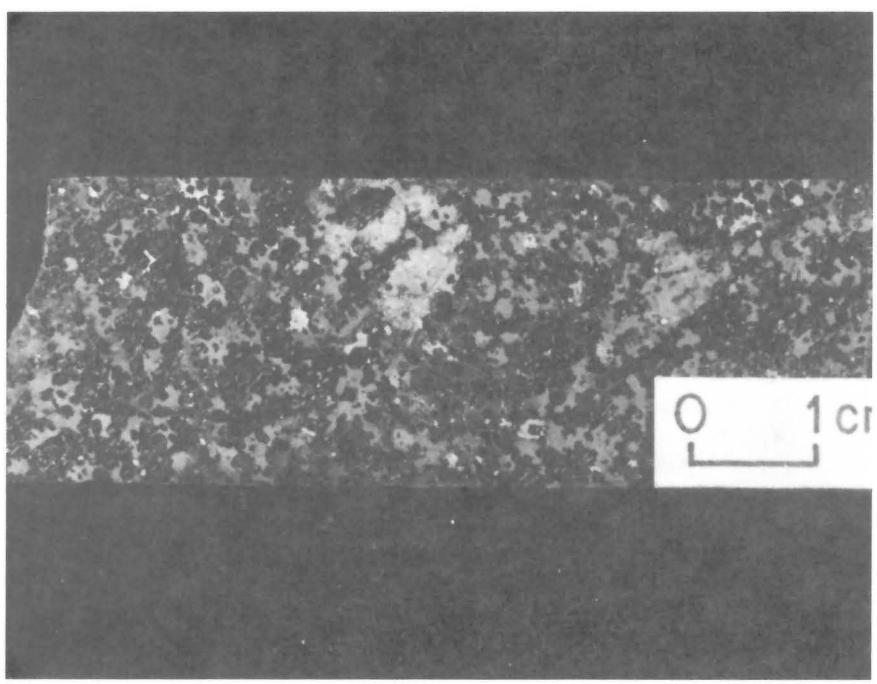


Plate 52: *Sulphide-bearing, heterogeneous olivine cumulate. Light grey areas are intercumulus sulphide. Large mid-grey poikilitic crystals are orthopyroxene, smaller poikilitic crystals are clinopyroxene. Dark areas are serpentinized olivine. UCLZ, DDH 38522-510.*

layer in being mottled and containing abundant oikocrysts and sporadically distributed poikilitic orthopyroxene crystals. The layer is characterized by numerous centimetre-scale plagioclase cumulate layers, and thus is identical to the uppermost UCLZ olivine cumulate layer intersected in drill hole 38523 with which it is correlated.

The rocks are similar to those previously described with cumulus rounded polyhedral olivine crystals, now altered to mesh-texture and curtain-growth serpentine, surrounded by 15 percent postcumulus material. The postcumulus phases, clinopyroxene, orthopyroxene and plagioclase, have been replaced by secondary minerals. Disseminated chromite constitutes from 1 to 3 percent of the rock and rare sulphide minerals (less than 1 percent) occupy intercumulus areas. The original rocks were plagioclase-bearing lherzolite.

Clinopyroxene cumulate layers

Clinopyroxene cumulate layers are characteristically thin (maximum thickness approximately 8.5 m) and in two cases represent the top of a cyclic unit (cyclic units 1 and 4). The rocks of the different layers possess similar characteristics: they range from grey green and greenish grey to brownish green, all are granular, and most are spotted or mottled. Those associated with cyclic units 1, 2 and 3 are sulphide free, whereas those associated with cyclic units 4 and 5 are sulphide bearing. The lower 6 m of cyclic unit 5 clinopyroxene cumulate layer contains up to 10 percent (visual estimate) intercumulus sulphide (Plate 53). Portions of this layer are coarser grained with individual crystals up to 4 mm in size, and sulphide minerals are also coarser in these rocks. Some rocks contain widely spaced, serpentine-filled fractures.

The rocks are composed of clinopyroxene as cumulus, roughly equidimensional prismatic crystals, that commonly formed as a continuous interlocking mosaic of irregularly shaped crystals, many individual crystals possessing complex mutual grain boundaries. Many of the crystals display a well developed parting and many are twinned. Cyclic unit 1 layer contains complex polycrystalline aggregates in which some individual crystals are characterized by coarse, blebby, myrmekite-like exsolution. Incipient to complete recrystallization of clinopyroxene to tremolite occurs in a few rocks. Orthopyroxene forms large (up to 5 mm) poikilitic crystals that contain numerous rounded clinopyroxene inclusions. In many rocks, these inclusions represent the nature of the original cumulus clinopyroxene crystals prior to their modification to continuous crystal mosaics by adcumulus growth. Orthopyroxene has been partly to completely replaced by tremolite that forms bastite-like pseudomorphs. It also contains inclusions of olivine, sulphide and plagioclase (rare). Plagioclase, replaced by epidote ± chlorite ± garnet is a common postcumulus phase and inclusions of lath plagioclase in orthopyroxene indicate that locally it was originally a cumulus phase. Olivine occurs as scattered individuals or groups of individual crystals. They are commonly partly preserved despite recrystallization to chlorite ± tremolite.

Plagioclase cumulate layers

The three plagioclase cumulate layers, 6.5, 27.3 and 52.0 m thick (approximate true thickness), respectively, form the uppermost layers to cyclic units 2, 3 and 5. The rocks are grey to bluish- and brownish-grey, granular, and delicately to strongly spotted or mottled. Some rocks display a well developed parallel orientation of elongate plagioclase crystals (Plate 54) and some rocks possess rough mm-scale lamination. Plagioclase of cyclic unit 3 displays a strongly developed apposition fabric (Jackson, 1961; Fig. 103).

In thin section, many of the rocks are characterized by pronounced parallel orientation of plagioclase laths and elongate, irregularly shaped clinopyroxene crystals. Lamination, caused by rough segregation of plagioclase-rich and plagioclase-poor lenses and

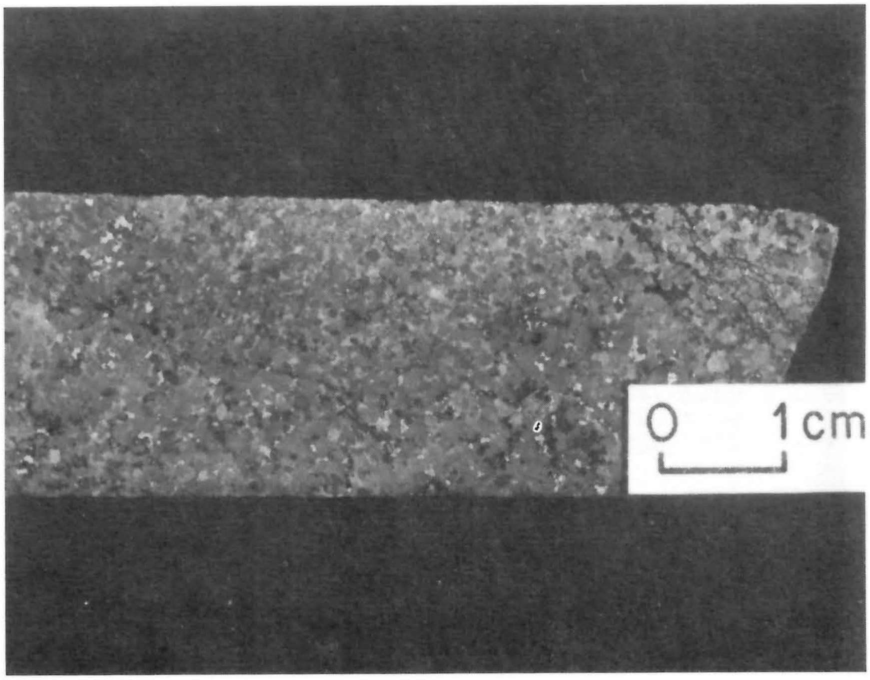


Plate 53: Sulphide-bearing clinopyroxene cumulate. More highly reflective whitish patches are intercumulus sulphide. Light grey intercumulus material is alteration after original postcumulus plagioclase. Mid grey crystals are cumulus clinopyroxene. Mid to dark grey kernel-like crystals at upper right are cumulus olivine. UCLZ, clinopyroxene cumulate, 208W section, DDH 38522-470.

laminae is common. Grain size gradation of plagioclase laths within plagioclase-rich laminae has been observed in a few rocks. Clinopyroxene, as irregular, commonly elongate crystals that possess parting, is twinned. Complex polycrystalline clinopyroxene aggregates display coarse, blebby myrmekite-like exsolution. The rocks are further characterized by the presence of large (up to 5 mm) olivine oikocrysts containing numerous plagioclase inclusions. Postcumulus, poikilitic orthopyroxene crystals are common, and the upper parts of the plagioclase cumulate layers of cyclic units 2 and 5 are characterized by the presence of cumulus orthopyroxene indicating that, in these cyclic units, the sequence of crystallization in the main magma was ol;cpx;pl;opx.

Plagioclase has been partly to completely converted to albite ± muscovite ± epidote ± chlorite ± garnet, but it is well preserved in many rocks. Clinopyroxene has been partly to completely converted to tremolite, and orthopyroxene has been replaced by fine grained tremolite giving rise to bastite-like pseudomorphs. Ilmenite, and its alteration products, are the dominant opaque minerals; sulphides are rare. The rocks were originally olivine gabbronorite in composition.

Olivine compositions

Olivines display an overall gradual decrease in Fo-content from the base to the top of the succession, ranging from Fo83.6 near the base to Fo79.2 near the top (Fig. 104). The variation in composition is smoothly regular due to variations within individual cyclic units. There is an indication of chemical grading within some individual UCLZ cyclic units as well as an indication of an overall progressive decrease in olivine Fo-content.

Drill hole 38510

UPPERMOST UCLZ UNIT

Olivine cumulate rocks

Approximately 2 m of original olivine cumulate are intersected at the base of drill hole 38510 (Fig. 98). This olivine cumulate, which is tentatively correlated with the UCLZ sequence, is light grey green and mottled. Close to the HRZ contact it is characterized by abundant postcumulus phases that segregate and isolate original cumulus olivine crystals (Plate 55). Clinopyroxene, plagioclase and hornblende were common postcumulus phases, the clinopyroxene and hornblende being replaced by tremolite and plagioclase by an isotropic mat of alteration products. Globules of sulphide (up to 2 mm) compose up to 10 percent of the rock (Plate 55). Close to the contact, the postcumulus phases compose more than 50 percent of the rock (Plate 55) that was an olivine melagabbronorite in original composition. At the base of the hole, the rock is somewhat better preserved and chromite constitutes approximately 3 percent of the rock whereas sulphide is no longer present. Original olivine has been replaced by antigorite, postcumulus clinopyroxene oikocrysts have been replaced by tremolite, postcumulus plagioclase has been replaced by chlorite and other unidentified alteration products, and postcumulus orthopyroxene has been replaced by talc + tremolite + chlorite. The rock at the base of the hole was originally plagioclase-bearing lherzolite.

380W SECTION - DRILL HOLE 13201

Drill hole 13201

CYCLIC UNIT

Drill hole 13201 penetrates the LCLZ-UCLZ contact separates nonorthopyroxene-bearing LCLZ rocks from orthopyroxene-bearing UCLZ rocks (Fig. 27). Here the UCLZ consists of a cyclic unit composed of thin olivine cumulate (10 m) and clinopyroxene cumulate (6.7 m) layers and a thicker plagioclase cumulate layer (minimum thickness 20 m), the upper contact of which was not penetrated by the drill hole.

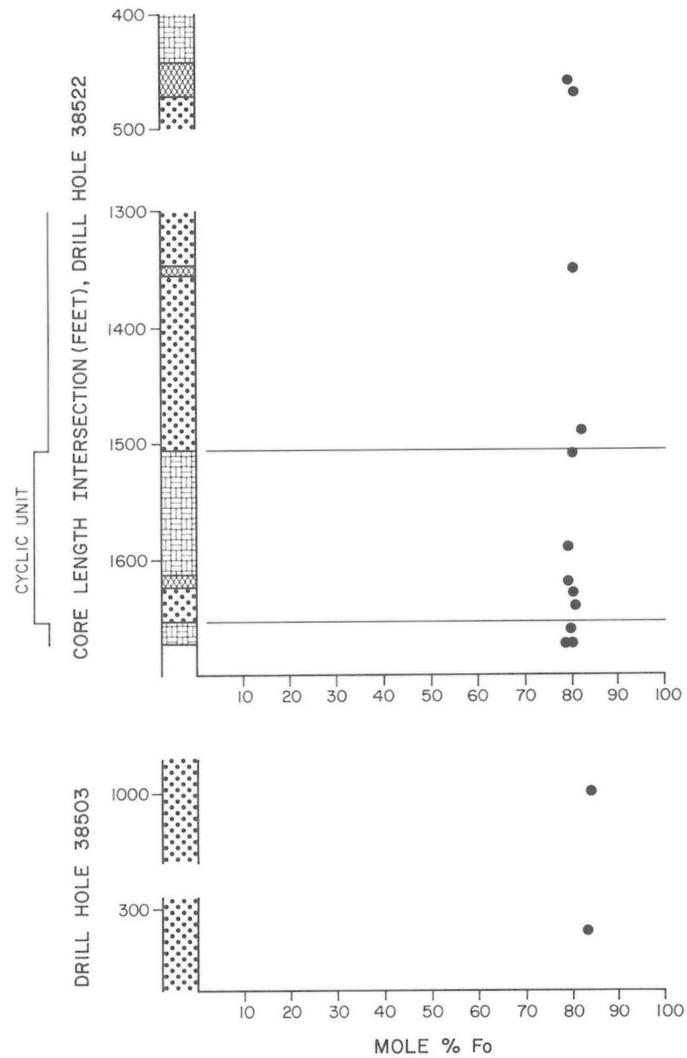


Figure 104: Olivine compositions, drill holes 38503 and 38522.

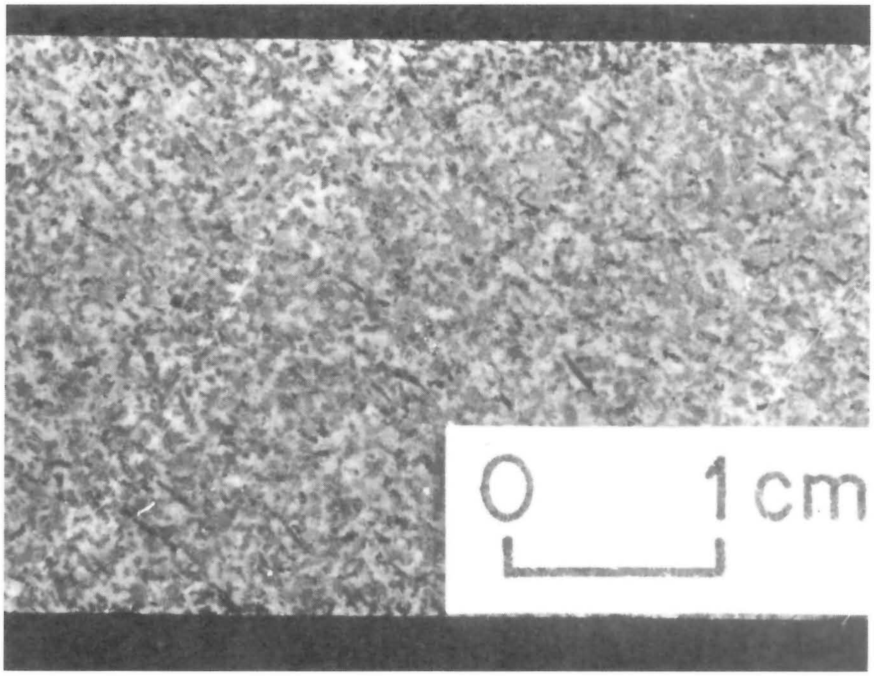


Plate 54: *Plagioclase (+ clinopyroxene + orthopyroxene) cumulate displaying primary lamination (from lower right to upper left). The lamination is caused by parallel orientation of original lath-like plagioclase crystals (light grey). It is enhanced by the parallel orientation of original lath-like orthopyroxene crystals (dark grey to black). The rock has been extensively recrystallized. UCLZ, plagioclase cumulate, DDH 38522-270.*

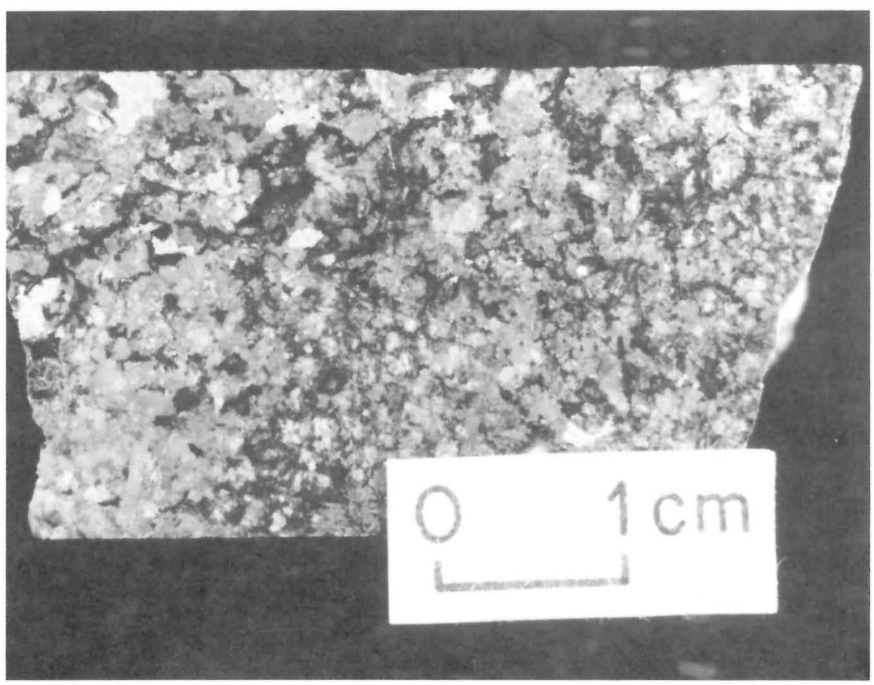


Plate 55: *Sulphide-bearing olivine cumulate within 2.0 m of the UCLZ-HRZ contact. More than 50 per cent of the rock is composed of postcumulus clinopyroxene, plagioclase and hornblende (mid- to dark grey). Sulphides (light grey) form large globule-like masses. UCLZ, olivine cumulate, DDH 38510-990.*

Olivine cumulate layer

The rocks are dark greenish black and mottled due to an abundance of large (up to 1 cm) oikocrysts. Serpentine veins are widely distributed throughout the layer. The rocks are characterized by abundant postcumulus material (up to 25 percent) that includes clinopyroxene oikocrysts, and original plagioclase oikocrysts that have been completely replaced by a finely intergrown mat of nearly isotropic chlorite. Tremolite ± chlorite ± carbonate replace clinopyroxene in a few rocks. Olivine originally formed randomly oriented (Fig. 105), polyhedral crystals, which are well developed where they occur as inclusions in large plagioclase oikocrysts. The rocks ranged in composition from plagioclase-bearing wehrlite to olivine melagabbronorite.

Clinopyroxene cumulate layer

The rocks are grey green and granular and are characterized by an interlocking network of irregularly shaped clinopyroxene crystals, many with interdigitated mutual contacts. Plagioclase was an original cumulus phase, forming lath-like crystals, that are preserved as inclusions along with clinopyroxene in large poikilitic orthopyroxene crystals. Clinopyroxene displays incipient alteration to tremolite, orthopyroxene has been replaced by tremolite that forms bastite-like pseudomorphs, plagioclase has been replaced by epidote + chlorite + muscovite + garnet, and original postcumulus olivine has been converted to chlorite. The rock was originally a plagioclase-bearing olivine websterite.

Plagioclase cumulate layer

The rocks are grey, granular and spotted, and some possess a distinct lamination. They are composed of original cumulus plagioclase laths and are characterized by large poikilitic orthopyroxene crystals. Irregular clinopyroxene fills the spaces between clusters of plagioclase laths. Quartz is widely disseminated through the rock (5 percent) and may in part be formed through recrystallization of plagioclase that alters to epidote + chlorite + muscovite. Clinopyroxene displays incipient recrystallization to tremolite, and orthopyroxene has been replaced by tremolite that forms bastite-like pseudomorphs. Ilmenite is a sparsely disseminated opaque phase. The rocks range from gabbronorite to quartz-bearing gabbronorite in composition.

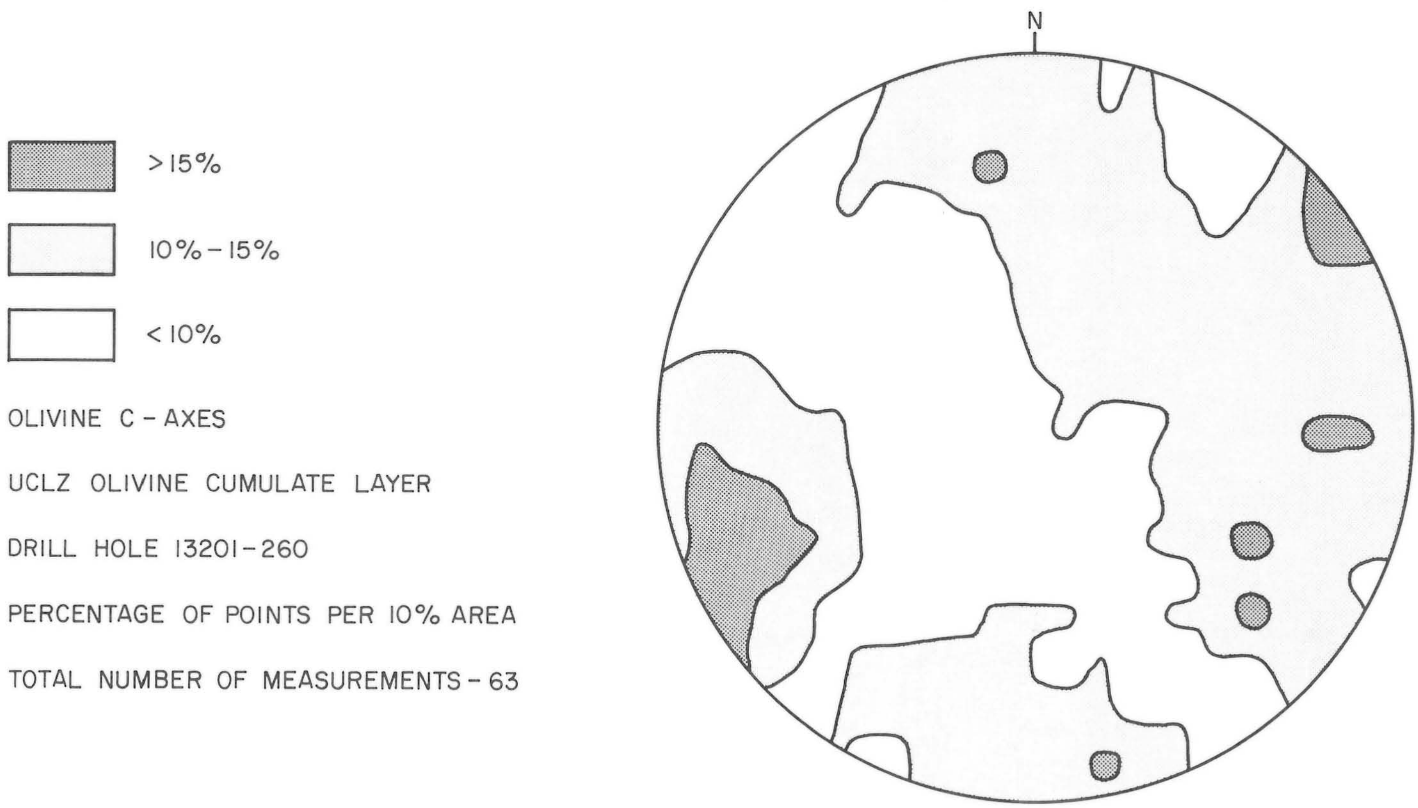


Figure 105: Fabric diagram, olivine c-axis, UCLZ olivine cumulate, drill hole 13201.

1086E SECTION - DRILL HOLES 13219 AND 13213

Drill hole 13219

The ground magnetic profile across this section strongly suggests the presence of a nonmagnetic layer(s) between the olivine cumulate intersected at the base of 13219 and that intersected at the top of 13213 (Fig. 69). The contact between LCLZ and UCLZ assemblages has been placed so as to separate olivine cumulate rocks of significantly different characteristics. Thus, the 52 m (approximate true thickness) of olivine cumulate rocks that were intersected at the base of 13219 are interpreted as representing the lowermost part of the first UCLZ cyclic unit of this sequence. The uppermost layers of the cyclic unit (clinopyroxene cumulate? plagioclase cumulate?) occur in the missing interval between 13219 and 13213 (Fig. 69).

CYCLIC UNIT 1

Olivine cumulate layer

The rocks range from medium- to dark-apple green to greenish black, and the rocks at the base of the hole are mottled due to more abundant postcumulus phases. Dimensional orientation of original elongate olivine crystals is well developed in a number of samples (Plate 56). Numerous intersecting, hair-like picrolitic serpentine veinlets are common.

The rocks are composed almost entirely of olivine, with intercumulus minerals composing less than 10 percent of most rocks in the lower part of the exposed layer. The original olivine crystals were tightly packed, giving rise to a mosaic of polygonal, equidimensional to elongate crystals. In many rocks original elongate olivine crystals display well developed dimensional orientation. It has been pseudomorphously replaced by mesh-texture serpentine throughout the sequence. Chromite, the only other cumulus mineral in this sequence, occurs as disseminated euhedral crystals and constitutes from 1 to 2 percent (visual estimate) of the rock. The predominant original postcumulus phase throughout most of this layer was plagioclase and it has been completely recrystallized to fine grained intergrowths composed of chlorite ± garnet. Serpentine, as bastite-like pseudomorphs, replaces original postcumulus clinopyroxene and orthopyroxene. Intercumulus sulphide occurs near the base of the layer where it constitutes less than 1 percent of the rock.

A 10 m interval (core length interval) of this succession is characterized by postcumulus phases in excess of 15 percent. These rocks are characterized by elongate, rounded polyhedral olivine crystals that display a well developed dimensional orientation. They are slightly coarser grained (Plate 56). Postcumulus phases were predominantly plagioclase and clinopyroxene, both now entirely converted to fine grained chlorite, and clinopyroxene bastite, respectively. These rocks were originally plagioclase-bearing wehrlite.

Orthopyroxene bastite replacing original postcumulus orthopyroxene occurs toward the base of the drill hole where the original rocks were plagioclase-bearing lherzolite.

Drill hole 13213

Drill hole 13213 intersects 60 m (approximate true thickness) of olivine cumulate rocks that form the basal layer of a cyclic unit that includes clinopyroxene cumulate and plagioclase cumulate layers. This cyclic unit is, stratigraphically, the second UCLZ cyclic unit of this sequence (Fig. 69).

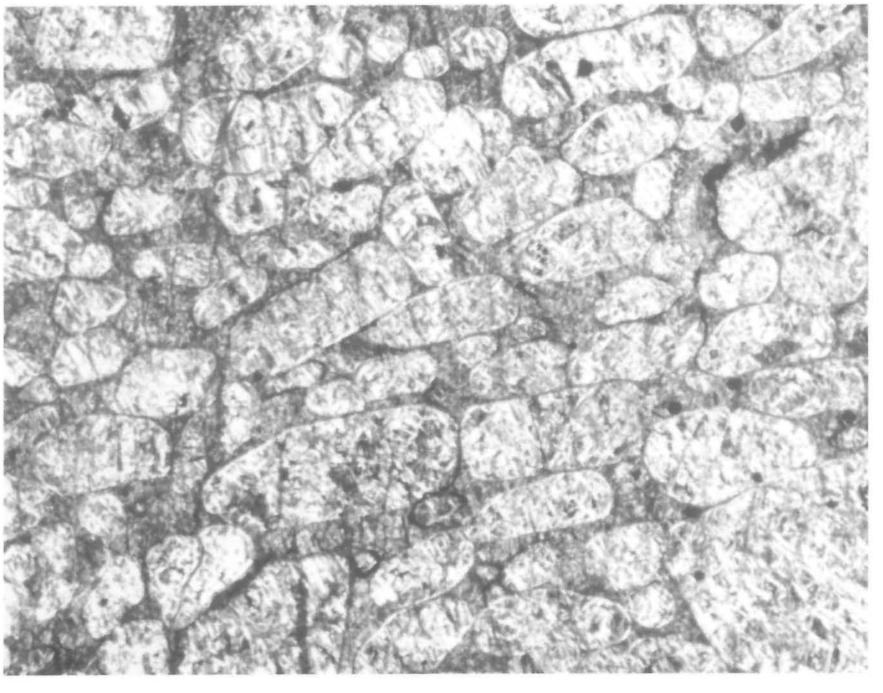


Plate 56: Laminated olivine cumulate displaying imbricate structure. Serpentine pseudomorphs after original elongate olivines. Serpentine in interstitial areas after original clinopyroxene. UCLZ, olivine cumulate, DDH 13219-1190, XN.

CYCLIC UNIT 2

Olivine cumulate layer

The rocks range from dark- and medium-apple green (original dunite) to greenish black and mottled (original wehrlite-lherzolite), and from dull and lustreless to waxy in appearance. Hair-like serpentine veinlets are widely disseminated.

LOWER PART

The rocks of lower part of the layer (uppermost part of the drill hole) are composed of closely packed pseudomorphs after original equidimensional to slightly elongate, polygonal olivine crystals that are replaced by mesh-texture serpentine. Pseudomorphs after olivine crystals up to 5 mm in diameter are present, although the average grain size is much less. Strong preferred orientation of originally elongate olivine crystals was noted in one sample. Intercumulus minerals compose less than 10 percent (visual estimate) and the original postcumulus phases have been replaced by chlorite, serpentine and phlogopite ($\pm$ magnetite). Chromite, the other cumulus phase, occurs as disseminated rounded euhedral crystals and constitutes from less than 1 to 2 percent (visual estimate) of the rock.

UPPER PART

The rocks of the upper part of the layer are characterized by much greater abundance of postcumulus material that makes up from 10 to 25 percent (visual estimate) of the rock, and reaches 30 percent (visual estimate) at the top of the layer adjacent to the overlying clinopyroxene cumulate. In the upper part of the layer original olivine crystals were granular, rounded polyhedral and prismatic in shape, with many crystals occurring as isolated individuals in large continuous oikocrysts (Plate 57). Preferred orientation of original elongate olivine crystals is sporadically developed. In some rocks, original olivine displays a variety of grain shapes and a substantial range in size (from 0.3 to 5 mm, Plate 58). Mesh-texture and curtain-growth serpentine pseudomorphously replace original olivine. Clinopyroxene, orthopyroxene and plagioclase, which constitute the principal postcumulus phases, are partly preserved in a few rocks, but are more commonly altered to secondary products. Clinopyroxene has been replaced by fine grained serpentine and clinopyroxene bastite and orthopyroxene by orthopyroxene bastite. Plagioclase has been converted to a variety of secondary minerals that commonly form a fine grained, nearly isotropic mat, and that include chlorite $\pm$ epidote $\pm$ garnet. Disseminated euhedral chromite constitutes from less than 1 to 3 percent of the rock, and in one sample, heavily disseminated chromite makes up 25 percent of the rock over a width of 3 mm. Phlogopite is a widely distributed intercumulus mineral (less than 1 percent), and ubiquitous secondary magnetite forms dust-like disseminations in intercumulus areas and ragged discontinuous veinlets with serpentine.

The original rock types ranged from plagioclase-bearing wehrlite and lherzolite to olivine melagabbronorite. The nonuniform nature of the layer is caused by variation in the ratio of cumulus olivine to postcumulus phases, variations in olivine grain size and shape, the sporadic distribution of dimensional orientation of elongate olivine crystals, and the heterogeneous distribution of postcumulus phases.

Clinopyroxene cumulate layer

The rocks are grey green and granular and are cut by rare, hair-like picrolitic serpentine veinlets. They are composed of cumulus clinopyroxene that originally occurred as equidimensional prismatic crystals separated by original postcumulus plagioclase (Plate 59). For the most part original equidimensional clinopyroxene has been

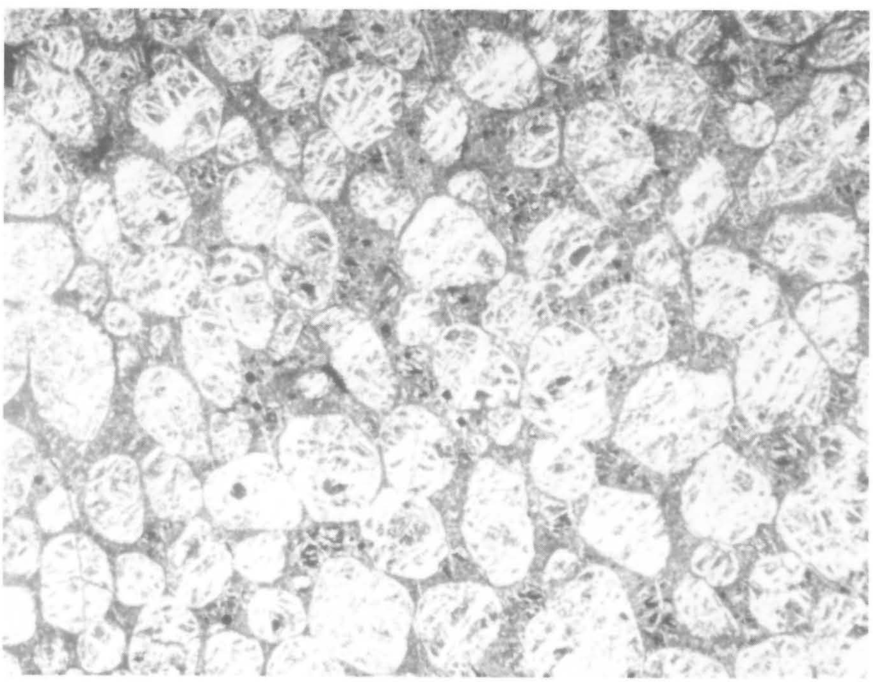


Plate 57: Olivine cumulate composed of granular, partly isolated olivine crystals pseudomorphously replaced by serpentine. Interstitial area is serpentine (bastite) after original clinopyroxene. UCLZ, olivine cumulate, DDH 13213-350, XN.

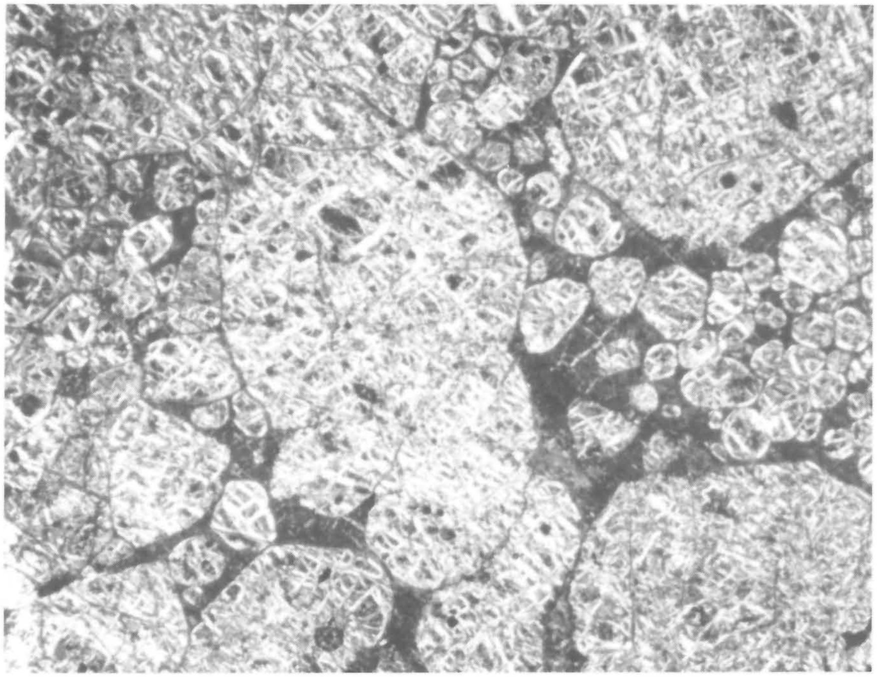


Plate 58: Olivine cumulate composed of olivine crystals (pseudomorphously replaced by serpentine) of vastly different grain size. UCLZ, olivine cumulate, DDH 13213-380, XN.

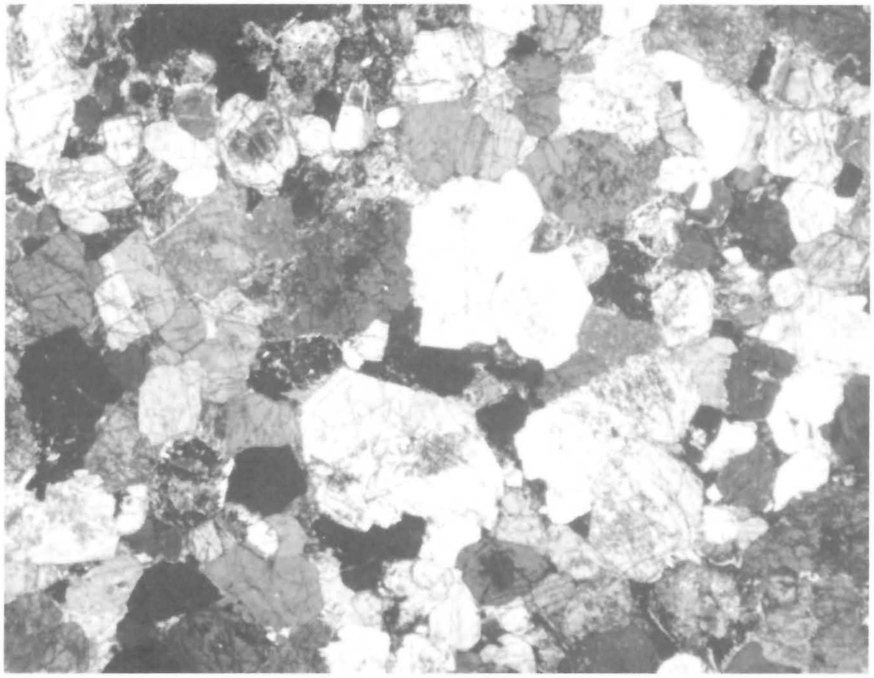


Plate 59: Clinopyroxene cumulate composed of equidimensional clinopyroxene crystals displaying incipient recrystallization to tremolite. Plagioclase is a postcumulus phase. UCLZ, clinopyroxene cumulate, DDH 13213-570, XN.

modified by adcumulus growth and it now exists as a continuous mosaic of highly irregular clinopyroxene crystals that share complex, strongly interdigitated mutual grain boundaries. Clinopyroxene displays incipient recrystallization to tremolite and original postcumulus plagioclase has been replaced by chlorite ± muscovite. Original postcumulus poikilitic orthopyroxene has been altered to bastite-like pseudomorphs composed of chlorite and tremolite. Original idiomorphic olivine crystals have been converted to chlorite + tremolite. The rock was originally a plagioclase-bearing olivine websterite.

Plagioclase cumulate layer

The rocks are grey and granular; most are spotted or mottled and many display well developed lamination. They display a substantial range in preservation, some rocks are almost fresh, others almost entirely recrystallized. The rocks are characterized by lath-shaped plagioclase that displays strong preferred orientation (Plate 60). With the exception of one determination (An_{91}), plagioclase ranges in composition from An_{93} to $An_{96.5}$ (9 determinations from 4 samples) and consequently displays little compositional variation from the base to the top of the layer (Fig. 106). Elongate clinopyroxene possesses highly irregular shapes, displays preferred orientation, and mm-scale plagioclase-rich plagioclase-poor laminae contribute to the overall lamination of the layer. The rocks are further characterized by relatively abundant (about 10%, visual estimate) postcumulus olivine that gives rise to the spotted or mottled character of the rock. Opaque minerals are entirely lacking in this unit. In fresh rocks, plagioclase displays incipient recrystallization to epidote that in places forms large crystalline patches. In highly recrystallized rocks, plagioclase has been completely converted to a fine grained aggregate of prehnite + chlorite + epidote. Postcumulus olivine is well preserved in fresh rocks, where it displays incipient recrystallization to serpentine along fractures. It has been totally converted to a felted mass of tremolite in highly recrystallized rocks. Orthopyroxene is rare; lacks inclusions and may represent a cumulus phase. In the most highly recrystallized rocks clinopyroxene is the only preserved primary mineral. The rocks are olivine gabbro to olivine gabbronorite in composition.

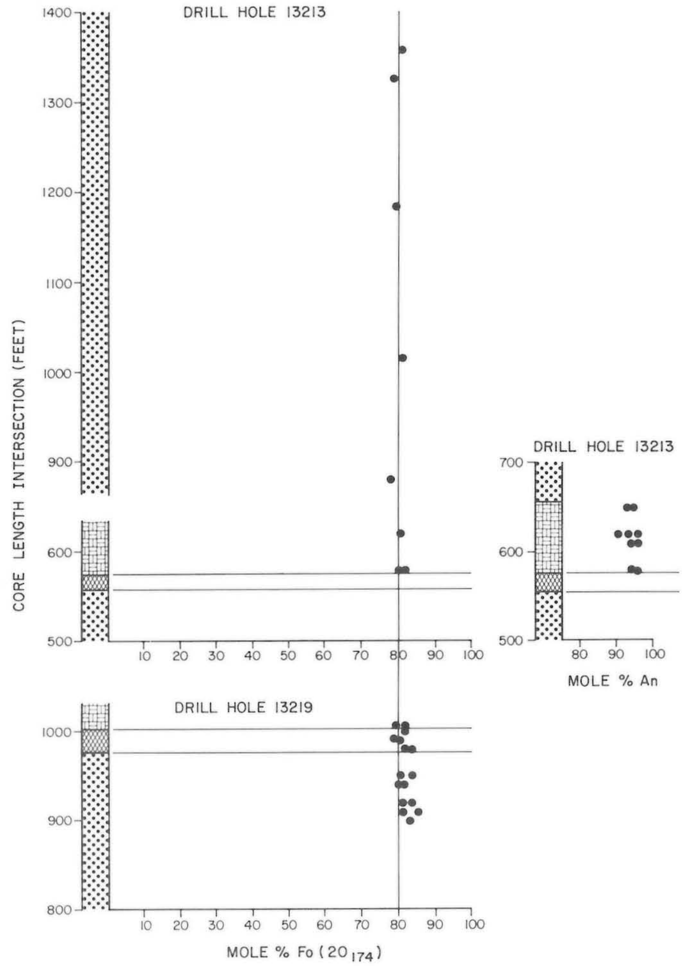


Figure 106: Olivine and plagioclase compositions 1086E section.

CYCLIC UNIT 3

Olivine cumulate layer

Approximately 97 m (true thickness estimate) of the olivine cumulate layer of the next overlying unit is intersected in the lower part of drill hole 13213 (Fig. 69). The rocks are grey green to dark apple green and mottled. Hair-like serpentine veinlets are widely distributed, and the rocks range from granular, to dull and lustreless, to waxy in appearance.

The unit is characterized by original cumulus olivine that displays a substantial range in grain size (0.3 to 5 mm) and grain shape within individual samples. Postcumulus phases display highly variable abundance and many of the rocks contain in excess of 25 percent postcumulus material. Like the underlying plagioclase cumulate, the rocks display a substantial range in state of preservation, some rocks possessing relicts of all original primary phases, others being so highly recrystallized that the primary textures can only be discerned with difficulty. Clinopyroxene, orthopyroxene and plagioclase are the main postcumulus mineral phases and red-brown hornblende is present in a few rocks.

Olivine has been pseudomorphously replaced by mesh-texture and curtain-growth serpentine; clinopyroxene has been partly to completely replaced by a variety of secondary minerals, including tremolite ± chlorite, fine grained featureless serpentine, and clinopyroxene bastite; orthopyroxene has been converted to orthopyroxene bastite; plagioclase has been replaced by a nearly isotropic mixture of chlorite ± epidote ± garnet. Disseminated euhedral chromite constitutes less than 1 to 2 percent of most rocks and 4 percent of one sample. Sparsely disseminated sulphide minerals (less than 1%) occur near the base of the layer. As a result of their heterogeneous character, original rock types ranged from plagioclase-bearing lherzolite and wehrlite to olivine melagabbronorite.

Olivine compositions

Olivine compositions display some limited variation (4% Fo) in UCLZ cyclic unit 2 plagioclase cumulate layer and in the overlying cyclic unit 3 olivine cumulate layer, although no regular trend can be discerned (Fig. 106). It is clear that these UCLZ olivines are less Fo-rich than those associated with the immediately underlying LCLZ rocks (Fig. 107).

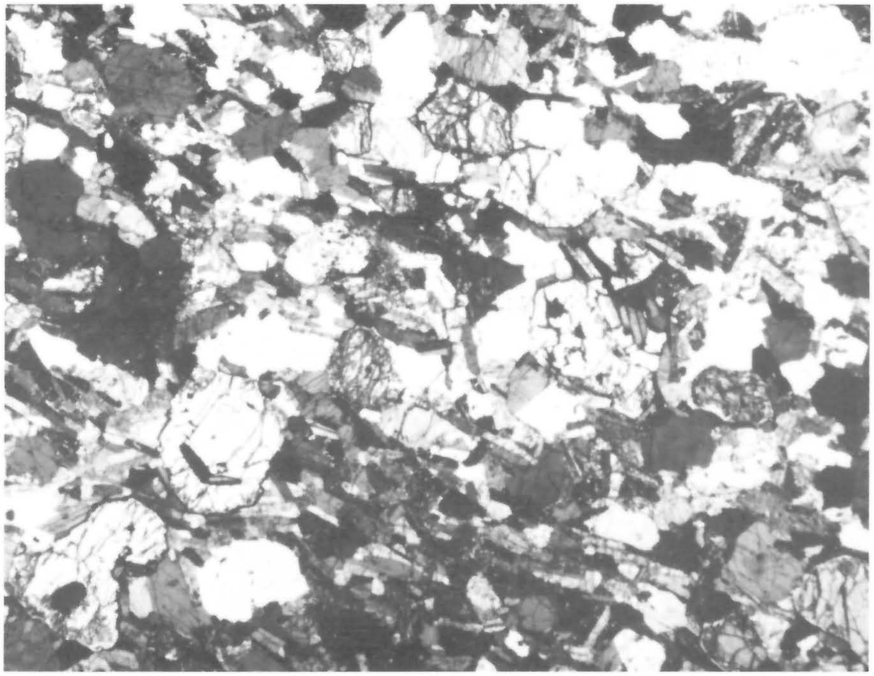


Plate 60: Plagioclase cumulate characterized by lath-like plagioclase crystals displaying well developed lamination (from lower right to upper left). Note plagioclase inclusions in fresh olivine. UCLZ, plagioclase cumulate, DDH 13213-580, XN.

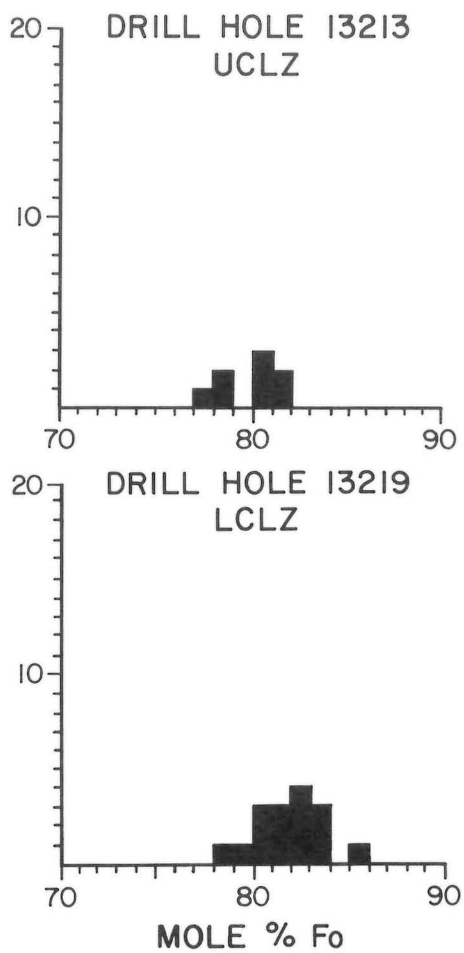


Figure 107: Comparison of LCLZ and UCLZ olivine compositions, 1086E section.

722E SECTION - DRILL HOLES 13215, 13220, 13223, 13224, 13228, 13229, 13211 AND 13232

Drill holes 13215, 13220, 13223, 13224, 13228 and 13229

POSSIBLE CYCLIC UNITS

The six holes, drilled in a westerly direction, intersect UCLZ olivine cumulate rocks, although an absence of outcrop and the possible presence of a fold and/or fault preclude determining if the olivine cumulate intersected in each of the holes belongs to the same layer (Fig. 92, 108, 109 and 110). The presence of a clinopyroxene cumulate and plagioclase cumulate in 13220 implies that portions of two cyclic units were penetrated by the hole. As a result of these uncertainties, detailed descriptions for each of these holes are not warranted and a general description of the olivine cumulate rocks is presented.

Olivine cumulate rocks

The rocks range from medium and dark apple green and greenish black to grey green, and many are mottled due to the distribution of postcumulus oikocrysts. Many of the rocks possess a waxy lustre, and are characterized by abundant whitish-green picrolitic serpentine veins, some of which are cm-scale parallel sets, and many with slickensided surfaces. In addition, there are numerous subparallel, mm-scale, hair-like to cross-fibre serpentine veinlets and carbonate-magnetite veins. The rocks become sheared and brecciated close to HRZ contact.

Throughout the olivine cumulate in this area, olivine was originally heterogeneous in terms of grain size and grain shape. A range in grain size from 0.25 to 5 mm in thin section is not uncommon. Grain shapes ranging from granular, to elongate polyhedral, to polygonal, to large scallop-shaped crystals are commonly observed in individual samples. A substantial range in intercumulus material has been

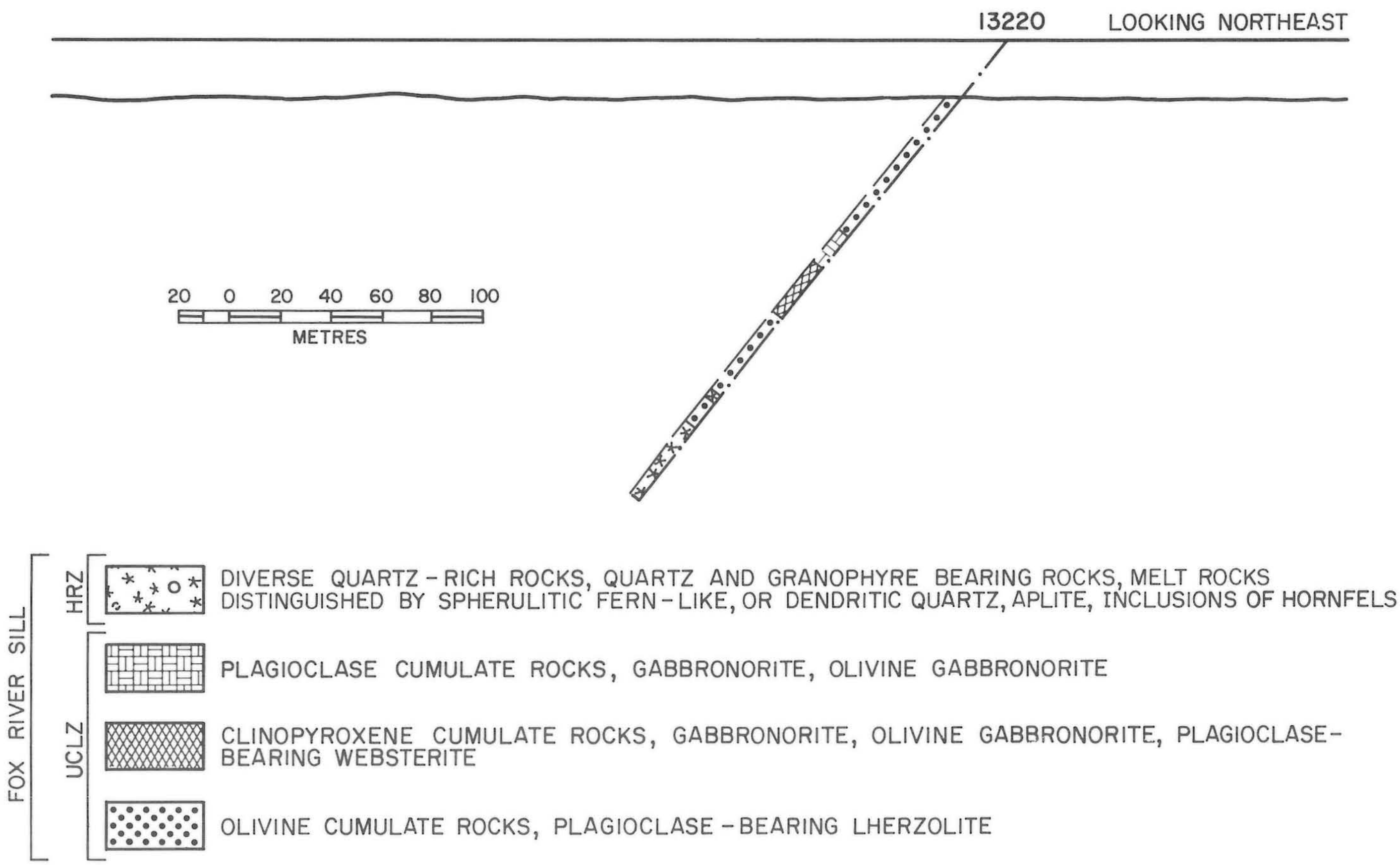


Figure 108: UCLZ-HRZ geology, drill hole 13220.

observed (from 5 to 25 percent) and plays a role in olivine grain shape. In rocks where intercumulus minerals make up approximately 5 percent, olivine forms a mosaic of polygonal crystals (Plate 61). In some rocks, original elongate olivine crystals display preferred orientation.

Olivine crystals have been pseudomorphously replaced by mesh-texture and curtain-growth serpentine. In several areas antigorite occupies the mesh centres of mesh-textured serpentine, and opaque mesh centres in some areas are caused by concentration of dust-like magnetite. Sheared serpentinite occurs near the HRZ contact in a few areas.

Clinopyroxene, which originally formed oikocrysts (up to 5 mm), is rarely preserved and has been converted to clinopyroxene bastite that preserves original parting. It has also been replaced by fine grained nearly isotropic serpentine, and rare chlorite that forms bastite-like pseudomorphs. Orthopyroxene originally formed oikocrysts and has been totally replaced by orthopyroxene bastite. Chlorite-bearing isotropic patches in intercumulus areas replace original postcumulus plagioclase. Garnet + chlorite ± epidote replace plagioclase in a few rocks. The rocks were originally plagioclase-bearing lherzolite in composition.

Disseminated euhedral chromite seems to be slightly more abundant in these rocks, where it ranges from 1 to 4 percent and constitutes approximately 10 percent of the rock (across about 5 mm) in two samples (Plate 62). Sulphide minerals are widely disseminated (usually less than 3 percent), and occur as intercumulus phases with well developed cusp shapes. Some form rounded blebs in serpentine pseudomorphs after olivine, and magnetite ± sulphide veinlets are common.

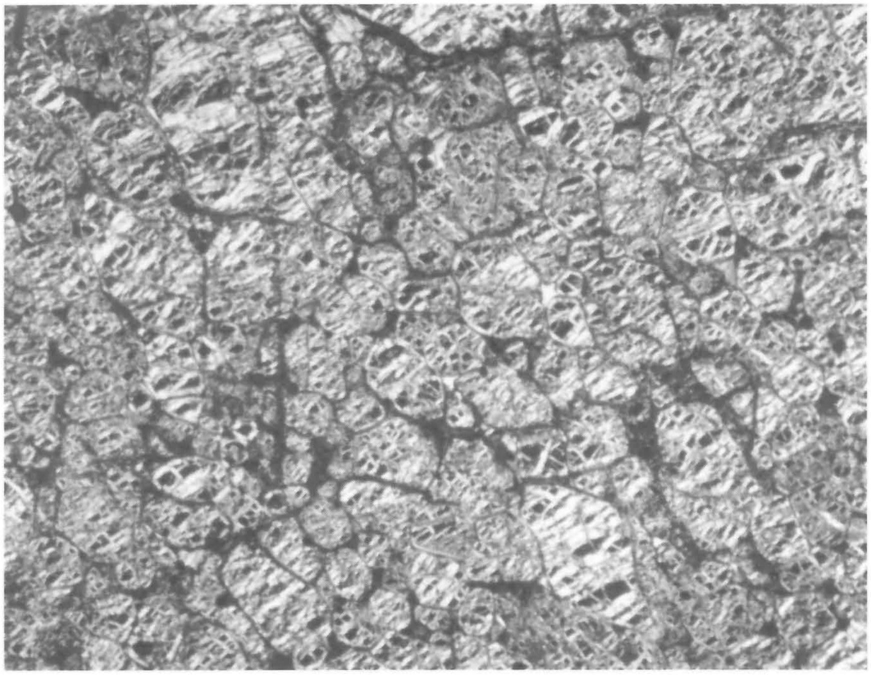
Secondary magnetite is widespread, forming partial rims around serpentine pseudomorphs after olivine, as concentrations of dust-like particles in intercumulus areas and in the cores of serpentine pseudomorphs, and as irregular patches and discontinuous veinlets with serpentine and carbonate ± sulphide.

Carbonate forms patches in some serpentine pseudomorphs and occurs as discontinuous veinlets.

Clinopyroxene cumulate rocks (drill holes 13220 and 13229)

The rocks are grey green and granular, and the contact with the olivine cumulate is sheared. They are highly altered, strongly deformed rocks, that contained relatively abundant plagioclase, now completely recrystallized to prehnite + epidote ± chlorite. Clinopyroxene is moderately well preserved as brownish, highly strained crystals, many with euhedral prismatic outlines. Complex polycrystalline clinopyroxene aggregates are composed of numerous highly irregular individuals. Original poikilitic orthopyroxene crystals have been replaced by tremolite. One rock is cut by mylonitic or crush zones that range from 0.2 to 4.0 mm wide. Chlorite-filled gash fractures are oriented approximately at right angles to the crush zones. These deformed rocks ranged from gabbronorite and olivine gabbronorite to plagioclase-bearing websterite in original composition.

Plate 61: *Mosaic of densely packed olivine crystals (pseudomorphously replaced by serpentine). Original dunite. UCLZ, olivine cumulate, DDH 13228-300, XN.*



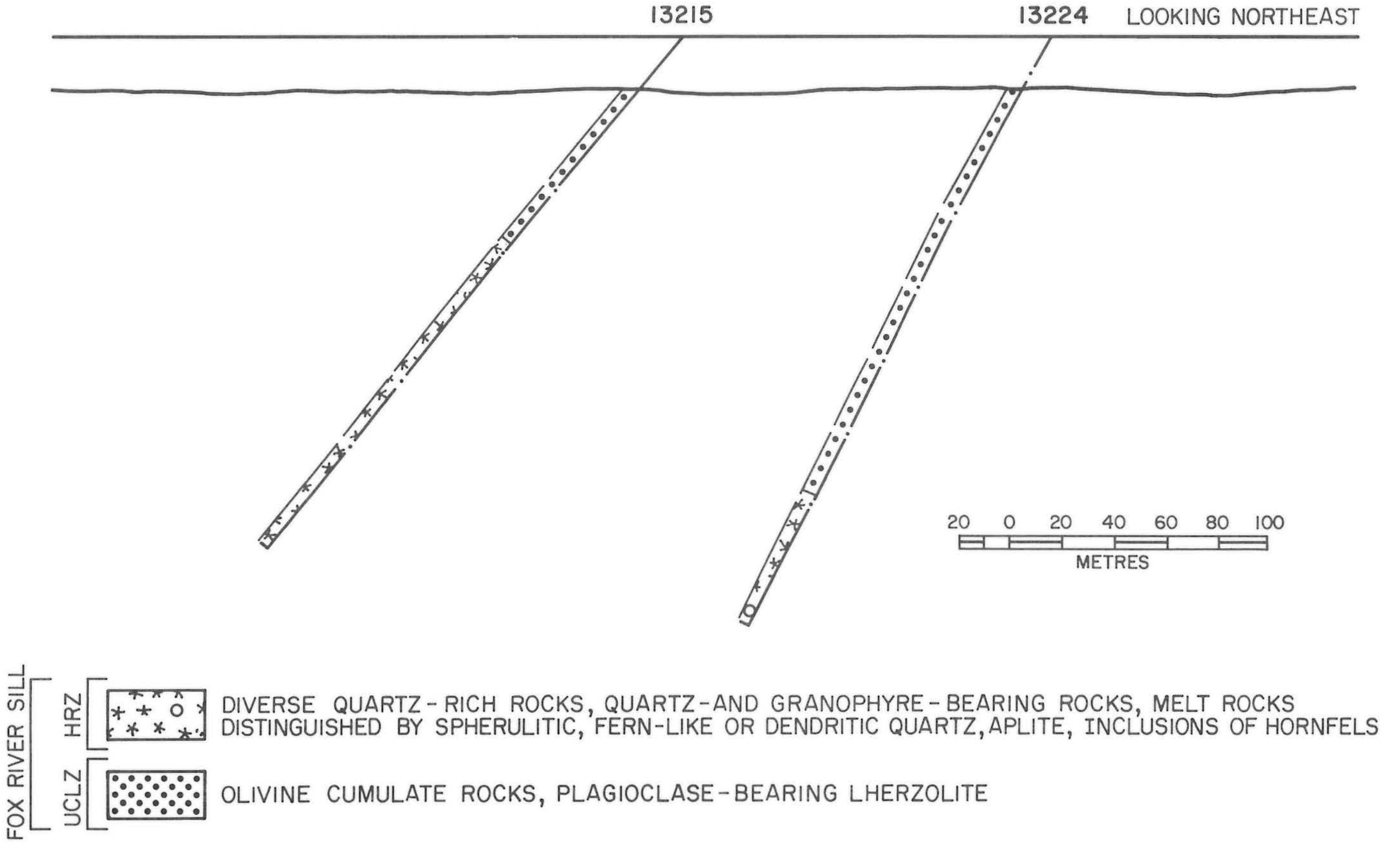


Figure 109: UCLZ-HRZ geology, drill holes 13215 and 13224.

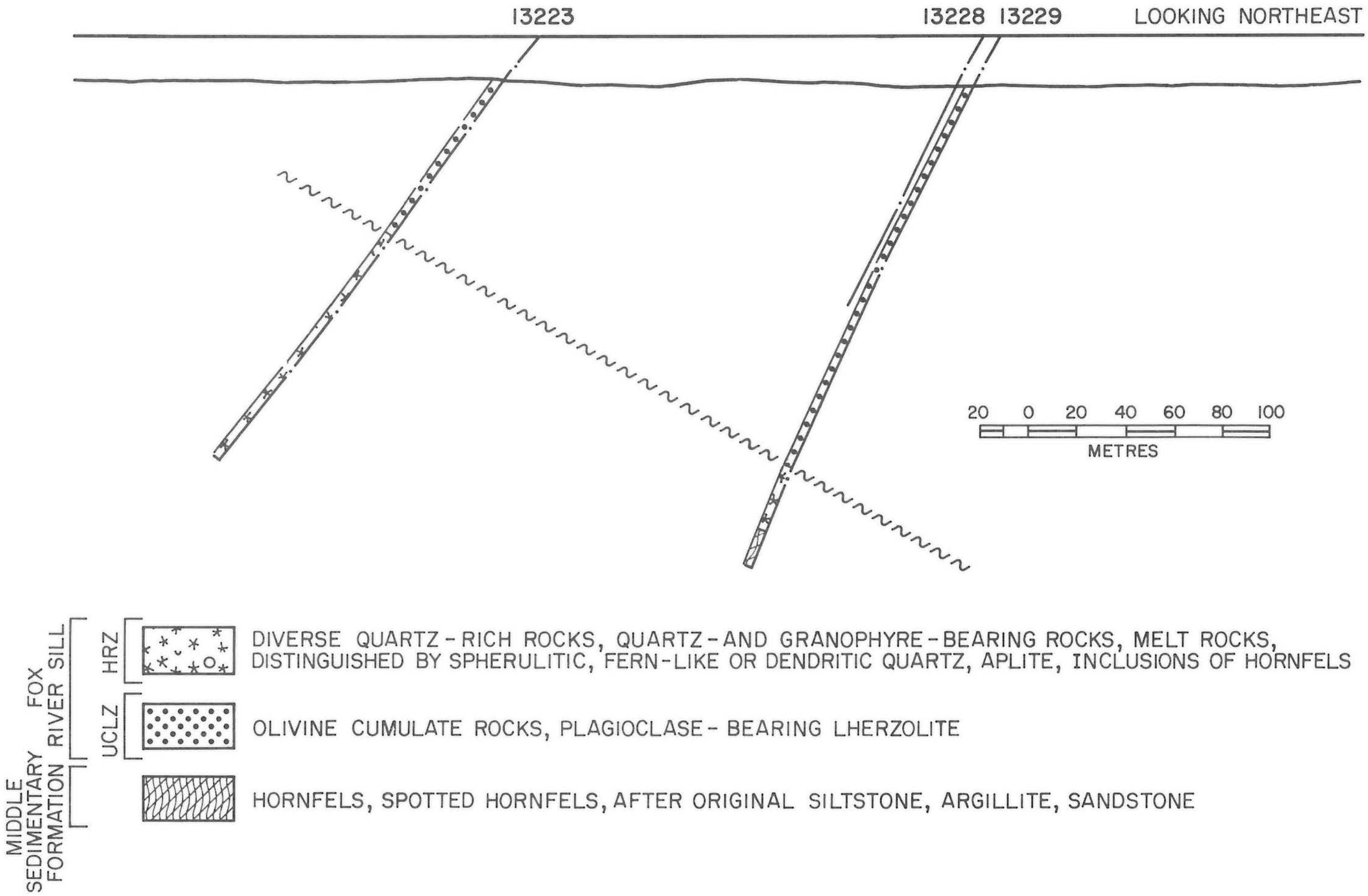


Figure 110: UCLZ-HRZ geology, drill holes 13223, 13228 and 13229.

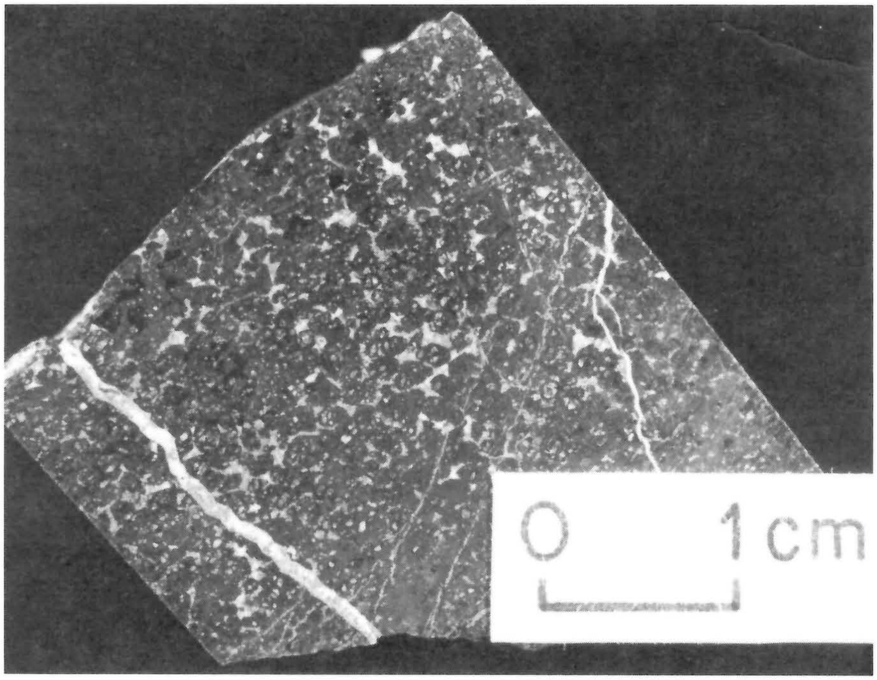


Plate 62: Disseminated chromite in olivine cumulate. Chromite occupies intercumulus areas (white to light grey). Note picrolitic serpentine ± magnetite veinlets. UCLZ, olivine cumulate, DDH 13228-385.

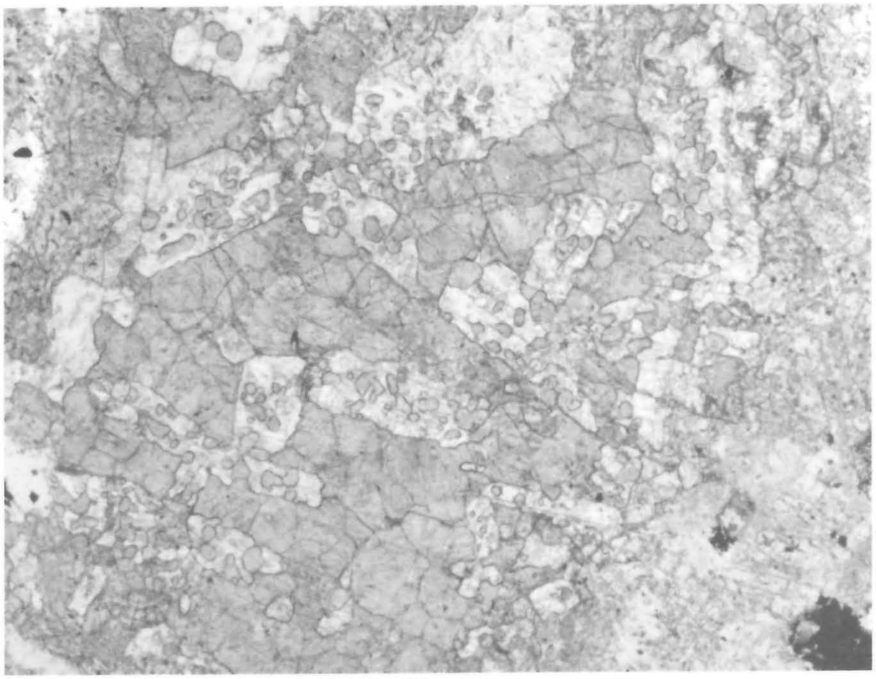


Plate 63: *Granular mosaic of clinopyroxene crystals forming a continuous phase. Subhedral plagioclase crystals (white) contain numerous inclusions of fine grained clinopyroxene crystals. Large orthopyroxene crystal (pseudomorphously replaced by chlorite) occurs at lower right. UCLZ, DDH 13229-645, PL.*

In one area rocks possess unusual textures that resemble transition zone rocks of major Molson dykes (Scoates and Macek, 1978). The rocks are composed of a granular aggregate of clinopyroxene crystals, many of which occur as inclusions in prismatic poikilitic plagioclase crystals (Plate 63). The rocks are melagabbronorite in composition and originally contained poikilitic orthopyroxene crystals. The unusual texture may reflect unusual conditions of nucleation and crystal growth close to the roof contact of the intrusion.

Plagioclase cumulate rocks (drill hole 13220)

The rocks are grey to bluish grey, granular and spotted to finely mottled. They are composed of randomly oriented plagioclase laths that have been replaced by epidote + albite + muscovite + chlorite. Irregularly shaped, twinned, brownish clinopyroxene, that displays incipient recrystallization to tremolite, occupies the space between plagioclase crystals. Many clinopyroxene crystals possess inclusions of plagioclase and are a postcumulus phase. Large (up to 5 mm) plate-like, poikilitic orthopyroxene crystals that contain numerous plagioclase inclusions have been replaced by tremolite ± chlorite that form bastite-like pseudomorphs. Ilmenite + alteration products are widely disseminated. The rocks were originally gabbronorite in composition.

Drill holes 13211 and 13232

The drill holes, collared on section lines approximately 120 m apart, were drilled in a northerly direction (Fig. 92). They intersected the uppermost part of the UCLZ and terminated in HRZ rocks (Fig. 111 and 112). The olivine cumulate-plagioclase cumulate pair represents the uppermost UCLZ cyclic unit, and the olivine cumulate, that separates the plagioclase cumulate from HRZ rocks represents the uppermost UCLZ unit in this area (Fig. 112). The uncertainty of structural relationships in this area precludes determining layer and contact attitudes.

UPPERMOST CYCLIC UNIT

Olivine cumulate layer

The rocks are grey green to greenish black, mottled, and characterized by numerous mm- and cm-scale picrolitic serpentine ± carbonate veins, many with slickensided surfaces and hematite staining. Some breccia zones have been observed.

The rocks are composed of serpentine pseudomorphs after olivine that was predominantly heterogeneous in terms of grain size and grain shape. Strongly developed preferred orientation of original elongate polyhedral olivine has been noted in several samples, and large rectangular crystals (3 x 1.5 mm) have been noted in a few rocks. Olivine grain size appears to decrease toward the plagioclase cumulate layer. Olivine has been replaced by mesh-texture serpentine, some with hourglass textures and curtain-growth serpentine. Coarse patches of lizardite, some with antigorite rims, replace olivine in a few rocks, and mesh-textured serpentine with antigorite cores has been noted. Olivine replaced by nonpseudomorphous antigorite has been observed. Fibrous secondary diopside is developed in the cores of some serpentine pseudomorphs.

Postcumulus mineral phases constitute from 10 to 25 percent of the rock. Clinopyroxene, which forms large oikocrysts (up to 2 cm), has been completely converted to clinopyroxene bastite, or to mixtures of secondary minerals that include tremolite ± fine grained nearly isotropic serpentine ± chlorite. Tremolite replacing clinopyroxene forms bastite-like pseudomorphs. Orthopyroxene occurs as oikocrysts that have been partly to completely replaced by orthopyroxene bastite or mixtures of serpentine ± tremolite ± talc ± chlorite. Some orthopyroxene possesses fine ruled-line exsolution lamellae (Bushveld-type exsolution). Original postcumulus plagioclase has been replaced by a mixture of secondary products including chlorite ± muscovite ± garnet. Postcumulus red-brown hornblende and phlogopite ± talc ± chlorite ± magnetite occupy intercumulus areas. Originally the rocks were plagioclase-bearing lherzolites.

Serpentine ± magnetite ± carbonate ± veins are common, some veins are zones of shear, and in some rocks there are several ages of serpentine veins. Secondary magnetite is relatively abundant (from 3 to 5 percent) and occurs as discontinuous veinlets, as irregular patches in intercumulus areas and in cores of some serpentine pseudomorphs after olivine. Evidence of late movement in these rocks is found in kinked secondary minerals.

Disseminated chromite constitutes from 1 to 3 percent of the rock and intercumulus sulphide minerals (up to 1 percent) have been observed.

Plagioclase cumulate layer

The rocks are light grey to brownish grey, massive and granular. They are strongly laminated as a result of segregation of the rock into mm-scale plagioclase-rich and plagioclase-poor laminae, and the lamination is enhanced by parallel orientation of elongate clinopyroxene crystals. Plagioclase has been replaced by epidote + tremolite + chlorite + sphene, epidote forming local masses of interlocking crystals. Chlorite forms bastite-like pseudomorphs after original poikilitic orthopyroxene. Elliptical patches of finely interwoven tremolite replace original olivine. The rocks are cut by irregular prehnite + epidote veins. Ilmenite and its alteration products are a widely disseminated phase. The rocks were originally gabbronorite in composition.

UPPERMOST UNIT

Olivine cumulate rocks

These olivine cumulate rocks separate the plagioclase cumulate layer from HRZ rocks in each drill hole. The rocks are medium grained, dark greyish green to greenish black and mottled. The rocks are highly fractured; fracture surfaces are polished and commonly displaying slickensides. Anastomosing picrolitic serpentine veins have been observed.

The rocks are characterized by a substantial increase in the volume of postcumulus phases (from 35 to 60 percent), and an apparent decrease in olivine grain size. They consist of a dense aggregation of poikilitic pyroxene and plagioclase crystals that form a discontinuous phase that effectively isolates individual olivine crystals from each other. Olivine tends to be fine grained (averaging less than 0.5 mm in size) in most rocks, although retaining its heterogeneous character in terms of shape and size. Olivine crystals that possess circular inclusions have been noted in a few rocks (Plate 64). The state of preservation of the rocks is highly variable, many being moderately

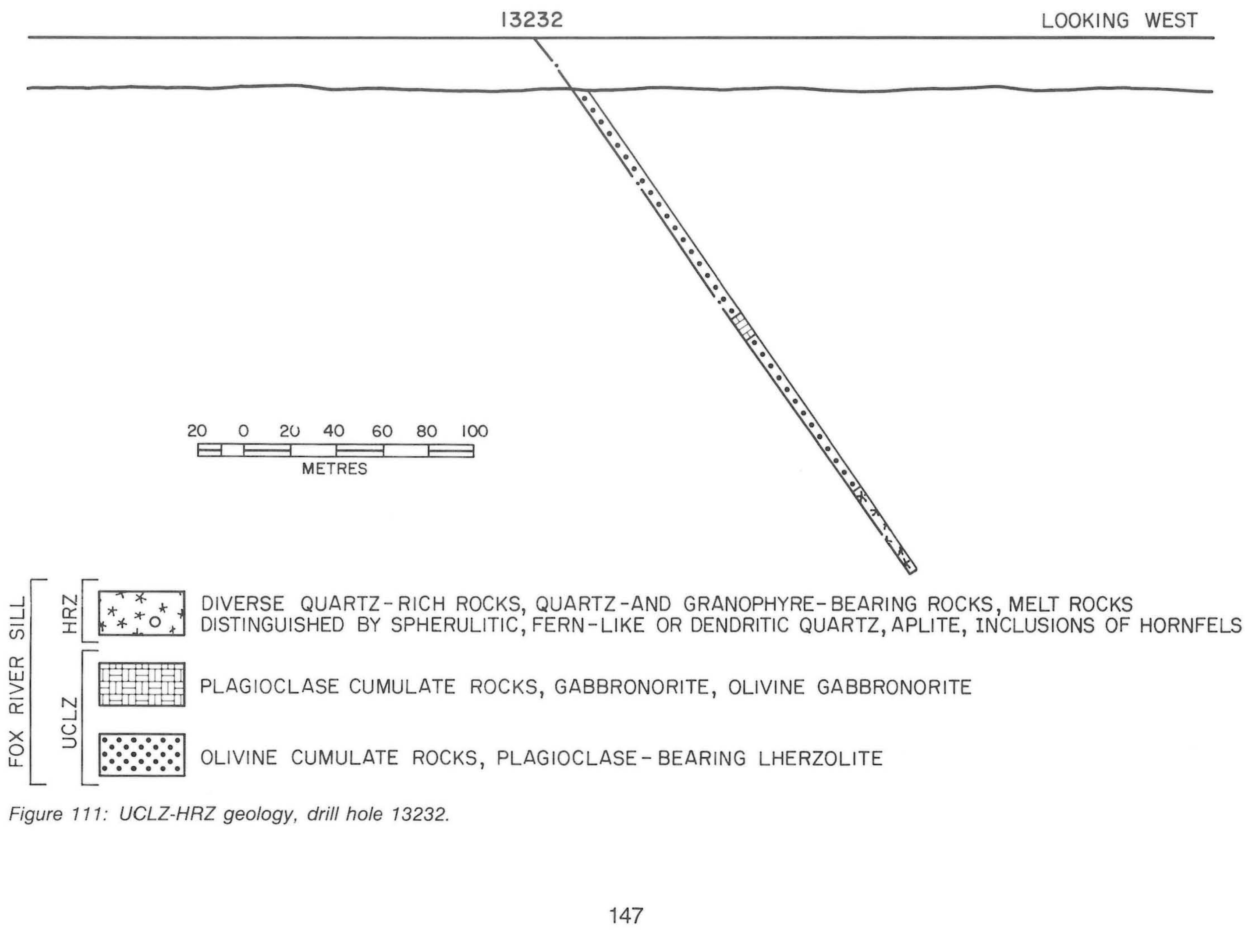


Figure 111: UCLZ-HRZ geology, drill hole 13232.

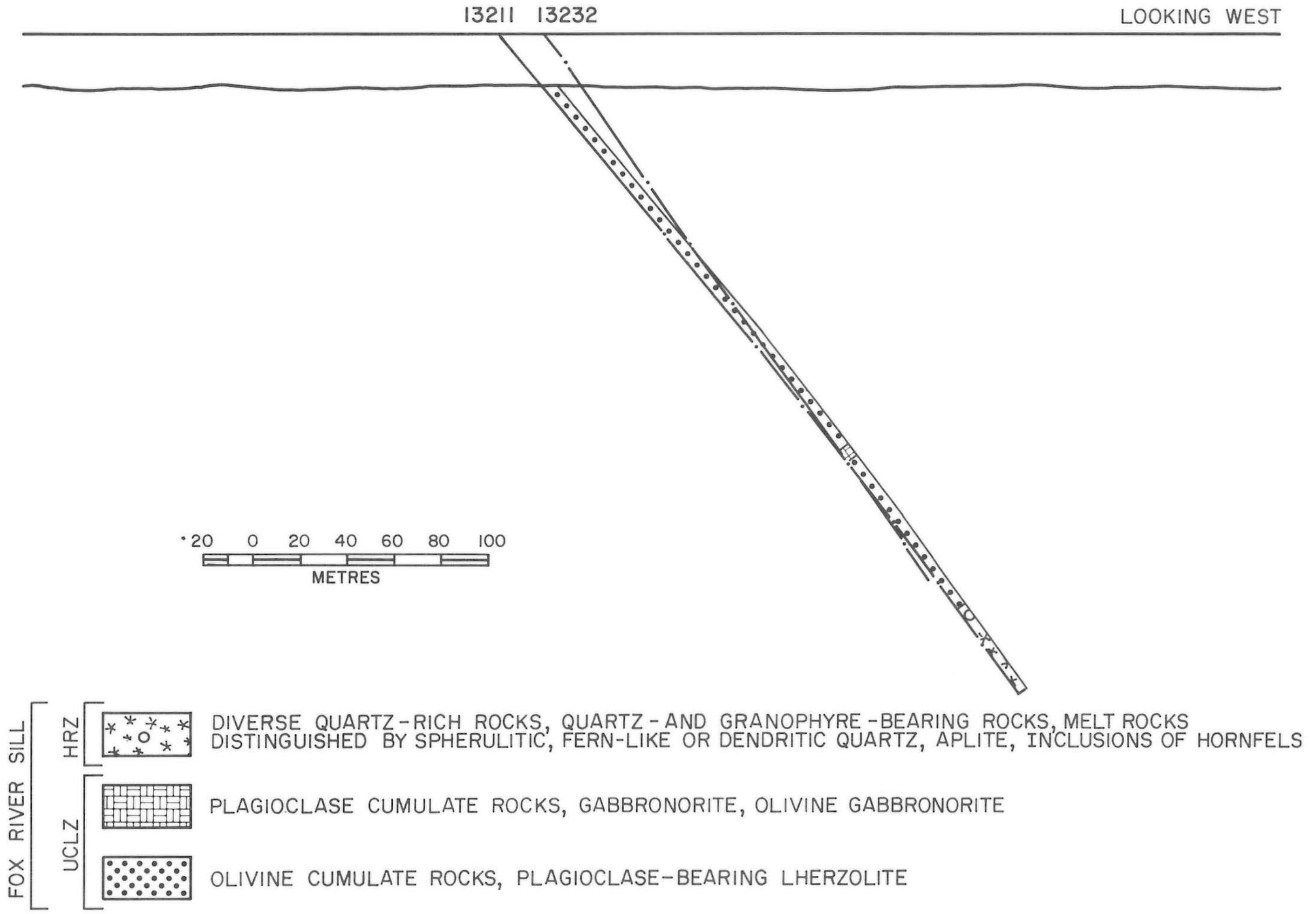


Figure 112: UCLZ-HRZ geology, drill hole 13211.

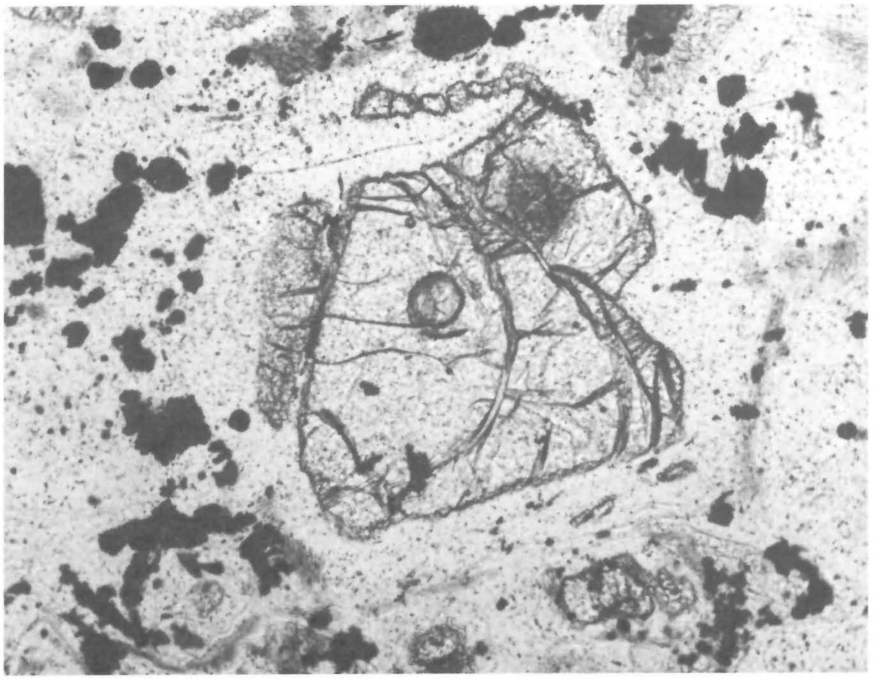


Plate 64: Circular inclusion in relict olivine. Red-brown hornblende, phlogopite and chlorite occur in the inclusion. The olivine has partly altered to serpentine and magnetite (black). UCLZ, olivine cumulate, DDH 13211-825, PL.

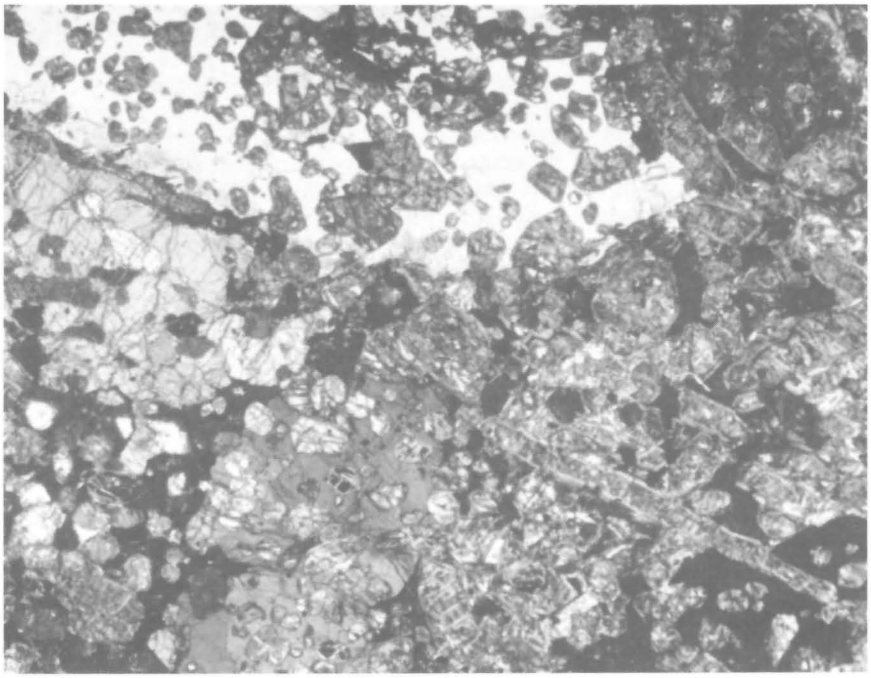


Plate 65: Poikilitic pyroxene and plagioclase crystals containing numerous inclusions of fine grained olivine. This unusual rock may represent an upper border group. UCLZ, olivine melagabbronorite, DDH 13232-690, XN.

well preserved with all primary minerals except plagioclase displaying some state of preservation. One rock is a mass of talc + tremolite that all but obliterates the original rock texture. Postcumulus red-brown hornblende and phlogopite have been noted and the ratio of postcumulus phases to olivine increases towards the HRZ contact. Opaque minerals, predominantly magnetite and chromite, are widespread and account for up to 5 percent of the rock, with chromite constituting 2 to 3 percent. Sphene is an unusual accessory phase and forms irregular masses commonly associated with phlogopite. The rocks were originally olivine melagabbronorite in composition. The fine grained nature of the olivine, large poikilitic pyroxene and plagioclase crystals (Plate 65), and the presence of hornblende and phlogopite suggest that these rocks may represent an upper marginal zone or upper border group.

OTHER DRILL HOLES

Drill hole 13205

CYCLIC UNIT 1

As previously noted, hole 13205 penetrates the LCLZ-UCLZ contact that separates rock successions that possess olivine cumulates of different character (Fig. 84). The LCLZ olivine cumulate rocks change progressively from serpentinized dunite to wehrlite toward the LCLZ-UCLZ contact. UCLZ olivine cumulate rocks are plagioclase-bearing wehrlite and lherzolite.

Olivine cumulate rocks

The rocks are dark apple green to dark greenish black, somewhat mottled and contain veins of picrolitic serpentine. They originally consisted of granular to rounded polyhedral olivines, now pseudomorphously replaced by mesh-texture and curtain-growth serpentine, and postcumulus clinopyroxene, many as large (up to 1 cm) oikocrysts. Original postcumulus plagioclase has been replaced by a nearly isotropic mat of epidote + chlorite + muscovite + garnet. Poikilitic orthopyroxene crystals contain numerous inclusions (Plate 66), and disseminated euhedral chromite constitutes from 1 to 3 percent of the rock. The postcumulus phases constitute 15 to 20 percent of the rock; this distinguishes these rocks from their LCLZ equivalents. Some rocks are totally serpentinized and although individual postcumulus phases are not readily identifiable, the original texture is well preserved. The original rocks ranged in composition from serpentinized plagioclase-bearing wehrlite to lherzolite.

Olivine Fabric Diagram

Although lamination of the original rocks is not readily visible, the well developed bull's-eye pattern of olivine c-axes from a sample at the base of the drill hole indicates a strong preferred orientation of olivine (Fig. 113). The poorly defined girdle indicates the plane of layering suggesting that some of the crystals lie in the plane with their c-axes in other orientations. Olivine composition from the same sample at the base of the hole is Fo_{82}.

Drill hole 13239

Drill hole 13239, drilled in a northwesterly direction, intersected 14 m of plagioclase cumulate, 119 m of olivine cumulate and 17 m of a hornfelsed siltstone-argillite sequence (Fig. 92 and 114). The latter is interpreted as forming part of a large raft of Middle sedimentary formation rocks (Geological Map GR81-1-1, in pocket).

POSSIBLE CYCLIC UNITS

The plagioclase cumulate likely represents the uppermost layer of a cyclic unit and the olivine cumulate represents the uppermost UCLZ unit. Other UCLZ units may overlie the hornfels if it represents a large raft of Middle sedimentary formation rocks.

Plagioclase cumulate rocks

The rocks are grey to slightly bluish grey, mottled and granular, and display a sharp, sheared contact with olivine cumulate rocks. They comprise laminated and massive varieties, the former being characterized by planar lamination of original elongate plagioclase and clinopyroxene crystals. The rock has been segregated into mm-scale, alternating plagioclase-rich and plagioclase-poor lenses and laminae. Plagioclase has been replaced by albite + epidote + chlorite + muscovite + sphene. Elongate clinopyroxene crystals possess highly irregular outlines that are controlled entirely by the shapes of the surrounding plagioclase crystals. Clinopyroxene is slightly brownish, displays parting, and is commonly twinned. Original poikilitic orthopyroxene crystals have been replaced by chlorite that forms bastite-like pseudomorphs. Original elliptical olivine crystals have been replaced by a felted mat of chlorite. Evidence of deformation takes the form of numerous veins, some of which display movement and patchy strain extinction in some clinopyroxene crystals.

Olivine cumulate rocks

The rocks are dark greenish black, mottled and fractured and are locally brecciated. They were originally composed of olivine, either as elongate crystals with a well developed preferred orientation, or as a heterogeneous mixture of large and small crystals possessing a variety of shapes. Rocks that possess a fabric consist of elongate, lath-shaped olivine with well developed parallel orientation (typical crystals 1.5 x 0.4 mm). Intercumulus minerals constitute approximately 20 percent of the work. Postcumulus phases include clinopyroxene, orthopyroxene, plagioclase, hornblende and phlogopite (Plate 67) as oikocrysts and poikilitic crystals (up to 1 mm). In heterogeneous rocks, olivine ranges in shape from rounded polyhedral, granular and polygonal, to elongate and roughly equidimensional crystals that range from 0.4 mm up to 6 x 75 mm at thin section scale. Circular inclusions, containing phlogopite + hornblende + chlorite + opaque minerals, are common in olivine throughout the olivine cumulate. Olivine ranges from being well preserved to being pseudomorphously replaced by mesh-textured serpentine, some of which displays hourglass structures, and some of that displays incipient recrystallization to antigorite. Clinopyroxene displays partial replacement by tremolite. Orthopyroxene is partly preserved and has been replaced by orthopyroxene bastite, talc and/or fibrous tremolite. Plagioclase has been replaced by chlorite ± epidote ± garnet ± muscovite. Serpentine ± magnetite ± sulphide veins are common, and evidence of deformation is found in the sporadic distribution of strain extinction and rare strain lamellae in pyroxenes.

Disseminated euhedral chromite makes up from 1 to 4 percent of the rock. The rocks were originally phlogopite-hornblende- and plagioclase-bearing lherzolite.

HORNFELS

The rocks are medium to dark grey, fine grained and laminated. Near the contact the rocks are brecciated and deformed, and are actinolite-chlorite-carbonate-bearing rocks quartz-rich portions. Subradial aggregates of fine grained fibrous amphibole in quartz-rich

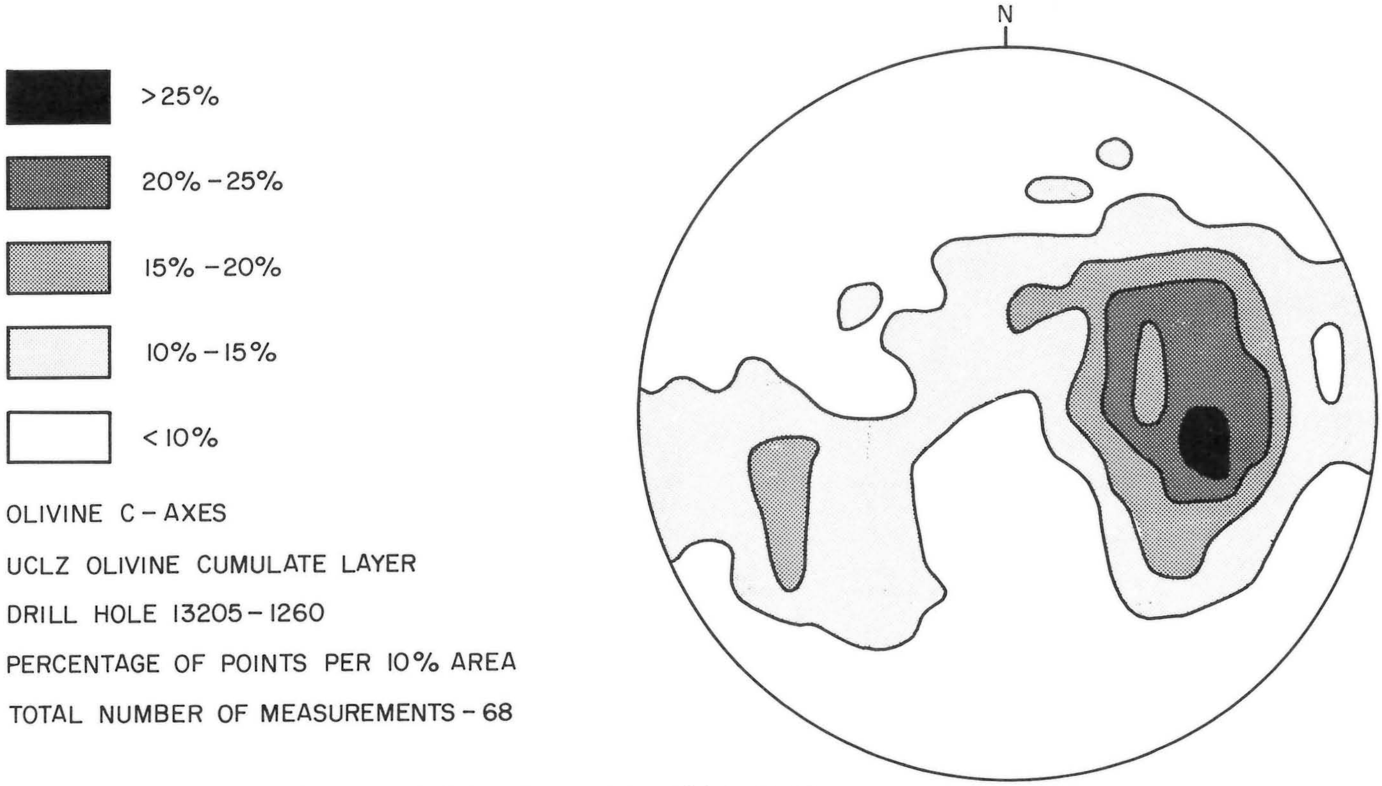


Figure 113: Fabric diagram, olivine c-axis, UCLZ olivine cumulate, drill hole 13205.

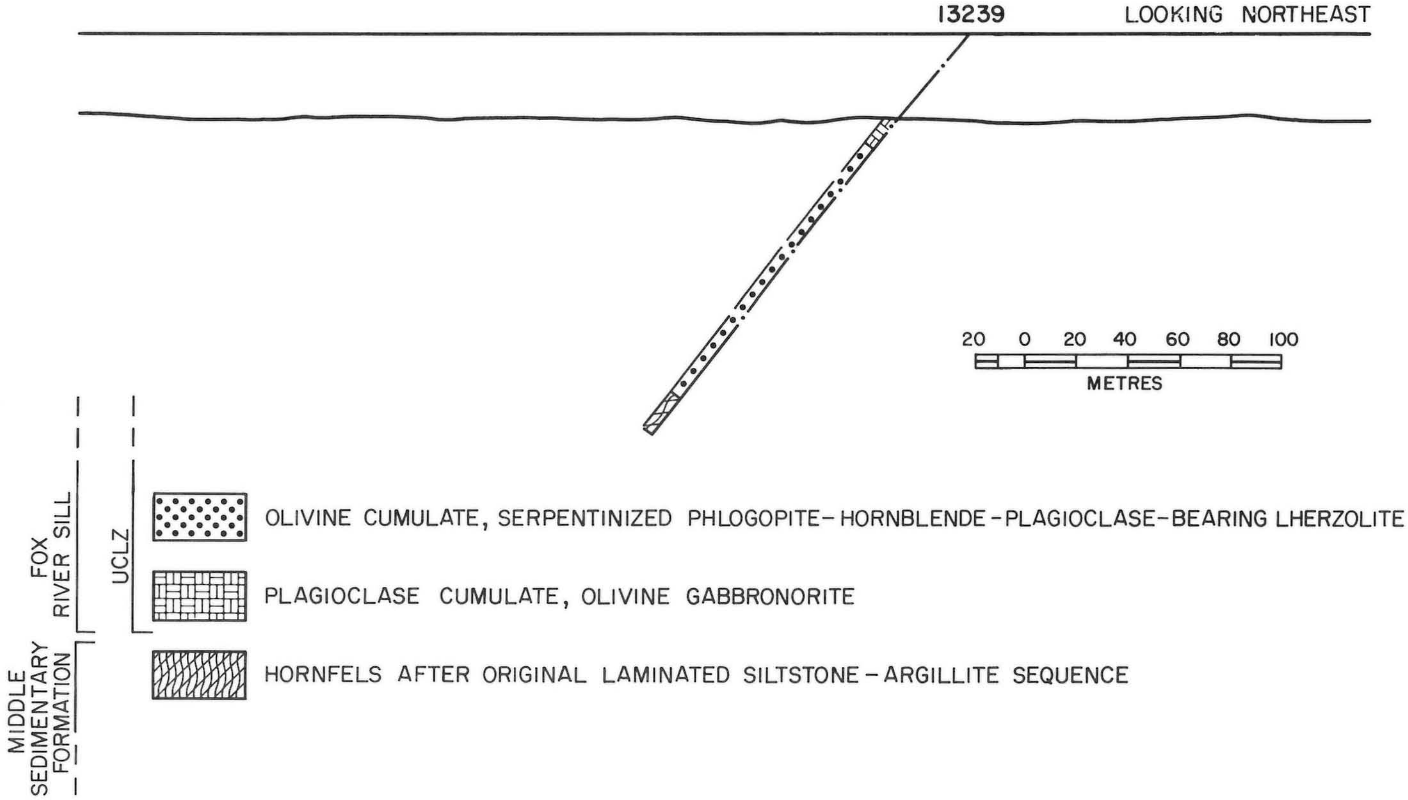


Figure 114: Upper UCLZ geology, drill hole 13239.

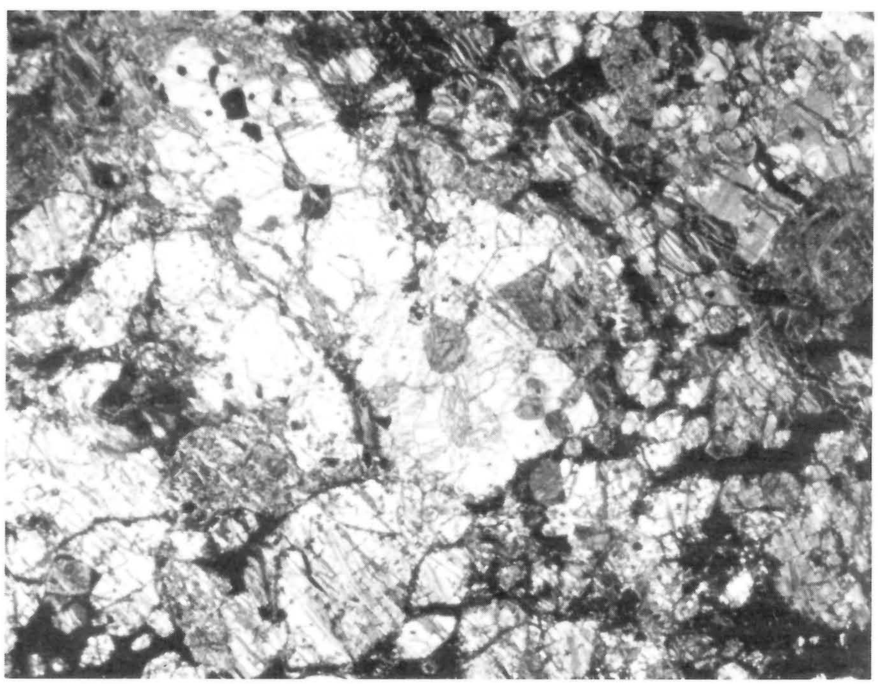


Plate 66: Olivine cumulate characterized by large poikilitic orthopyroxene crystal (white area, centre to upper left). Curtain-growth serpentine has pronounced orientation (lower right to upper left). UCLZ, olivine cumulate, DDH 13205-1260, XN.

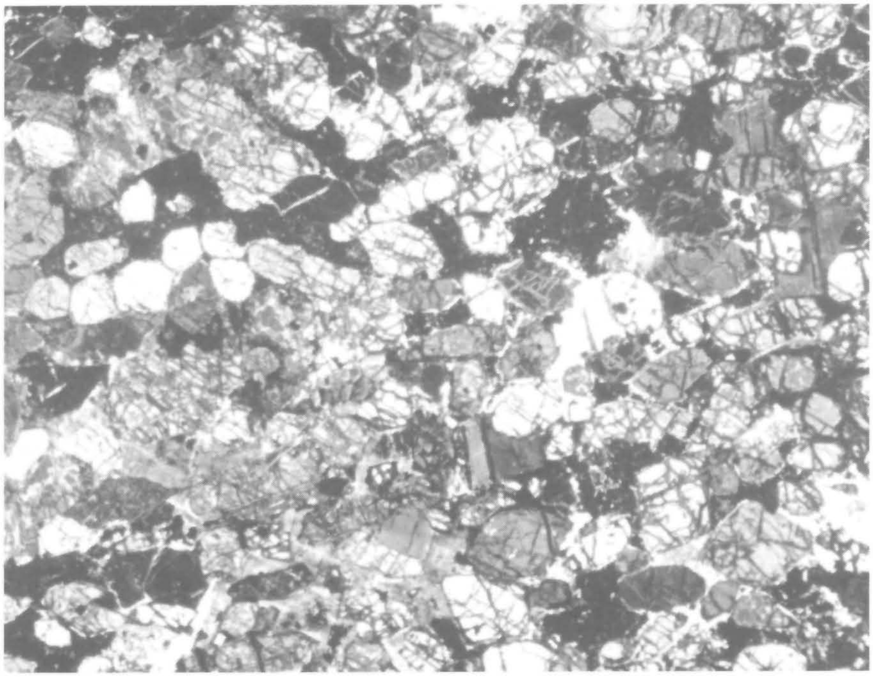


Plate 67: *Olivine cumulate characterized by well preserved, granular to lath-shaped olivine crystals. Post-cumulus minerals include pyroxenes and plagioclase, and primary hornblende and phlogopite. UCLZ, olivine cumulate, DDH 13239-205, XN.*

portions outline original spherulites indicating the former existence of glass. Original mm-scale sedimentary lamination is well preserved and serves to illustrate the brecciated nature of the rocks. Fibrous tremolite-filled fractures are common. The rocks represent brecciated hornfelsed Middle sedimentary formation laminated siltstone-argillite.

SUMMARY

UCLZ rocks overlie LCLZ rocks from which they are recognized on the basis of a number of distinct characteristics, and they are in turn, overlain by a suite of heterogeneous rocks that comprise the HRZ. UCLZ rocks are widespread although they appear to be absent in the easternmost part of the west lobe of the intrusion. The contact between UCLZ and LCLZ rocks has been penetrated by drill holes in four widely separated areas, two holes being east and two being west of the pinch-and-swell structure (Fig. 92 and Map GR81-1-1).

East of the structure, the uppermost LCLZ cyclic unit is composed of olivine cumulate, clinopyroxene cumulate and plagioclase cumulate layers, the latter being rare in LCLZ cyclic units. In the drill holes that penetrate the contact (13205 and 13219), the uppermost LCLZ olivine cumulate layer changes in original composition upward from dunite to wehrlite. In contrast, the olivine cumulate layer of the lowermost UCLZ cyclic unit contains postcumulus orthopyroxene, and the rocks ranged from wehrlite and lherzolite, to olivine gabbronorite in original composition.

West of the pinch-and-swell structure, in drill hole 13231, the uppermost LCLZ cyclic unit is composed of a thick olivine cumulate layer and a thin clinopyroxene cumulate layer. The olivine cumulate ranges from dunite to plagioclase-bearing wehrlite and lherzolite in original composition, but does not display a regular or progressive change in composition with stratigraphic height. The overlying UCLZ rocks are composed of nine rather thin cyclic units, the first six of which are composed of sulphide-bearing olivine cumulate-clinopyroxene cumulate layers. This succession contrasts markedly with underlying LCLZ cyclic units that are composed of relatively thick olivine cumulate and thin clinopyroxene cumulate layers. The UCLZ rocks contain orthopyroxene, a mineral that is rare in LCLZ rocks, and they are also sulphide-bearing at the contact, sulphide minerals being rare in LCLZ rocks.

Although the UCLZ-LCLZ contact can be positioned according to the same set of criteria (presence or absence of orthopyroxene, abundance of plagioclase cumulate), in detail, UCLZ-LCLZ contact relations east and west of the pinch-and-swell structure are apparently different. This may reflect the fact that on either side of the pinch-and-swell structure UCLZ rocks developed in a slightly different manner.

UCLZ cyclic units, west of the structure, are variably composed, consisting of olivine cumulate-clinopyroxene cumulate, olivine cumulate-clinopyroxene cumulate-plagioclase cumulate, clinopyroxene cumulate-plagioclase cumulate, olivine cumulate-plagioclase cumulate and olivine cumulate-orthopyroxene cumulate layers. This variable composition of cyclic units contrasts with the simple olivine cumulate-clinopyroxene cumulate cyclic unit that dominates the LCLZ succession. The variation in cyclic units simply illustrates that the order of crystallization was much more variable in UCLZ than in LCLZ rocks.

Although olivine cumulates dominate the UCLZ cumulus succession, one of the distinguishing characteristics of UCLZ rocks is the relatively greater abundance of plagioclase. This is illustrated in the many cyclic units that are capped by plagioclase cumulate layers. This is also demonstrated, towards the top of the zone, in olivine cumulate layers that contain abundant postcumulus plagioclase, such that some of these rocks are melatroctolite in composition.

Evidence of deposition of crystals during magmatic current activity is relatively abundant. Direct evidence such as lineate lamination of olivine and clinopyroxene c-axes has been documented in fabric diagrams from a number of areas. Centimetre-scale grain size graded layers are common in one 250 m thick olivine cumulate layer. This suggests that this thick layer may be constructed of hundreds of cm-scale beds or layers, each representing a small-scale density current deposit. The uppermost olivine cumulate layer in the western part of the intrusion (exposed in drill holes 38522 and 38523) is characterized by numerous cm-scale (1 cm to 1 m thick) plagioclase cumulate layers. Thus, this 160 m thick layer is constructed of numerous, small-scale olivine cumulate-plagioclase cumulate cyclic units, each of which may also represent deposition from small-scale density currents of the type described by Irvine (1980).

East of the pinch-and-swell structure, the lowermost UCLZ cyclic units (drill holes 13219 and 13213) are composed of olivine cumulate-plagioclase cumulate layers. In the olivine cumulate rocks, orthopyroxene is a common postcumulus phase, and postcumulus phases constitute more than 10 percent of the rocks. Lineate lamination of olivine in the olivine cumulate of the lowermost UCLZ cyclic unit in this area suggests deposition of olivine in a magma current regime.

The ratio of postcumulus phases to cumulus olivine increases substantially near the HRZ contact, where UCLZ rocks are characterized by numerous large, irregularly shaped poikilitic crystals that isolate individual cumulus olivine crystals. These rocks, which contain hornblende and phlogopite as primary postcumulus phases, were originally olivine melagabbronorite in composition. Rocks, similar to Molson dyke transition zone rocks (Scoates and Macek, 1978), have been recognized close to the HRZ contact in two widely separated areas.

In Molson dykes, transition zone rocks occur between the chilled margin and the central zone of major dykes, and they owe their unusual textural features in part to rapid cooling. The occurrence of similar rocks at the contact between UCLZ and HRZ assemblages suggests that they may represent a locally developed upper border zone.

The rocks close to the HRZ contact display many of the characteristics of MZ cyclic unit 1, olivine cumulate rocks. The abundance of postcumulus phases and fine olivine grain size reflects the rapid crystallization of magma due to high heat loss through the roof of the intrusion. The presence of postcumulus hornblende and phlogopite likely reflects salic contamination of the magma through incipient melting of roof rocks. These hydrous phases also indicate that the sediments were hydrous at the time of the initial intrusion of magma, a conclusion supported by the brecciated nature of the overlying sedimentary succession (Middle sedimentary formation) and the presence of miarolitic cavities in melt rocks.

It is clear that the overall composition of UCLZ rocks is substantially different from LCLZ rocks, and consequently the magma pulses that gave rise to the UCLZ succession were compositionally different to those that gave rise to LCLZ rocks. The contrast between the simple olivine cumulate-clinopyroxene cumulate LCLZ cyclic units and the variety of cyclic units that comprise the UCLZ succession indicates that UCLZ rocks were derived from magma that was somewhat less basic than the magma batches that gave rise to LCLZ rocks. The observation that this change is abrupt over nearly three-quarters of the length of the west lobe of the intrusion suggests that the change in magma composition represents a major event in the magmatic history of the intrusion.

Concentrations of disseminated chromite appear to be more abundant in UCLZ rocks and a number of chromiferous rocks (chromite more than 4 percent) have been observed. However, because of the telescoped nature of much of the core, a detailed evaluation of the distribution of chromite is not possible. Disseminated sulphide is rare in LCLZ rocks; it is more abundant in UCLZ rocks where many concentrations of disseminated sulphide (more than 5 percent) display a direct relationship with pyroxene cumulate rocks.

Hybrid Roof Zone (HRZ) rocks are exposed in drill core from drill holes in two widely separated areas of the Sill. The rocks are a heterogeneous mixture of Sill rocks and roof rocks (Middle sedimentary formation) with much hybridization caused by incorporation of roof rocks into the Sill magma, and abundant evidence of melting of roof rocks. The zone is approximately 40 m thick in the western part of the intrusion and may be substantially thicker in the vicinity of the pinch-and-swell structure in the central part of the intrusion.

208W SECTION - DRILL HOLE 38510

Drill hole 38510

The drill hole penetrates the UCLZ-HRZ contact, the HRZ-Middle sedimentary formation contact and a sequence of Middle sedimentary formation rocks that contain two small mafic intrusions (Fig. 98).

MIDDLE SEDIMETNARY FORMATION AND DERIVED HORNFELS

Drill hole 38510 intersects a sequence of fine grained and finely laminated sedimentary rocks (Middle sedimentary formation), that have been converted to hornfels adjacent to HRZ rocks of the Sill in the upper part of the hole (Fig. 98). The original sedimentary rocks are medium to dark grey, extremely fine grained, fissile and composed of numerous mm-scale laminations. The rocks range from silty to sandy argillite, with alternating silty or sandy (quartz) and argillaceous laminae. Some sandy laminae display microscopic-scale grain size grading. Rare carbonate-bearing laminae have been observed. The contact between laminated sedimentary rocks and hornfels is gradational, the rocks becoming progressively darker grey and finer grained. Hornfels is fine grained, dark charcoal grey and fissile. An increasing frequency of quartz and aplite veins (up to 3 cm wide) is evident toward the contact with HRZ rocks of the Sill. Original sedimentary lamination is preserved in most hornfels, and the rocks contain abundant chlorite, some of which forms spots in original sandy or silty portions of the rock. Argillite displays recrystallization to muscovite that forms mats of intersecting lath-like crystals in some rocks. Tremolite + muscovite-rich rocks are common close to the HRZ contact. The contact between hornfels and HRZ rocks is a zone of aplite that contains unmelted hornfels.

MAFIC INTRUSION

The small mafic intrusion in the upper part of the hole is composed of fine grained, grey, granular rocks, some of which are delicately mottled or spotted and megascopically identical to HRZ rocks. The rocks possess a variety of textures and compositions that suggest a hypabyssal intrusive environment. Rocks near both contacts display dendritic clinopyroxene intergrown with plagioclase that is similar to intergrowths described from some Upper volcanic formation volcanic rocks (Scoates, 1981). Some rocks are quartz- and granophyre-bearing. The central part of the intrusion is composed of equidimensional clinopyroxene, lath-like plagioclase and irregularly shaped areas filled with chlorite and epidote that are interpreted to represent original miarolitic cavities. The intrusion may represent a frozen conduit that acted as a feeder to the lavas of the overlying Upper volcanic formation.

HYBRID ROOF ZONE

HRZ rocks are fine grained, grey, granular and finely mottled or spotted. The rocks are predominantly quartz-bearing gabbronorites that are characterized by randomly disposed, lath-like plagioclase and interstitial, pale brown clinopyroxene. The latter forms elongate, slightly curving bladed crystals, and a few crystals display subradially developed divergent terminations. Many of the clinopyroxene crystals are twinned, and hourglass and sector-zoned crystals have been observed. Plagioclase has been replaced by muscovite + epidote + chlorite + carbonate, and clinopyroxene displays incipient to complete recrystallization to pale yellow-green actinolite. Clear quartz crystals form irregularly shaped interstitial patches. Orthopyroxene, now replaced by chlorite + tremolite, originally formed large (up to 5 mm), highly irregular, poikilitic crystals that contain numerous inclusions of plagioclase laths. Ilmenite, partly to completely replaced by sphene and other Ti-rich alteration products, occurred as large skeletal crystals. Globular sulphide grains (less than 1 percent) are widely disseminated and apatite is a rare accessory mineral.

At the base of the HRZ, near the contact with underlying UCLZ olivine cumulate rocks, are two unusual rocks. One is composed of a mosaic of fine grained (0.2 x 0.04 mm) plagioclase laths and coarser (3 x 0.5 mm) elongate, bladed clinopyroxene crystals, many of which are curving and branching. These crystals are commonly twinned and are further characterized by serrated, sieve-like grain boundaries; they contain numerous inclusions of fine grained plagioclase. The clinopyroxene crystals are brownish and their grain margins are more intensely coloured. Some dendritic crystals display divergent terminations. The rock is quartz- and granophyre-bearing. This unusual rock is in contact with a granophyre that is dominated by spherulites of granophyre in a matrix of randomly disposed, plagioclase laths. Rhomb-shaped crystals of untwinned alkali feldspars occupy the cores of many granophyre spherulites. Sphene, zircon and numerous needle-like inclusions of an unknown phase are common accessory minerals.

462W SECTION - DRILL HOLE 38523

Drill hole 38523

Drill hole 38523 collared approximately 1600 m east of 38510 intersects a sequence of finely laminated sedimentary rocks (Middle sedimentary formation), their hornfels equivalent, and approximately 40 m of HRZ rocks (Fig. 95).

MIDDLE SEDIMENTARY FORMATION ROCKS AND DERIVED HORNFELS

The sedimentary rocks are a fine grained, finely laminated, medium- to dark-grey sequence of argillite, shale, sandstone and siltstone. The rocks have a well developed fissility, and are composed of silty and sandy lenses and laminae interlaminated with argillite and shale. The laminae have been disrupted by numerous closely spaced (about 1 mm) sinuous planes that give rise to continuous pinch-and-swell structures that, in turn, define lenses of sandy and silty material. Pyrite crystals are widely disseminated (less than 1 percent), and rare sulphide veinlets have been observed. The fine grained portions of the rock are composed of a fine grained mass of muscovite whose lath-like crystals display parallel orientation that is slightly oblique to the direction of lamination. The pyrite noted above occur as elongate crystals that have well developed pressure shadows. Tourmaline, sphene and zircon are accessory phases.

The contact between sedimentary rocks and their hornfels equivalent is gradational, the sedimentary rocks becoming finer grained, and the lamination less distinct. The rocks are medium to dark grey and are cut by rare carbonate stringers. They are segregated into light and dark areas, the light areas being crudely equidimensional to elliptical and composed of muscovite and quartz. Altered ilmenite occurs in the cores of some light patches. The dark areas form a continuous to discontinuous network that surrounds and isolates the light patches; they are composed of fine grained chlorite and quartz.

HYBRID ROOF ZONE

HRZ rocks range from grey and slightly bluish grey to greenish grey, and from fine- to coarse-grained; the rocks are granular. At the contact, the rocks are a mixture of fine grained, grey, pepper-and-salt textured quartz-bearing gabbronorite with inclusions of hornfels. The zone is characterized by rocks that represent a heterogeneous sequence of fine- to coarse-grained quartz-bearing and quartz-free gabbronorite, coarse grained pyroxene-rich, and fine grained original olivine cumulate rocks. The pyroxene-rich rocks are brownish green to grey green, granular and mottled. The olivine-rich rocks are dark greenish black and mottled. Sulphide minerals are locally significant as finely disseminated grains that make up 5 percent of some rocks.

The gabbronorites comprise quartz- and granophyre-bearing, as well as quartz- and granophyre-free, varieties. Some were originally partly cumulate in origin whereas others were apparently noncumulate. Plagioclase, which originally formed crystals that ranged from lath-like to stubby and prismatic in shape, has been recrystallized to muscovite ± albite ± epidote ± chlorite. Clinopyroxene originally formed brownish crystals, many of which are twinned and zoned, some of which are composed of divergent segments, and others that are stubby equidimensional, prismatic crystals. In some apparently noncumulate rocks, clinopyroxene formed long (up to 1 cm) slender, curving twinned crystals. Clinopyroxene ranges from being partly preserved to being totally recrystallized to tremolite as single crystals or as fibrous felted mats. Orthopyroxene commonly formed large irregularly shaped poikilitic crystals, although it formed regular prismatic crystals in one rock. It has been pseudomorphously replaced by chlorite + tremolite that form an interwoven intergrowth. Skeletal ilmenite, altered to sphene and other Ti-rich products, is an ubiquitous phase.

One noncumulate rock is characterized by clusters of prismatic to highly irregular complex crystals of clinopyroxene; some of the latter contain apparently relict patches of wormy, myrmekite-like exsolution lamellae. These densely packed clinopyroxene crystal clusters are contained within large (up to 5 mm) poikilitic plagioclase crystals. The rock is similar in composition and texture to possible upper border group rocks described from the uppermost part of the UCLZ succession in a few localities.

A dyke-like(?) tonalite to quartz diorite consists of an interlocking mosaic of albite and abundant interstitial quartz. Tremolite-actinolite replaces an original prismatic mafic mineral that constituted less than 10 percent of the rock. Ragged sphene crystals are a disseminated accessory phase.

The original olivine cumulate rocks, which are isolated by gabbronorite, range from olivine melagabbronorite to lherzolite in composition. One rock is dominated by large (5 mm) poikilitic clinopyroxene, orthopyroxene and plagioclase crystals, and the ratio of cumulus olivine to postcumulus phases is estimated to be 1:5. Phlogopite and red-brown hornblende are present as postcumulus phases. The rocks have been substantially recrystallized with secondary tremolite being a common phase. Chromite constitutes from 1 to 3 percent of the rocks.

722E SECTION - DRILL HOLES 13211, 13215, 13220, 13223, 13224 13229 AND 13232

HRZ rocks are exposed in drill core from a number of drill holes collared north and west of 722E section in the central part of the Sill. Here, a major pinch-and-swell structure marks the midpoint of the intrusion (West lobe), where the overall strike of the intrusion changes by approximately 10o. The irregular structure is composed of a constriction to the west and an adjacent protuberance to the east. An absence of outcrops makes critical evaluation of this structure impossible; however, several drill holes in the area permit some observations of units and the nature of contacts. The shape of the structure, is clearly defined by aeromagnetic anomaly patterns that suggest a fold; however, olivine cumulate rocks close to the UCLZ-HRZ contact are highly fractured, and many possess microfaults suggesting that faulting may be significant. The presence of a fault is further indicated by the UCLZ-HRZ contact in each of the seven drill holes that defined a plane (038°/46°) (Fig. 115). A fault plane with this attitude could explain the lack of correlation between drill hole 13220 and drill holes 13215 and 13224. The irregular pinch-and-swell structure is likely caused by a combination of folding and faulting that in turn is related to the large-scale flexure of the Sill that resulted in its change in strike in this area.

HYBRID ROOF ZONE

HRZ rocks represent a diverse suite of quartz-rich rocks and quartz- and granophyre-bearing rocks that owe their origin, at least in part, to melting of quartz-rich sedimentary roof rocks of the Middle sedimentary formation (melt rocks). Direct evidence of melting of these sedimentary rocks comes from the very well preserved devitrification textures. Fine grained, felsic rocks that range in composition from granite to quartz-rich granitoid (more than 60 percent quartz; Streckeisen, 1976) and that contain abundant granophyric intergrowths, are interpreted to represent more extensive melting of sediment. The resulting melts cooled slowly enough to permit some crystallization; however, many of these rocks also display devitrification textures.

The distribution of the numerous rock types that compose HRZ assemblages within individual drill holes tends to be highly irregular. In a few examples, a regular progression exists from melt rock through hornfels to moderately well preserved sedimentary rocks. However, in many holes granophyre-bearing aplite and quartz-rich granitoids occur at intervals, separated by hornfels, spotted hornfels and melt rock containing different proportions of unmelted material.

Melt rocks are characterized by fibrous quartz that forms spherulitic, fern-like or dendritic growths (Plates 68 and 69), many displaying cuneiform, micrographic intergrowths near their outer boundary. These complex structures may have originally been composed of cristobalite that inverted to quartz. They are virtually identical to structures associated with the devitrification of rhyolite glass (Lofgren, 1971a, 1971b). Partly preserved quartz-rich sediment is present in most of these rocks. Such features suggest these rocks originated through melting of quartz-rich siltstone, producing glass that subsequently devitrified.

Individual spherulites and dendrites contain numerous muscovite-bearing pseudomorphs after original rhombic crystal inclusions, some of which display simple twins. Chlorite pseudomorphously replaces original slender laths or acicular crystals. Quartz + chlorite + sphene that forms a complex, mosaic-like mass, which in some areas retains the character of the original quartz-rich siltstone, occupies the areas between the spherulites.

Some rocks are composed of a mosaic of quartz grains and chlorite ± sphene. Although spherulitic and dendritic structures may be

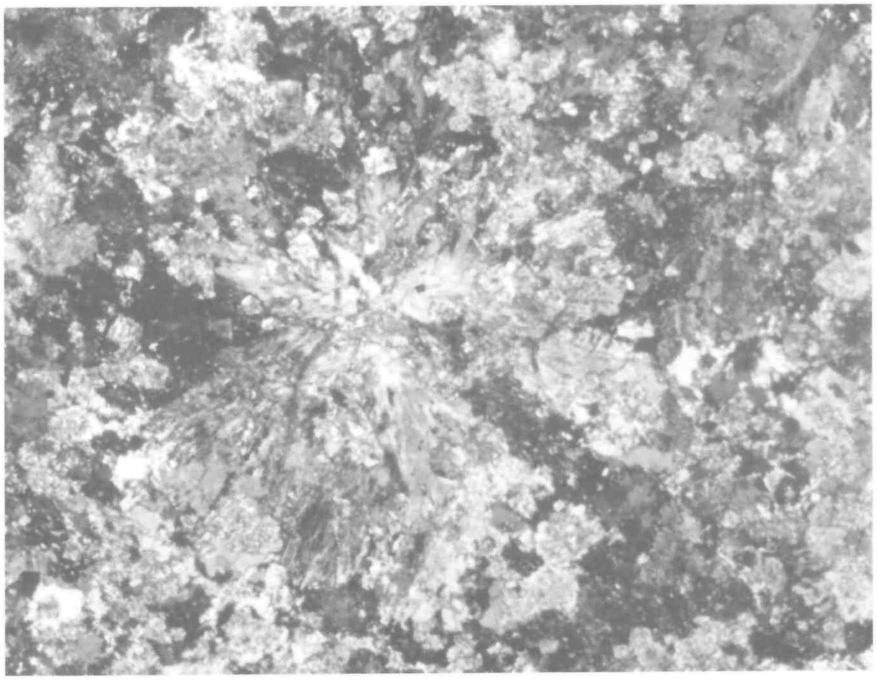
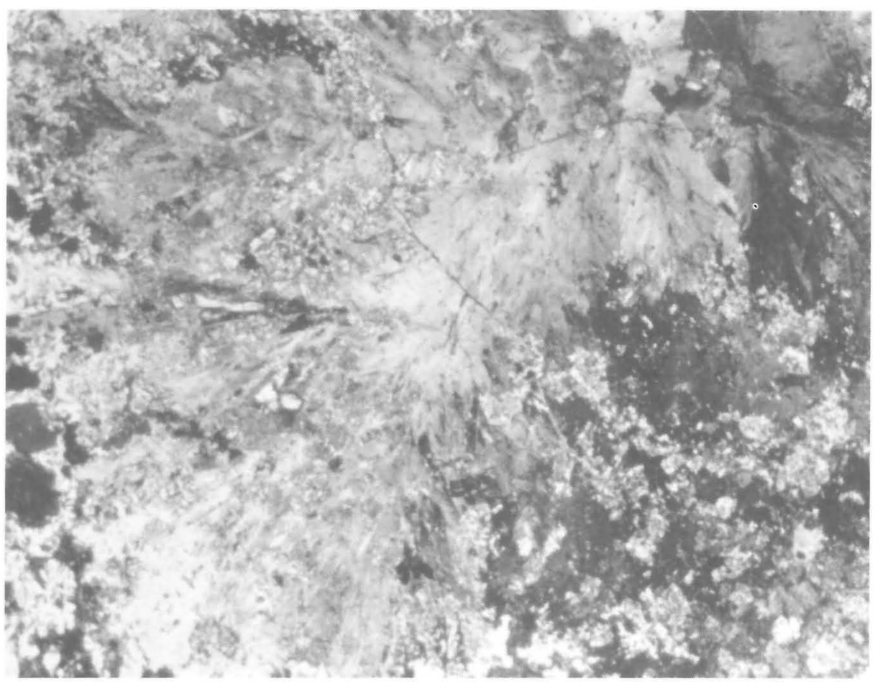


Plate 68: *Radiating fibrolamellar quartz spherulite (devitrification texture). Remainder of rork is composed of chlorite + muscovite + quartz + sphene. Note granophyric textures at or near the outer boundary of the spherulite. HRZ, DDH 13211-1025, XN.*

Plate 69: *Radiating fibrolamellar quartz spherulite (devitrification texture). HRZ, DDH 13221-1025, XN.*



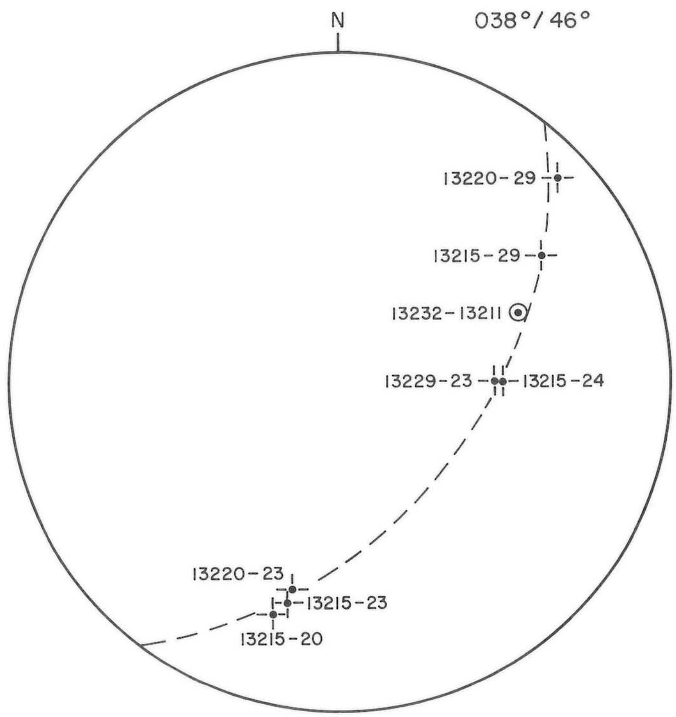


Figure 115: Stereographic projection of plane defined by UCLZ-HRZ contact, 722E section area.

absent, there is commonly local development of micrographic intergrowths (Plate 70). Incipient development of spherulites and dendrites has been noted in other rocks. Smoothly elliptical to circular areas filled with chlorite ± sulphide may represent original miarolitic cavities (Plate 71). Apatite is a locally abundant accessory mineral, and much of the chlorite is decorated by clusters of apatite haloes. Pyrite is widely disseminated is some rocks.

Granophyre-bearing aplites are characterized by an intersecting network of plagioclase laths with the resulting triangular and rhomb-shaped spaces between plagioclase crystals being occupied by quartz + chlorite (Plate 72). Interstitial quartz displays incipient spherulitic and dendritic development, or well developed graphic intergrowths. The rocks appear to have been composed predominantly of plagioclase and quartz (80 percent or greater, visual estimate). Chlorite replaces original lath-like to irregularly shaped crystals. Plagioclase has been partially to completely replaced by muscovite. Irregular patches of sulphide ± quartz ± chlorite are widely disseminated.

Rare quartz-bearing gabbros containing randomly oriented laths and prismatic crystals of plagioclase, are characterized by large (up to 3 mm) skeletal ilmenite crystals. The irregularly shaped interstitial areas are occupied by tremolite ± chlorite that replaces original clinopyroxene. Quartz crystals (about 5 percent) occupy interstitial areas, and a few grains display granophyric intergrowths. One such rock contains substantial carbonate that overprints and partially masks the primary rock texture.

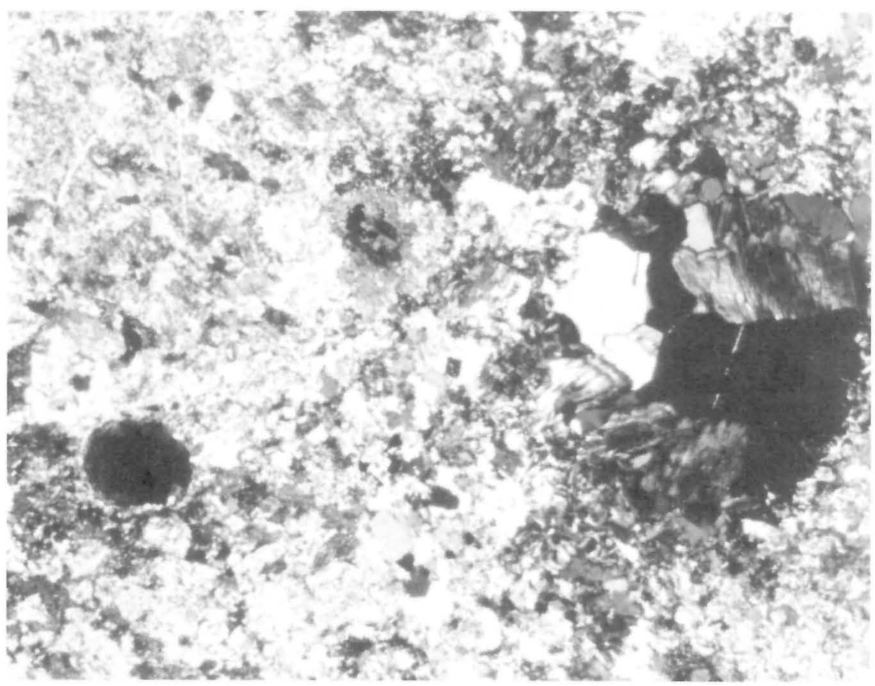
Some HRZ rocks possess a fine grained groundmass that is composed of fine graphic intergrowths, many of which display a regular, parallel line orientation, and some that create a rough herringbone-like pattern. Muscovite-bearing pseudomorphs, after original rhombic crystals (0.15 x 0.10 to 1.5 x 0.5 mm) are widely distributed, as are slender, lath-like to acicular crystals (0.25 x 0.03 to 1.5 x 0.07 mm) that have been pseudomorphously replaced by chlorite.

Hornfels constitutes much of the HRZ; the original sedimentary lamination which consisted of alternating quartz-rich and quartz-poor laminae is usually preserved (Plate 73). Individual quartz grains possess indistinct, diffuse grain boundaries. Quartz-poor laminae are muscovite-rich and contain irregular chlorite patches and abundant irregularly shaped sphene crystals. In a few rare examples, quartz grains are subangular, and subangular plagioclase grains are present.

Fine grained and coarse grained spotted hornfels are present; the coarser appears to be derived from the finer grained hornfels. The fine grained hornfels consists of irregular chlorite patches in muscovite-rich (quartz-poor) laminae. The coarse grained variety is formed by the enlargement of chlorite patches that coalesce to form a partly continuous phase (Plate 74). This in turn segregates crudely equidimensional islands of muscovite-rich rock (up to 1 mm). The continuous contact between chlorite-rich and muscovite-rich parts is decorated by numerous irregularly shaped sphene crystals. Some muscovite-rich spots have chlorite cores.

Plate 70: *Quartz-rich granophyre. Mafic mineral in chloritized phlogopite. HRZ, DDH 13215-340, XN.*

Plate 71: *Circular area filled with chlorite + quartz + sulphide, possibly representing original mariolitic cavity. HRZ, DDH 13211-1125, XN.*



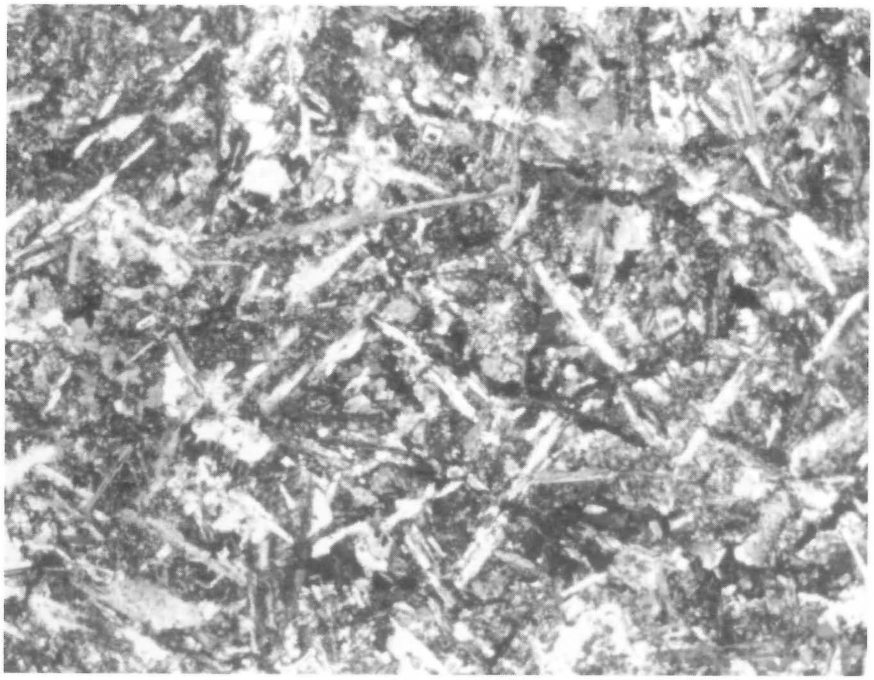
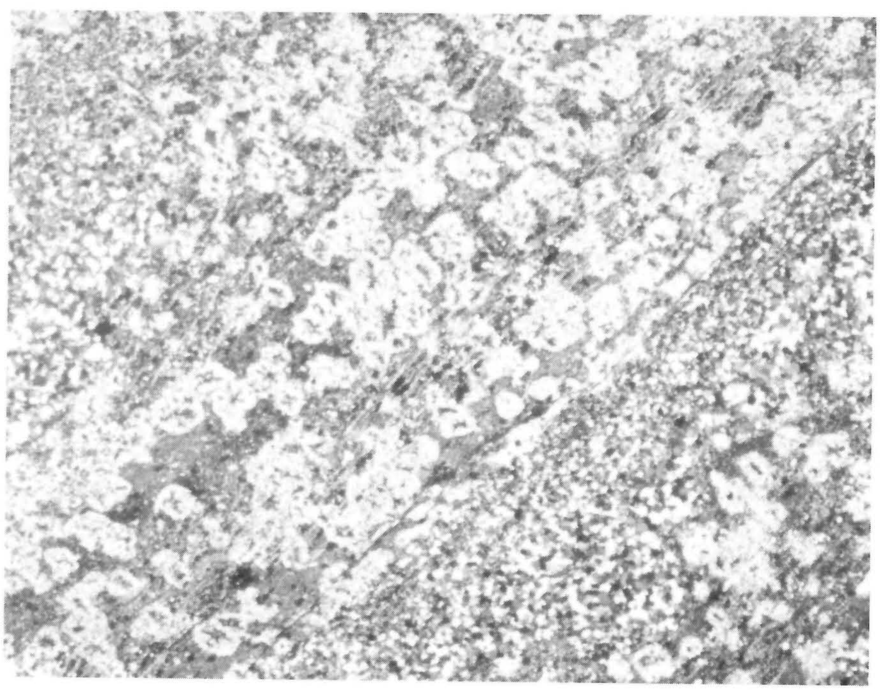


Plate 72: *Randomly disposed acicular plagioclase laths in a groundmass composed of quartz and chlorite and minor sphene. A plagioclase-phyric aplite. HRZ, DDH 13215-770, XN.*

Plate 73: *Spotted hornfels with preserved sedimentary lamination (from lower left to upper right). HRZ, DDH 13215-730, XN.*



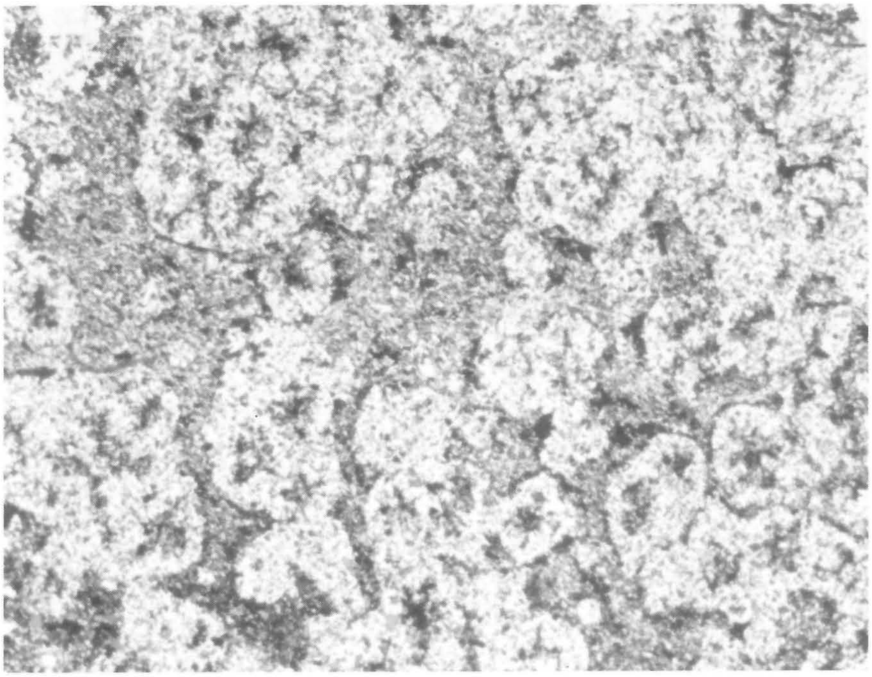


Plate 74: *Spotted hornfels. Light ovoid areas are muscovite and quartz, dark areas are chlorite and sphene. HRZ, DDH 13215-730, XN.*

670E SECTION - DRILL HOLES 38516, 38517, 38518 AND 38519

Middle sedimentary formation rocks that overlie the Sill, north of the 'pinch' portion of the pinch-and-swell structure, have been converted to hornfels and are host to numerous intrusions and melt rocks. Some of the intrusions and melt rocks are identical to HRZ rocks and the area appears to be underlain by a substantial intrusion breccia or agmatite (Fig. 116 and 117). Some idea of the complex nature of the roof rock sequence that overlies the Sill can be determined from Figure 118, a compilation of the geology seen in drill holes 38516, 38517, 38518 and 38519. In this compilation, drill holes 38516 and 38517 have been projected onto 670E section, along which drill holes 38518 and 38519 were collared. Although melt rocks and intrusions of various kinds appear to be more abundant than hornfels derived from Middle sedimentary formation rocks, the fact that many melt rocks were clearly derived from sedimentary rocks implies that the area originally was underlain by rocks belonging to the Middle sedimentary formation. Intrusive rocks comprise three distinct types:

1) mafic-ultramafic intrusions that possess evidence of rapid crystallization at their chilled(?) contacts;
2) diverse quartz- and granophyre-bearing rocks, including melt rocks displaying well preserved devitrification textures; and
3) fine- to medium-grained diabase.

The mafic-ultramafic intrusions may represent conduits through which magma from the Sill chamber found egress to feed lavas of the overlying Upper volcanic formation.

The sporadic distribution of granophyre-bearing rocks and melt rocks illustrated in Figure 118 suggests that melting of sedimentary rocks was initiated at different points within the sedimentary sequence above the Sill. Aplitic rocks and mafic granophyre represent small-scale intrusions, whereas the norite-websterite-olivine melagabbronorite sequence represents a larger scale intrusion. The former represent melt rocks and hybrid rocks formed through contamination, whereas the latter represent an earlier, more basic magmatic phase of the Sill. The widespread distribution of intrusive rocks may reflect the brecciated nature of Middle sedimentary formation rocks that overlie the Sill, the brecciation being accomplished during intrusion of the Sill into wet sedimentary rocks.

SUMMARY

The HRZ represents a heterogeneous suite of rocks that separates UCLZ cyclic units from hornfels derived from Middle sedimentary formation rocks. This relationship appears to be straightforward in the western part of the intrusion where approximately 40 m of HRZ rocks separates UCLZ cumulates from hornfels. In the area of the pinch-and-swell structure, near the midpoint of the intrusion, the roof rocks have been invaded by aplite, and melt rocks (rocks possessing preserved devitrification textures) are widely distributed. Here, the complex relationship has been caused by brecciation of Middle sedimentary formation rocks during intrusion of the Sill, and intrusion of the brecciated sedimentary rocks by a variety of igneous rocks including those derived through extensive melting of the sedimentary sequence itself.

There seems little doubt that the quartz- and granophyre-bearing rocks, that otherwise possess characteristics of other Sill units, owe their origin entirely to contamination of Sill magma through melting of roof rocks. The evidence for this comes from the fact that a progression can be recognized from hornfels, through spotted hornfels that possesses a number of small fibrous quartz spherulites and dendrites, to melt rocks that are characterized by a dense cluster of fibrous quartz spherulites and dendrites. Melt rocks display a wide range in the ratio of melted and unmelted constituents. The end product of this progression ranges from granophyre, composed of spherulites and dendrites of granophyre, many with a core of alkali feldspar, to aplite composed of an interlocking mosaic of albite with abundant quartz and granophyre. Granophyre and aplite represent melt that cooled more slowly so that plagioclase crystals could

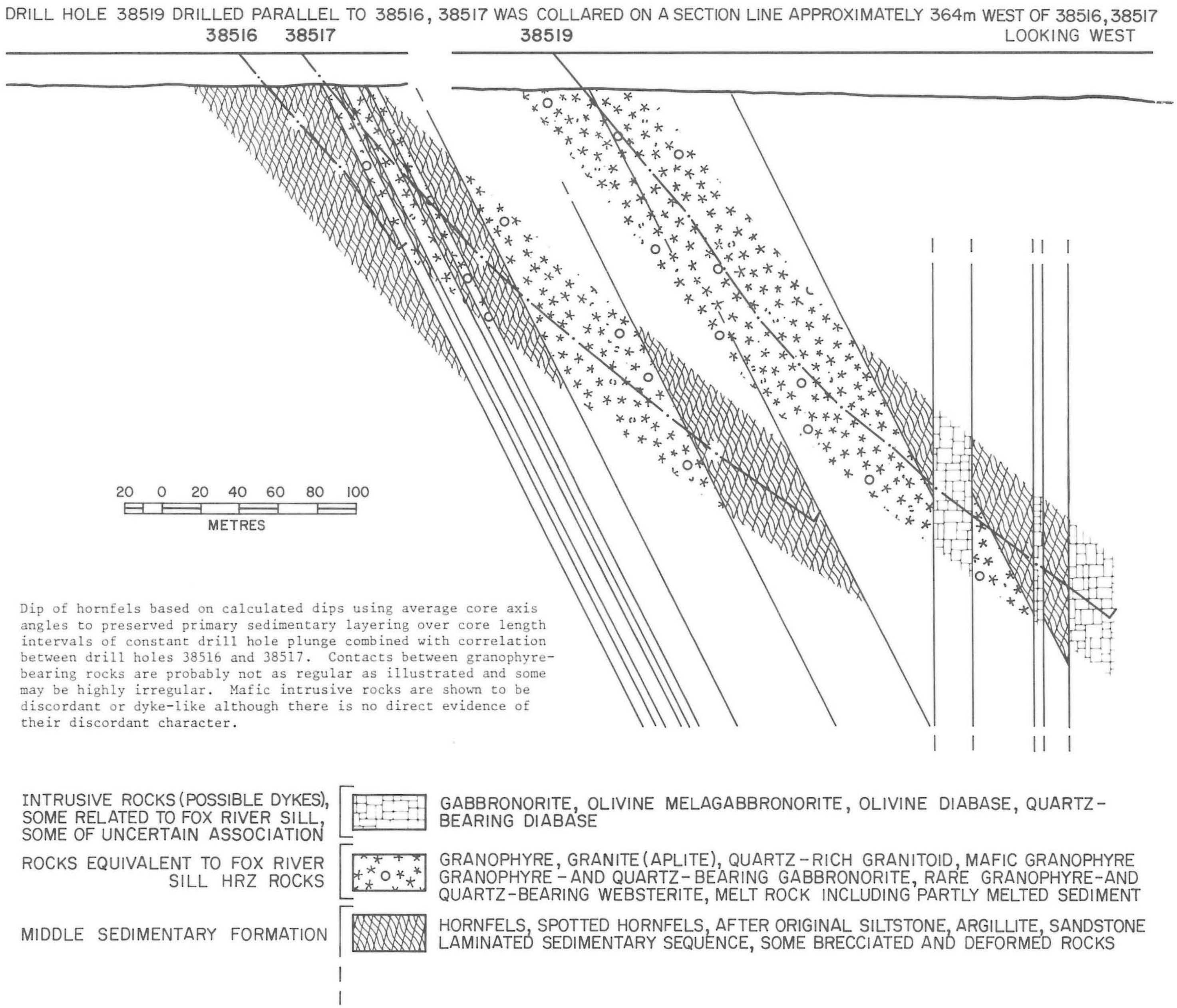


Figure 116: Geology 670E section.

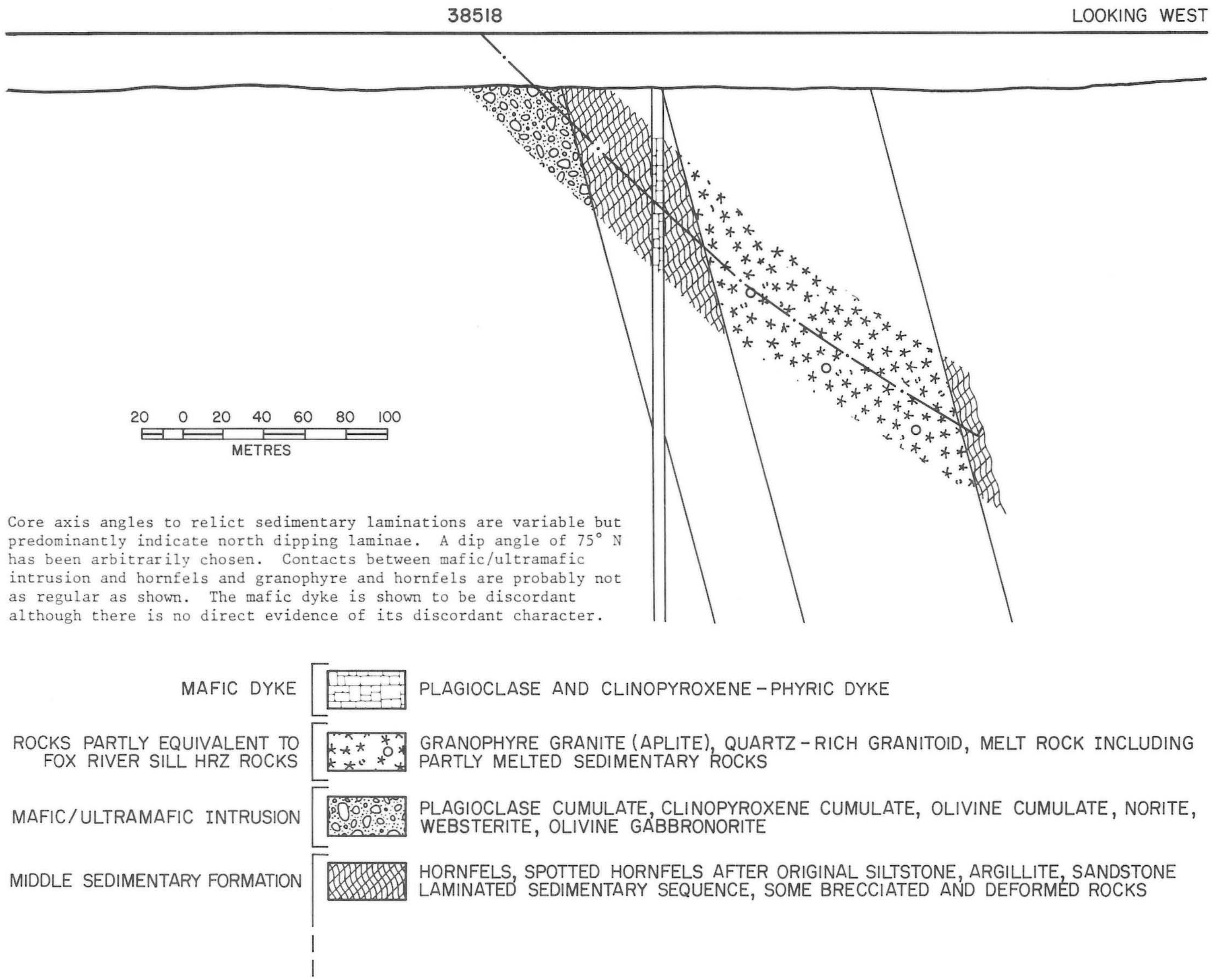


Figure 117: HRZ-Middle sedimentary formation geology, drill holes 38518.

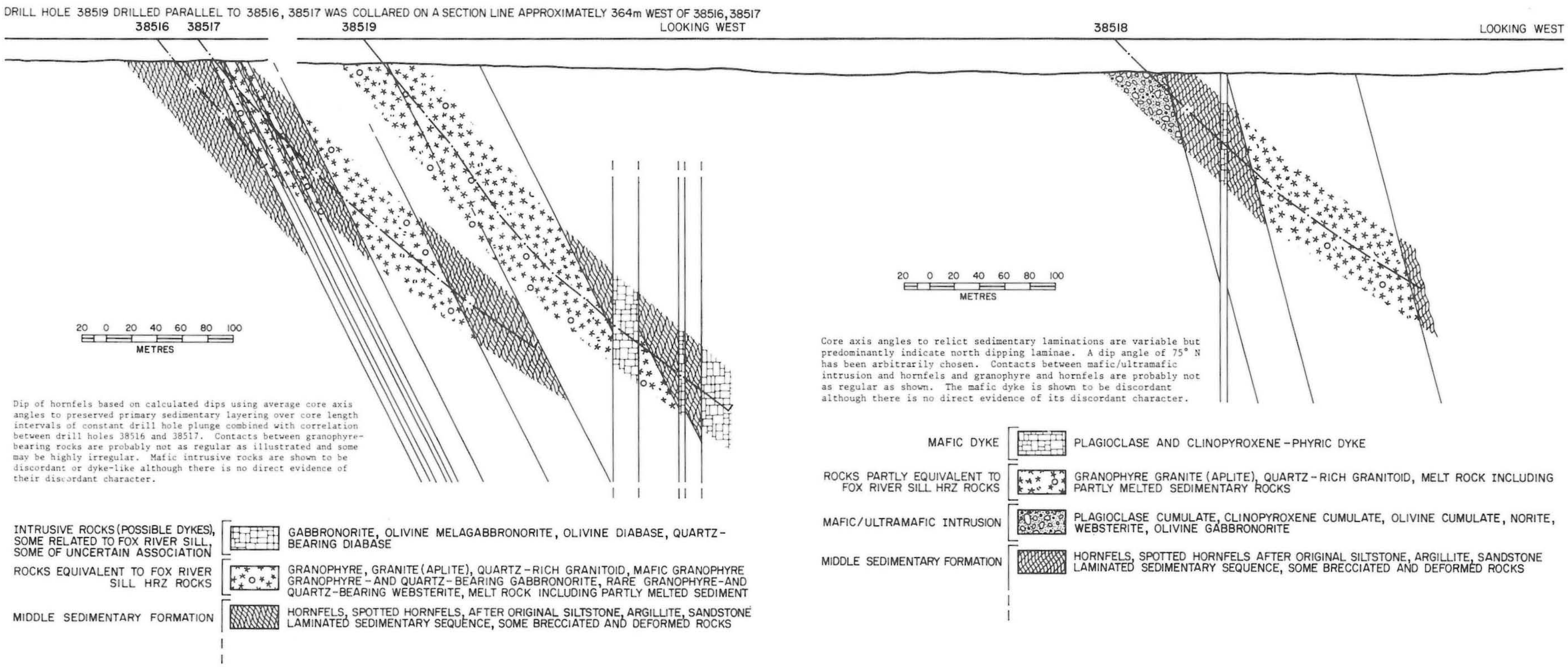


Figure 118: Geology compilation 670E section.

develop, although evidence in the form of rare dendrites and spherulites suggests that even in these rocks some quenching may have taken place. Veins of aplite and granophyre suggest that some of this material intruded the sedimentary sequence, and evidence from 610E section suggests that, in places, larger-scale intrusion of melt took place.

Recognition of the generation of "granitic" liquid through melting of sedimentary roof rocks and consequent contamination of the Fox River Sill magma may be significant in terms of magmatic ore deposits. Irvine (1975) suggested a mechanism whereby contamination of basic magma could be extremely important in determining the precipitation of magmatic ores such as chromitite layers, concentrated deposits of magnetite and immiscible sulphide liquid. He subsequently revised his ideas with respect to chromitite layers but suggested that the mechanics of salic contamination are still applicable to sulphide deposits (Irvine, 1977).

The mafic and ultramafic intrusions, including diabase, that have been noted in Middle sedimentary formation rocks are likely related to the main Fox River Sill magmatic event. Some may represent feeders to flows of the overlying Upper volcanic formation.

Melting of roof rocks has been noted in other major stratiform intrusions. The roof to the Muskox intrusion consists partly of hornfelsed schist, partly of granite, and partly of quartzite metamorphosed from sandstone (Irvine, 1975). Irvine suggested that the granophyre at the top of the intrusion represents magma formed mainly by melting of the schist and granite that floated at the top of the intrusion. The enormous Bushveld complex contains roof rocks that are mainly felsite, and highly metamorphosed pelitic sediments that display evidence of partial melting (Wager and Brown, 1968). The granophyre in the complex, together with the associated granite, occurs both at the roof contact and as sills in the felsite and is locally as much as 2100 m thick. Irvine (1975) reported that the steeply dipping layered rocks of the Stillwater complex have been unroofed by a combination of erosion and deformation and no mention is made of xenoliths, assimilation, or contamination in the available descriptions of the body. Although the Great Dyke has been unroofed by erosion it does contain various country rock xenoliths in the gabbro cumulates that form the upper part of the complex. Worst (1960) noted that, among the sedimentary xenoliths, quartzite appeared to survive the best, suggesting that it was refractory enough to withstand melting in a basic or moderately ultrabasic magma.

GEOCHEMISTRY

CHEMICAL VARIATION

Whole rock chemical analyses have been performed on 12 MZ rocks, 24 LCLZ rocks, 25 UCLZ rocks and 3 HRZ rocks, and within each zone the analyses have been organized according to their relative stratigraphic positions (Tables 9, 10, 11 and 12). The rocks are hypersthene- but not quartz-normative and LCLZ + UCLZ rocks form a series along the FeO-MgO join of the standard AFM diagram (Fig. 119). On the same diagram MZ rocks form a field extending out from the FeO-MgO join toward the centre of the diagram, and HRZ rocks, which display the greatest FeO-enrichment, occupy a field near the centre of the diagram. The greater abundance of total alkalies in MZ and HRZ rocks is interpreted as indicating contamination through incorporation of sedimentary material.

Olivine cumulate rocks form a cluster of points at the MgO corner of the CaO-MgO-Al_2O_3 diagram (Fig. 119). Clinopyroxene cumulate rocks cluster near the midpoint of the CaO-MgO join and plagioclase cumulate rocks form a field on the Al_2O_3 side of the centre of the diagram. On the Jensen cation diagram (Fig. 119), the various cumulate rocks trend in a serial-like fashion to the tholeiite and calc-alkalic fields. The serial nature of the rocks is displayed on the MgO vs. TiO_2 diagram (Fig. 120) and the majority of Sill rocks contain less than 0.5 percent TiO_2. The majority of Sill rocks plot in the komatiite field of the FeO/FeO + MgO + MnO vs. Al_2O_3 diagram (Fig. 120), the highly aluminous rocks being plagioclase cumulates. A direct relationship between increasing MgO/MgO + FeO + MnO ratio and increasing NiO and Cr_2O_3 abundances is demonstrated in Figure 120. The better defined relationship with NiO is caused by the fact that much of the NiO occurs in olivine and its alteration products, whereas the more poorly defined relationship with Cr_2O_3 is caused by the fact that in olivine cumulate rocks, all of the Cr_2O_3 occurs in chromite which as previously noted has a somewhat variable distribution throughout the Sill.

Table 9: Chemical Analyses and CIPW Norms, Marginal Zone

			Cycle 1				Cycle 2				Cycle 3	
	255-5	.41	213-1	271-3	272	256-1	256-2	273-2	273-1	273-3	274-1	274-4
SiO2	41.10	40.90	48.25	46.40	41.60	41.05	49.25	45.75	48.80	39.50	46.65	47.75
AlO3	8.95	7.00	14.10	15.85	7.20	4.90	3.60	10.95	16.80	6.30	4.70	15.95
Fe2O3	1.85	3.91	0.75	1.03	3.35	5.16	1.05	1.22	1.07	3.03	1.76	0.82
FeO	9.13	8.22	6.38	5.99	9.17	6.17	6.23	7.42	4.77	8.70	7.26	4.33
CaO	6.20	5.52	10.50	12.20	6.85	4.30	14.40	9.82	11.80	4.45	16.50	14.35
MgO	21.50	21.60	12.30	11.40	23.30	29.30	17.30	17.00	9.93	26.55	17.80	11.60
Ma2O	0.63	0.41	2.60	1.61	0.19	0.33	0.69	0.44	2.35	0.75	0.30	1.30
K2O	0.12	0.09	0.27	0.68	0.11	0.13	0.09	0.08	0.59	–	–	0.40
TiO2	0.54	0.42	0.39	0.42	0.25	0.31	0.41	0.38	0.34	0.18	0.35	0.18
P2O5	0.09	0.05	0.04	0.04	0.04	0.07	0.04	0.01	0.04	0.24	0.04	–
MnO	0.16	0.19	0.14	0.13	0.20	0.16	0.15	0.15	0.12	0.15	0.18	0.11
NiO	0.16	0.14	0.04	0.04	0.13	0.20	0.06	0.09	0.03	0.15	0.10	0.04
Cr2O3	0.35	0.45	0.18	0.14	0.33	0.48	0.61	0.24	0.15	0.38	0.60	0.09
H2O	6.23	7.84	4.07	3.89	6.59	7.40	3.59	5.86	3.28	9.57	3.48	2.84
S	0.01	0.02	–	0.02	0.04	0.02	0.01	0.02	0.02	0.08	0.04	0.02
CO2	0.16	0.13	0.03	0.25	0.20	0.16	0.14	0.11	0.12	0.1	0.27	0.26
-O/S	–	0.01	–	0.01	0.02	0.01	–	0.01	0.01	0.03	0.02	0.01
TOTAL	100.19	99.88	100.04	100.08	99.53	100.13	99.62	99.53	100.20	100.17	100.01	100.03
Mg/Mg + Fe + Mn	0.662	0.674	0.631	0.618	0.653	0.728	0.702	0.662	0.629	0.696	0.663	0.691
					CIPW Norms							
Q	–	–	–	–	–	–	–	–	–	–	–	–
C	–	–	–	–	–	–	–	–	–	–	–	–
Or	0.73	0.56	1.62	4.11	0.68	0.78	0.55	0.49	3.53	–	–	2.39
Ab	5.83	3.84	23.70	14.78	1.78	3.02	6.34	4.13	21.35	7.04	2.76	11.79
An	21.89	17.74	26.41	34.80	19.24	11.73	12.19	28.92	33.95	14.46	11.75	36.89
Di	6.12	7.40	16.65	17.13	10.79	7.17	41.74	14.44	16.35	4.87	48.55	23.65
He	1.24	1.00	4.33	4.35	1.92	0.47	6.77	3.11	3.67	0.73	8.89	4.39
En	27.41	22.97	2.82	1.75	21.93	26.06	18.14	27.86	4.01	14.40	4.93	4.42
Fs	5.56	3.12	0.73	0.45	3.91	1.72	2.94	5.99	0.90	2.15	0.90	0.82
Fo	23.02	33.14	17.49	16.40	29.75	39.59	7.38	10.47	11.66	44.86	15.83	12.08
Fa	4.67	4.50	4.55	4.17	5.30	2.61	1.20	2.25	2.61	6.68	2.90	2.24
Mt	2.00	4.27	0.80	1.10	3.15	5.50	1.12	1.33	1.13	3.31	1.88	0.87
Il	0.78	0.61	0.55	0.60	0.36	0.44	0.58	0.55	0.48	0.26	0.50	0.25
Cr	0.40	0.53	0.20	0.16	0.38	0.55	0.70	0.28	0.17	0.44	0.69	0.10
Hm	–	–	–	–	–	–	–	–	–	–	–	–
Ap	0.19	0.11	0.09	0.09	0.09	0.15	0.09	0.02	0.09	0.53	0.09	–
Py	0.03	0.05	–	0.05	0.11	0.05	0.03	0.05	0.05	0.14	0.11	0.05
C (Graphite)	–	0.06%	–	–	–	–	.01%	.02%	–	–	.03%	.02%

Table 10: Chemical Analysis and CIPW Norms, Lower Central Layered Zone

	249-2	294-3	258	259-1	247-2	276	277	263	265.6	265.5	265.4	265.3
SiO2	47.45	44.40	42.28	36.80	50.55	51.75	32.6	51.50	34.13	31.30	34.10	34.65
AlO3	5.30	4.95	1.50	1.45	3.35	1.75	1.75	1.70	.43	.60	.50	.25
Fe2O3	2.02	2.75	7.02	7.86	1.62	1.06	9.89	1.36	8.34	8.68	6.95	7.67
FeO	7.05	8.27	3.82	2.50	3.91	4.22	2.10	5.20	1.95	1.76	1.17	1.48
CaO	14.75	8.15	7.60	1.13	17.00	18.5	.08	17.45	.20	NIL	NIL	NIL
MgO	17.75	24.00	27.90	34.70	20.1	20.30	35.3	20.25	37.00	38.30	37.25	36.20
Ma2O	.35	.35	.14	.08	.10	NIL	NIL	.15	.06	.08	.08	.07
K2O	.09	.12	.06	.07	TRACE	NIL	NIL	.05	.03	.03	.03	.03
TiO2	.29	.34	.10	.08	.23	.10	.04	.14	.02	.02	.03	.02
P2O5	.06	.06	.06	.04	NIL	NIL	NIL	.07	NIL	NIL	NIL	.12
MnO	.16	.16	.15	.11	.14	.13	.19	.12	.16	.14	.10	.12
NiO	.09	.14	.17	.23	.07	.06	.21	.06	.24	.22	.22	.23
Cr2O3	.69	.35	.58	.65	.42	.74	.75	.70	.85	.75	.79	.85
H2O	.06	.02	.01	.01	.01	.02	.19	.01	.18	.06	.18	.22
S	.06	.02	.01	.01.	.01	.02	.19	.01	.18	.06	.18	.22
CO2	.21	.20	.32	1.08	.23	.30	1.13	.15	.93	2.25	1.66	.94
-O/S	.02	–	–	–	–	–	.07	–	.07	.02	.07	.09
TOTAL	100.03	100.07	99.51	99.55	100.15	100.15	101.16	99.50	99.65	100.19	99.59	99.66
Mg/Mg + Fe + Mn	.777	.787	.829	.865	.867	.872	.849	.867	.872	.875	.898	.884

	249-2	249-3	258	259-1	247-2	276	277	263	265-6	265-5	265-4	265-3[1]
Q	–	–	–	–	–		–	–	–	–	–	
C	–	–	–	–	–	–	1.94	–	–	.53	.41	
Or	.55	.73	.37	.44	–	–	–	.3	.19	.20	.20	
Ab	3.22	3.22	1.31	.77	.90	–	–	1.34	.59	.79	.79	
An	12.95	11.86	3.43	3.64	8.69	4.73	.44	3.81	.89	–	–	
Di	42.16	20.18	28.23	1.68	56.14	63.46	–	60.75	.15	–	–	
He	7.19	3.14	.18	–	4.34	5.45	–	4.98	–	–	–	
En	15.07	23.02	30.24	32.26	19.15	17.13	25.06	19.82	22.91	8.87	23.59	
Fs	2.57	3.57	.19	–	1.48	1.47	–	1.62	–	–	–	
Fo	10.56	26.06	27.02	52.29	6.17	4.96	61.94	4.20	66.07	80.47	67.52	
Fa	1.80	4.06	.17	–	.48	.43	–	.34	–	–	–	
Mt	2.23	2.94	1.66	5.29	1.69	1.10	4.11	1.42	3.49	3.39	1.46	
Il	.41	.49	.15	.12	.32	.14	.06	.20	.03	.03	.05	
Cr	.74	.40	.68	.78	.47	.82	.93	.78	1.03	.92	.48	
Hm	–	–	2.35	–	–	.488	–	4.00	4.39	4.38		
Ap	.13	.13	.13	.09	–	–	–	.15	–	–	–	
Py	.11	.05	.03	.03	.03	.05	.35	.03	.31	.11	.32	
Lc	–	–	–	–	–	–	–	–	–	–		
Ne	–	–	–	–	–	–	–	–	–	–		
C (Graphite)	–	–	–	–	–	–	–	–	–	–		
Cu	–	–	–	–	–	–	–	–	–	–		

Table 10: Chemical Analysis and CIPW Norms, Lower Central Layered Zone — Continued

	265-2	265-1	56-9	264	279	280	215-3	37-345	37-585	37-625	37-1035	31-150
SiO2	34.85	33.05	32.00	52.65	32.75	48.75	34.80	34.25	49.35	45.45	35.75	34.70
AlO3	.60	.55	.86	1.80	TRACE	1.95	.60	1.04	3.48	16.88	2.00	3.25
Fe2O3	7.31	9.43	6.73	1.06	7.08	.99	5.61	7.17	2.42	.56	6.45	5.84
FeO	1.60	1.86	1.74	2.97	.56	2.74	1.02	2.35	2.70	2.61	3.05	2.73
CaO	NIL	NIL	NIL	18.50	.06	17.20	.01	.01	17.80	16.3	.02	.07
MgO	37.40	35.50	36.20	20.10	38.40	22.20	38.5	38.10	20.50	13.0	36.6	36.90
Ma2O	.04	.08	NIL	.13	.30	.20	.03	.01	.14	.47	.03	.11
K2O	.05	.06	NIL	.04	NIL	NIL	NIL	NIL	.03	1.07	.05	.08
TiO2	.03	.03	NIL	.12	.02	.08	NIL	.03	.18	.07	.05	.04
P2O5	.04	.04	.02	.08	.02	.02	.03	.03	.02	NIL	.02	.02
MnO	.13	.15	.12	.09	.13	.10	.09	.10	.11	.08	.11	.07
NiO	.23	.20	.31	.05	.38	.10	.35	.29	.06	.04	.31	.27
Cr2O3	.75	.83	.90	.98	1.23	.79	.73	.59	.52	.07	.92	.35
H2O	15.80	16.60	16.53	1.60	16.9	4.21	16.10	14.77	2.88	3.44	13.68	14.41
S	.03	.07	.02	.01	.05	.14	.12	.08	.02	.02	.17	.09
CO2	.90	1.30	1.28	.20	1.68	.32	1.27	.57	.08	.12	.13	.72
-O/S	–	.03	.01	–	.02	.06	.05	.03	.01	.01	.06	.04
TOTAL	99.7	99.72	98.70	100.38	99.54	99.73	99.22	99.38	100.28	100.17	99.31	99.63
Mg/Mg + Fe + Mn	.888	.858	.916	.899	.906	.914	.918	.884	.880	.879	.879	.892

	265-2[1]	265-1[1]	56-9[1]	264	279[1]	280	215-3[1]	37-345[1]	37-585	37-625	37-1035[1]	31-150
Q				–		–			–	–		–
C				–		–			–	–		3.38
Cr				.23					.18	2.53		.50
Ab				1.15		1.81			1.25	–		1.05
An				4.16		4.46			8.76	41.05		.23
Di				65.97		62.72			61.54	29.32		–
He				2.89		2.49			1.85	2.94		–
En				21.36		8.30			11.39	–		24.32
Fs				.94		.33			.34	–		–
Fo				.39		16.63			10.73	16.09		63.14
Fa				.02		.66			.32	1.61		–
Mt				1.10		1.04			2.52	.59		6.39
Il				.17		.11			.25	.10		.05
Cr				1.08		.89			.58	.08		.42
Hm				–		–			–	–		.07
Ap				.17		.04			.04	–		.05
Py				.03		.21			.05	.05		.22
Lc				–		–			–	3.07		–
Ne				–		–			–	2.55		–
C (Graphite)	–	–	–	–	–	–	.01%	.02%	–	–	.03%	.02%
Cu	–	–	–	–	–	–		–	TRACE	.015%	–	TRACE

[1]Rocks possess insufficient SiO_2 for CIPW norm calculation

Table 11: Chemical Analysis and CIPW Norms, Upper Central Layered Zone

	31-645	31-1080	31-1280	42-455	42-585	03-340	03-380	03-730	03-1110	03-1310	03-1380	22-1620
SiO2	40.35	48.95	48.40	39.30	47.00	35.45	34.85	35.10	35.35	48.95	45.30	49.90
AlO3	3.10	4.00	15.65	3.05	8.25	2.35	2.65	2.50	3.05	3.45	20.00	4.61
Fe2O3	4.02	.56	.93	6.00	.63	6.69	6.53	7.39	5.15	2.54	.77	1.44
FeO	3.45	6.91	4.64	3.72	5.33	2.32	2.79	2.66	3.13	4.0	2.98	6.18
CaO	3.99	17.00	15.2	1.46	18.7	.03	.03	1.57	.11	16.0	16.7	14.8
MgO	33.10	18.90	10.5	34.4	15.6	36.3	35.2	35.30	36.1	20.9	9.32	20.0
Ma2O	.02	.18	1.74	NIL	.15	.03	.05	NIL	.01	.21	.61	.27
K2O	.08	.06	.31	.04	.04	.04	.03	.02	.05	.04	1.07	.04
TiO2	.09	.24	.29	.10	.42	.01	.05	.08	.07	.22	.07	.20
P2O5	.02	.02	.02	.03	.05	.02	.03	.04	.02	.03	.01	.04
MnO	.08	.15	.11	.10	.14	.10	.13	.18	.10	.14	.08	.17
NiO	.16	.05	.03	.13	.05	.27	.24	.29	.27	.05	.02	.05
Cr2O3	.26	.49	.07	.23	.44	1.02	1.14	.68	.90	.67	.05	.71
H2O	10.94	2.59	2.34	11.00	3.53	14.11	14.83	13.49	14.38	3.06	3.34	1.87
S	.12	.31	.01	.12	.02	.04	.07	.01	.06	.03	.02	.02
CO2	.16	.08	.07	.12	.05	.30	.26	.15	.30	.09	NIL	NIL
-O/S	0.5	.12	–	.05	.01	.02	.02	–	.02	.01	.01	.01
TOTAL	99.89	100.37	100.31	99.75	100.39	99.08	98.90	99.50	99.05	100.42	100.39	100.
Mg + Fe + Mn	.892	.817	.770	.869	.822	.885	.877	.868	.891	.853	.816	.823

	31-645	31-1080	31-1280	42-455	42-585	03-340	03-380	03-730	03-1110	03-1310	03-1380	22-1620
Q	–	–	–	–	–	–		–	–	–	–	–
C	–	–	–	.48	–	2.64		–	3.31	–	–	–
Or	.49	.36	1.84	.25	.24	.25		.13	.32	.24	5.99	.24
Ab	.19	1.62	14.59	–	1.37	2.9		–	.10	1.89	–	2.41
An	8.42	9.93	34.12	7.31	22.09	.02		7.22	.45	8.36	49.35	11.17
Di	9.32	50.65	27.30	–	49.66	–		.65	–	53.55	23.93	43.25
He	.22	8.76	5.87	–	7.88	–		–	–	3.14	3.75	5.92
En	27.79	8.85	–	38.44	.68	32.05		21.94	31.50	15.87	–	20.43
Fs	.66	1.53	–	.50	.11	–		–	.09	.93	–	2.80
Fo	46.56	13.49	11.58	45.04	13.71	56.58		61.29	56.56	11.30	10.59	9.56
Fa	1.11	2.33	2.49	.59	2.18	–		–	.15	.66	1.66	1.31
Mt	4.35	.59	.98	6.51	.67	4.09		5.90	5.78	2.66	.82	1.49
Il	.13	.33	.41	.14	.60	.02		.12	.11	.31	.10	.28
Cr	.30	.55	.08	.27	.50	1.22		.81	1.08	.75	.06	.79
Hm	–	–	–	–	2.27		1.56	–	–	–	–	
Ap	.04	.04	.04	.07	.11	.05		.09	.05	.06	.02	.08
Py	.32	.81	.03	.32	.05	.11		.03	.17	.05	.05	.03
Lc	–	–	–	–	–	–		–	–	–	.34	–
Ne	–	–	–	–	–	–		–	–	–	3.33	–

Table 11: Chemical Analysis and CIPW Norms, Upper Central Layered Zone — Continued

	22-1510	22-1100	22-770	69-281	22-510	22-470	22-400	22-220	23-1220	23-980	23-730	241-1	241-2
SiO2	46.70	35.10	35.90	36.7	40.20	43.95	46.60	39.00	38.40	37.90	39.30	43.10	41.55
AlO3	18.85	2.65	2.90	3.6	3.45	3.60	12.06	3.43	3.30	1.95	3.70	9.15	7.30
Fe2O3	.67	6.52	6.54	6.76	5.45	1.69	.88	6.06	6.53	6.38	5.58	1.62	2.96
FeO	3.62	2.65	3.40	2.67	4.40	8.08	4.33	6.75	3.53	3.31	5.14	11.09	7.10
CaO	16.0	1.84	1.73	.4	5.40	12.4	16.5	.65	1.76	.25	3.13	8.60	6.85
MgO	11.2	35.1	34.2	34.8	30.6	22.7	15.0	32.9	33.6	36.5	31.0	18.30	24.75
Ma2O	.70	.01	.01	NIL	.05	.20	.29	.01	.05	.05	.10	.24	NIL
K2O	.48	.05	.06	NIL	.02	.05	.61	.04	.02	.07	.09	NIL	.10
TiO2	.11	.07	.11	.08	.17	.34	.16	.10	.19	.08	.22	.52	.39
P2O5	.01	.02	.02	.02	.03	.05	.04	.04	.06	.04	.03	.04	.03
MnO	.10	.15	.15	.10	.11	.21	.12	.11	.14	.09	.13	.23	.16
NiO	.02	.29	.22	.21	.09	.06	.03	.12	.24	.11	.19	.07	.15
Cr2O3	.03	.84	.93	1.00	.59	.56	.22	.12	.89	.87	.66	.13	.25
H2O	2.06	13.51	12.61	12.82	9.05	4.61	3.39	10.92	10.72	12.16	10.12	6.04	7.66
S	.02	.02	.13	.08	.50	1.88	NIL	.10	.03	.10	.06	.01	.03
CO2	.13	.23	.16	.56	NIL	.15	.11	.32	.05	.06	.10	.83	.30
-O/S	.01	.01	.05	.03	.20	.75	–	.04	.01	.04	.02	–	-
TOTAL	100.69	99.06	99.04	99.77	99.93	99.78	100.15	100.63	99.50	99.90	99.53	99.97	99.58
Mg + Fe + Mn	.822	.878	.866	.875	.853	.805	.836	.826	.862	.877	.843	.718	.816

	22-1510	22-1100	22-770	69-281	22-510	22-470	22-400	22-220	23-1220	23-980	23-730	241-1	241-2
Q	–	–	–	–	–	–	–	–	–	–	–	–	–
C	–	–	–	3.38	–	–	–	2.60	.16	1.63	–	–	–
Cr	2,83	.32	.38	–	.12	.30	3.64	.25	.12	.43	.56	–	.62
Ab	6.25	.10	.10	–	.46	1.81	2.63	.09	.47	.47	.94	2.28	–
An	45.66	7.54	8.20	1.97	9.40	8.87	30.10	3.09	8.70	1.02	9.83	25.26	20.42
Di	22.17	1.68	.65	–	14.10	37.31	36.72	–	–	–	4.81	11.97	10.52
He	3.67	–	–	–	.28	5.05	5.12	–	–	–	.18	3.69	1.30
En	.97	19.91	25.90	39.17	26.07	8.63	.61	40.99	36.30	37.50	31.54	22.59	25.39
Fs	.16	–	–	–	.52	1.17	.09	2.78	—	–	1.18	6.97	3.14
Fo	14.04	62.25	55.81	47.05	40.36	27.02	17.13	40.28	45.35	50.57	41.78	18.63	30.47
Fa	2.32	–	–	.81	3.66	2.39	2.73	–	–	1.56	5.75	3.76	
Mt	.70	5.46	6.63	4.64	5.86	1.79	.93	6.61	6.91	6.12	6.11	1.79	3.23
Il	.15	.10	.16	.12	.24	.48	.23	.15	.28	.12	.32	.77	.57
Cr	.03	1.01	1.11	1.19	.68	.63	.25	.14	1.04	1.01	.77	.15	.29
Hm	–	1.23	.44	1.91	–	–	–	–	.14	.55	–	–	–
Ap	.02	.05	.05	.04	.07	.11	.09	.09	.13	.09	.07	.09	.07
Py	.03	.03	.22	.14	.80	2.97	–	.16	.05	.16	.11	.03	.02
Lc	–	–	–	–	–	–	–	–	–	–	–	–	–
Ne	–	–	–	–	–	–	–	–	–	–	–	–	–

[1]Rocks possess insufficient SiO_2 for CIPW norm calculation

Table 12: Chemical Analyses and CIPW Norms, Hybrid Roof Zone

	23-680	23-650	23-590
SiO2	55.05	53.80	53.30
AlO3	13.30	14.65	13.81
Fe2O3	.86	.76	1.24
FeO	7.35	8.39	10.19
CaO	8.93	6.38	6.09
MgO	6.49	7.41	5.61
Na2O	4.29	4.61	5.28
K2O	.47	.38	.23
TiO2	.80	.77	1.11
P2O5	.09	.08	.17
MnO	.13	.12	.12
NiO	.01	.01	NIL
Cr2O3	.015	.03	NIL
H2O	2.01	2.68	2.67
S	NIL	NIL	.09
CO2	.12	.07	1.07
-O/S	–	–	.04
TOTAL	99.92	100.14	99.94
Mg/Mg + Fe + Mn	.584	.590	.467

	23-680	23-650	23-590
Q	.44	–	–
C	–	–	–
Or	2.82	2.27	1.40
Ab	39.05	41.87	48.92
An	15.87	18.38	13.73
Di	14.68	6.71	6.97
He	8.09	3.79	6.07
En	10.83	11.61	4.14
Fs	5.97	6.55	3.61
Fo	–	4.30	6.26
Fa	–	2.43	5.45
Mt	.91	.80	1.34
Il	1.13	1.09	1.60
Cr	.01	.03	–
LHm	–	–	–
Ap	.19	.17	.37
Py	–	–	.13
Lc	–	–	–
Ne	–	–	–
C (Graphite)	–	–	–
Cu	–	–	–

STRATIGRAPHIC CHEMICAL VARIATIONS

Marginal zone

MZ rocks in the Great Falls area display a slight overall trend toward gradually increasing MgO/MgO + FeO + MnO ratio with stratigraphic height (Fig. 121). Within the lowermost two cyclic units, the MgO/MgO + FeO + MnO ratio decreases upwards from the olivine cumulate layer to the plagioclase cumulate layer. This suggests that the lower two MZ cyclic units developed through fractional crystallization and normal differentiation processes. The overall trend toward slightly increasing MgO/MgO + FeO + MnO ratio implies that each successive magma batch, that gave rise to an individual MZ cyclic unit, was slightly more MgO-rich than the preceding magma batch.

Within individual MZ cyclic units NiO and Cr_2O_3 display overall trends of decreasing abundance upward (Fig. 121). Cr_2O_3 displays an initial increase in all three cyclic units before decreasing upward. When viewed with the data for the overlying LCLZ rocks, Cr_2O_3 in MZ rocks seems to be part of a distinct overall trend of increasing Cr_2O_3 abundance with stratigraphic height. This overall trend in MZ rocks also reflects the more MgO-rich nature of the successive magma batches that gave rise to MZ cyclic units. S has a low abundance in MZ rocks and displays a decrease in abundance from base to top of the upper two cyclic units. Each successive cyclic unit displays a slightly greater abundance of S suggesting that successive magma batches contained slightly higher S concentrations.

Lower Central Layered Zone

LCLZ rocks display a sharp increase in MgO/MgO + FeO + MnO ratio in cyclic unit 1 followed by a gradual, progressive increase to cyclic unit 6, and the lack of variation indicates little evidence of normal differentiation due to fractional crystallization. The relatively constant nature of the MgO/MgO + FeO + MnO ratio in Great Falls area LCLZ rocks is also displayed by 462W section LCLZ rocks at the top of the LCLZ succession (Fig. 121). Thus, LCLZ rocks are characterized chemically by a high and unvarying MgO/MgO + FeO + MnO ratio. That this characteristic is not an effect of redistribution of MgO (or FeO) due to the extensive serpentinization of the olivine cumulate rocks can be seen by the fact that the same observation is duplicated by clinopyroxene cumulate rocks that are fresh and little altered. The overall trend toward increasing MgO/MgO + FeO + MnO ratio with stratigraphic height observed with MZ rocks continues through the LCLZ succession and is interpreted as reflecting the very large magma batches that gave rise to the succession of LCLZ cyclic units.

Like the MgO/MgO + FeO + MnO ratio, NiO displays a well defined increase in abundance with stratigraphic height in the olivine cumulate layer of cyclic unit 1. Within the olivine cumulate layers of cyclic units 3 and 6 and those of 462W section there is little evidence of depletion of NiO, and a case can be made for an overall trend of increasing NiO abundance in olivine cumulate rocks with stratigraphic height. Clinopyroxene and plagioclase cumulate layers, as expected, display low NiO abundances. If the distribution of NiO has not been affected by the extensive serpentinization of the olivine cumulate rocks, the apparent lack of NiO depletion with stratigraphic height in the olivine cumulate layer of cyclic unit 4 implies that fractional crystallization of olivine did not deplete the magma in NiO. The possible presence of a small amount of Ni-sulphide as indicated by the distribution of S in this layer likely does not significantly affect the overall NiO abundance in the rock. In the absence of other evidence, it may be that individual olivine cumulate layers are themselves formed from numerous magma batches, each batch containing the same or a slightly greater concentration of NiO.

Cr_2O_3 displays a well defined trend of increasing abundance with stratigraphic height from cyclic unit 1 to cyclic unit 5. This portion of the trend is unbroken by clinopyroxene cumulate layers that contain appropriate Cr_2O_3 abundances. An overall trend of decreasing Cr_2O_3 abundance is relatively persistent from cyclic unit 5, stratigraphically upward to the LCLZ-UCLZ contact. Decreasing abundance of Cr_2O_3 within individual cyclic units above cyclic unit 4 is clearly displayed. In olivine cumulate rocks that were originally dunite in composition, the level of Cr_2O_3 directly reflects the abundance of chromite in the rock. The trend of increasing Cr_2O_3 within the thick olivine cumulate layer of LCLZ cyclic unit 4 indicates that fractional crystallization and accumulation of olivine was accompanied by a progressive increase in the chromite content of the rock. The trend of Cr_2O_3, like the trends of MgO/MgO + FeO + MnO and NiO, is the reverse of what would be expected during fractional crystallization and normal differentiation of basic magma. One possible explanation is that individual olivine cumulate layers in the lower part of the LCLZ were formed from numerous successive magma batches, each batch being more Cr_2O_3-rich than the preceding batch. From cyclic unit 5 to the LCLZ-UCLZ contact, fractional crystallization and differentiation resulted in a progressive depletion in Cr_2O_3.

S abundance is low in LCLZ rocks, all but one value being less than 0.2 percent. It displays a decrease in abundance from base to top of four cyclic units and this could be interpreted as indicating that some magma batches contained small amounts of immiscible sulphide that settled out rapidly to form small concentrations at the base of olivine cumulate layers.

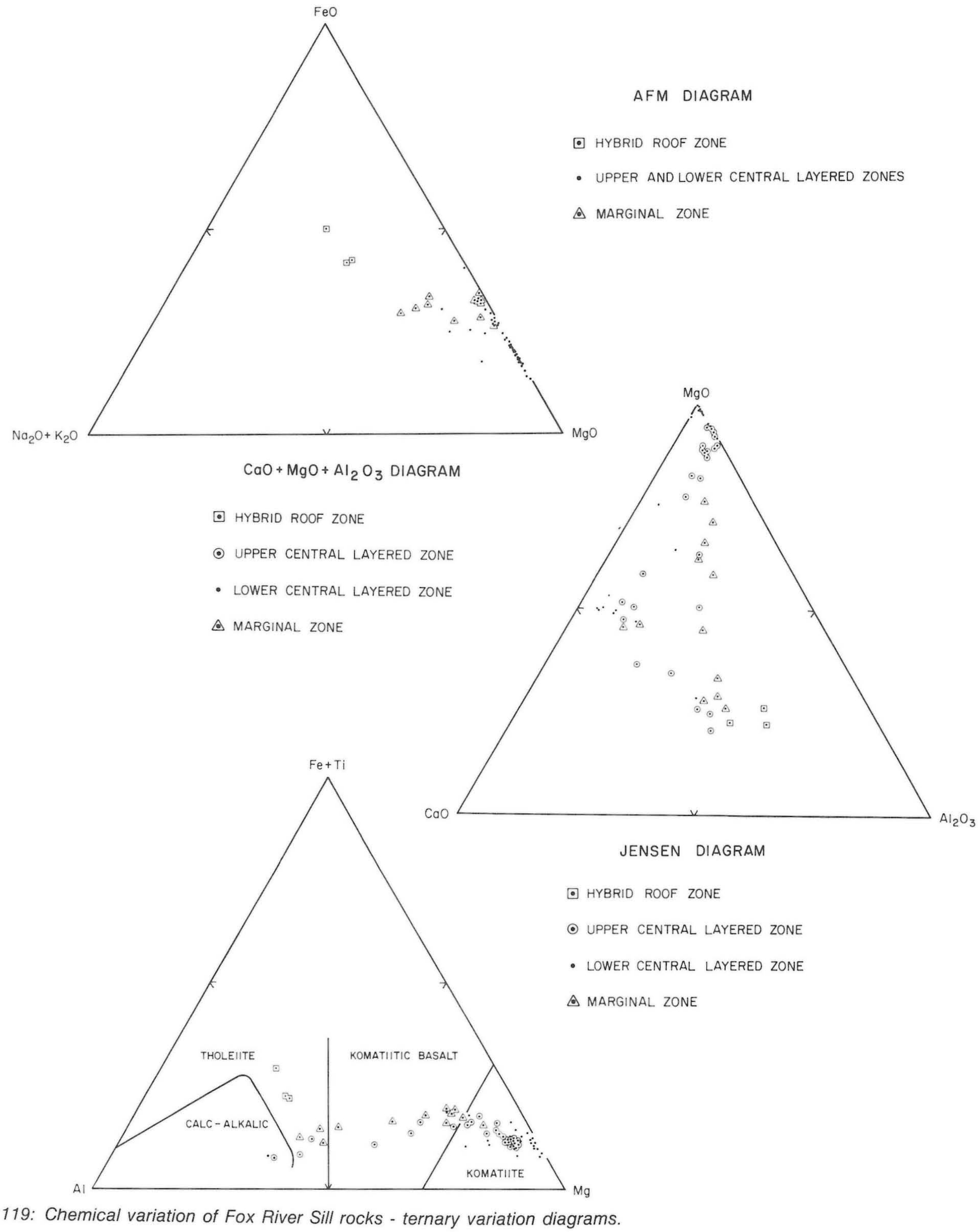


Figure 119: Chemical variation of Fox River Sill rocks - ternary variation diagrams.

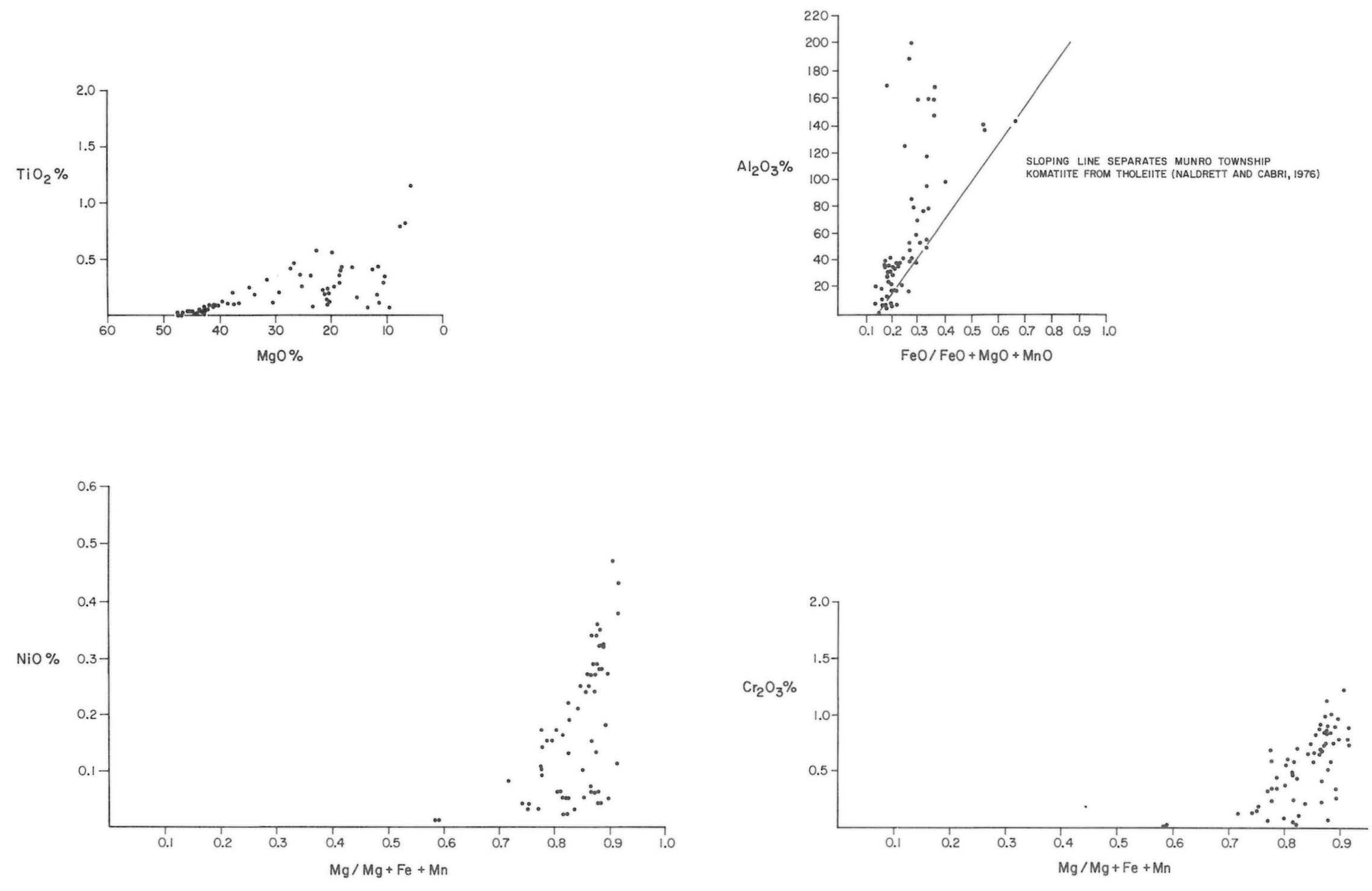


Figure 120: Chemical variation of Fox River Sill rocks - binary variation diagrams.

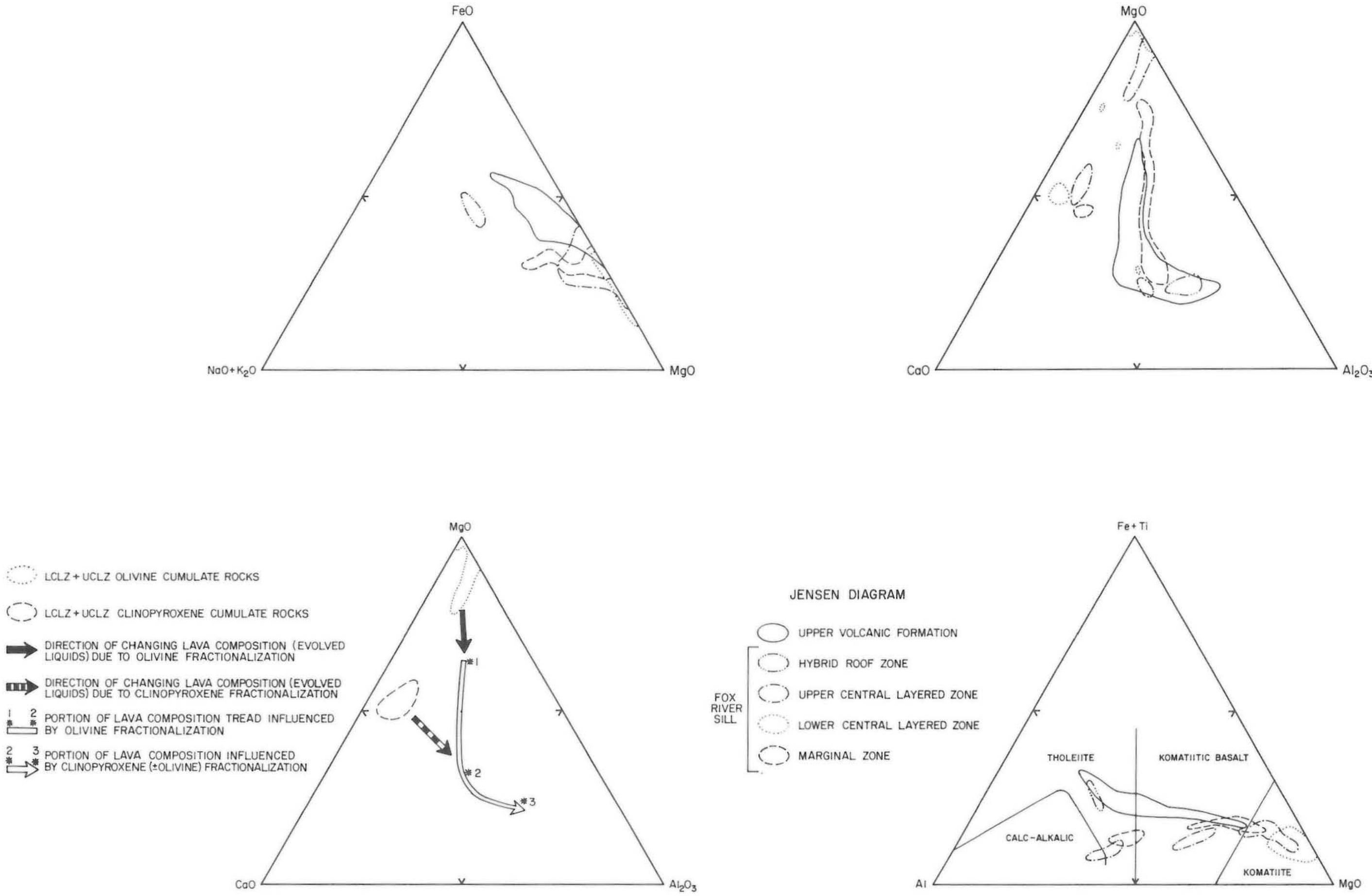


Figure 121: Stratigraphic variation of MgO/MgO + FeO + MnO, NiO, Cr_2O_3 and S in the Fox River Sill.

Upper Central Layered zone and Hybrid Roof Zone

UCLZ rocks display a somewhat lower and more variable MgO/MgO + FeO + MnO ratio, and individual cyclic units display a slight decrease in the ratio from base to top. This contrasts with the lack of variation of the ratio in LCLZ rocks. NiO displays a greater tendency to decrease in abundance within individual cyclic units with increasing stratigraphic height. The best example can be found in UCLZ cyclic unit 19 where apparently strong depletion of NiO accompanied fractional crystallization of olivine in the olivine cumulate layer. Cr_2O_3 likewise displays a decrease in abundance within individual cyclic units, and S is somewhat variable, achieving nearly 2 percent near the top of cyclic unit 19. The saw-tooth variation of Cr_2O_3 and S in the olivine cumulate layer of cyclic unit 16 may possibly reflect small-scale magma replenishment.

HRZ rocks possess the lowest MgO/MgO + FeO + MnO ratios and contain the least NiO and Cr_2O_3.

Elemental carbon

Elemental carbon has been determined chemically in 17 of the 64 analyzed samples, 12 of those samples coming from the UCLZ succession (Table 11). Graphite has not been identified in Sill rocks, although in small quantities it would be difficult to distinguish in rocks that contain other opaque phases. It should be noted that, with one exception (215-3), elemental carbon was determined from LCLZ and UCLZ drill core samples. It was also determined from one MZ hand specimen (41). The implication may be that some of the elemental carbon was due to contamination by oil or other organic compounds used in the drilling process. However, the presence of elemental carbon in two hand specimens suggests that some of the elemental carbon determined during chemical analysis may be caused by graphite in the rocks. Graphite has been observed in flow tops of certain Lower and Upper volcanic formation lava flows (Scoates, 1981) where it may represent incorporation of interflow, sulphide-bearing carbonaceous shale. The problem of curatorial contamination of samples by organic matter has been discussed by Elliott *et al.* (1982).

Graphite has been noted in a number of layered complexes and its occurrence has been predicted in the Skaergaard Intrusion (Sato and Valenza, 1980) on the basis of oxygen fugacity data that suggest substantial reducing conditions during crystallization. Graphite occurs in association with platinum group element concentrations in the Bushveld Complex and Stillwater Complex, and Elliott *et al.* (1982) suggest that reduced conditions prevailed during the formation of the Merensky Reef and the "zone of interest" in the Stillwater Complex. They suggest further that the geochemical association of primary graphite with platinum group metals as seen in the Merensky Reef, *etc.*, may have implications for platinum group metal prospecting. In this light, further work should be performed on Fox River Sill rocks to determine if graphite is present, and if it is present, to determine its distribution.

Nature of successive magma injections

The four zones of the Sill are characterized by distinctive rock units, and three of the zones are characterized by a regular arrangement of rock units. It is clear that these zones also possess unique chemical characteristics or trends. Individual MZ cyclic units represent fractional crystallization and differentiation of basic magma batches, each of which was slightly more basic than the preceding batch. The trends for MgO/MgO + FeO + MnO, NiO and Cr_2O_3 within individual MZ cyclic units are consistent with normal fractional crystallization and differentiation of basic magma. The trends of MgO/MgO + FeO + MnO, NiO and Cr_2O_3 for the lower half of the LCLZ succession are unusual, and reversed to what would be expected from "normal" fractional crystallization and differentiation of basic magma. The overall trend for the lower half of the LCLZ succession is toward a steadily progressive increase in MgO/MgO + FeO + MnO ratio, and in abundance of NiO and Cr_2O_3. This same observation can also be applied to individual cyclic units within the lower part of the zone (e.g. LCLZ cyclic units 1 and 4). The sharp increase in MgO/MgO + FeO + MnO ratio and NiO abundance, that marks the lowermost part of LCLZ cyclic unit 1 olivine cumulate layer, implies that the magma that produced the lowermost LCLZ olivine cumulates was significantly more basic than the magma that gave rise to the underlying MZ cyclic units. The continued gradual increase in Mg/Fe ratio and NiO abundance, and the well defined progressive increase in Cr_2O_3 abundance, suggests that the magma from which the rocks constituting LCLZ cyclic units 1 to 5 crystallized became progressively more basic with time. Thus, a simple continuous process of differentiation of basic magma cannot explain the variations in major and minor element chemistry observed in the lower part of the LCLZ. The explanation of how fractional crystallization was accomplished without consequent depletion of MgO and NiO may involve an almost continuous sequence of small-scale injections of fresh magma, each successive batch being at least as basic and probably slightly more basic than the preceding batch. LCLZ cyclic units 1 to 5 may have originated in this fashion, whereby the relatively thick olivine cumulate layers were formed by numerous, small-scale cyclic repetitions of the type described from the Muskox Intrusion (Irvine and Smith, 1967, Irvine, 1970a). The limited data from the upper part of the LCLZ indicate a slight overall depletion of NiO and a somewhat more pronounced overall depletion of Cr_2O_3, suggesting that fractional crystallization and "normal" differentiation were operative during the formation of these rocks.

UCLZ rocks display slight lower overall MgO/MgO + FeO + MnO ratios, and individual UCLZ cyclic units display a decrease in the ratio from base to top. Depletion of NiO and Cr_2O_3 within individual units has also been noted, and suggests fractional crystallization accompanied by "normal" differentiation. Individual UCLZ cyclic units seem to represent the fractional crystallization and "normal" differentiation of individual magma batches. The gradual decrease of MgO/MgO + FeO + MnO ratio with height combined with an indication of decreasing overall Cr_2O_3 abundance suggests the successive fresh magma batches that gave rise to UCLZ cyclic units were slightly less basic than preceding batches.

Fractional crystallization and the derivation of evolved liquids

Fox River Sill and Upper volcanic formation rocks have been interpreted as representing parts of a consanguineous magmatic suite (Scoates, 1981 and 1984). The interpretation was based on well defined progressive changes in mineralogical and chemical composition with stratigraphic height demonstrated by Upper volcanic formation rocks. The interpretation is reinforced by the coherence of fields for Fox River Sill rocks, and the fields for Upper volcanic formation rocks on binary and ternary diagrams. Upper volcanic formation lavas and sill rocks form slightly overlapping contiguous fields in the Al_2O_3 vs FeO/FeO + MgO and TiO_2 vs MgO diagrams (Fig. 122).

STANDARD AFM DIAGRAM

LCLZ and UCLZ rocks form overlapping elongate fields along the MgO portion of the MgO-FeO join (Fig. 123). These rocks represent accumulated fractionated crystals and display no significant FeO-enrichment. Upper volcanic formation rocks define a field that overlaps the more FeO-rich portions of the LCLZ and UCLZ fields and display FeO-enrichment.

CaO-MgO-Al_2O_3 DIAGRAM

The fields at the MgO corner of the CaO-MgO-Al_2O_3 diagram represent LCLZ and UCLZ olivine cumulate rocks, and the three fields near the midpoint of the CaO-MgO join represent LCLZ, UCLZ and MZ clinopyroxene cumulate rocks, respectively (Fig. 123). The majority of MZ rocks occupy an elongate field that trends away from the MgO corner toward the midpoint of the CaO-MgO-Al_2O_3 join. Fox River volcanic rocks also define a similar field in this part of the diagram, and the two fields overlap. Thus, with the exception of two clinopyroxene cumulate rocks, MZ rocks have a substantially different trend than other Sill rocks. HRZ rocks define a small field on the Al_2O_3 side of the diagram's midpoint. LCLZ olivine cumulate and clinopyroxene cumulate rocks are the least aluminous of Fox River rocks. UCLZ olivine cumulate and clinopyroxene cumulate rocks are more aluminous than their LCLZ counterparts as indicated by the positions of their respective fields, which are shifted towards the Al_2O_3 corner of the diagram. Thus, the general observation, that plagioclase is somewhat more abundant in UCLZ olivine and clinopyroxene cumulates, is illustrated by the more aluminous character of these rocks. Since both LCLZ and UCLZ rocks were formed through the same process of fractional crystallization of successive magma batches, their different compositions likely reflect different magma compositions, LCLZ rocks being derived from more primitive magma. Thus, the interpretation based on petrography, that the magma pulses that gave rise to UCLZ rocks were compositionally different to those that gave rise to LCLZ rocks, is reinforced by chemical characteristics of the rocks.

As previously noted, MZ rocks have a trend similar to that displayed by Fox River volcanic rocks on the CaO-MgO-Al_2O_3 diagram. The trend of the field representing volcanic rocks can be considered as a liquid trend (Scoates, 1981), and the fields representing LCLZ and UCLZ olivine, clinopyroxene and plagioclase cumulate rocks represent fractionated crystals. MZ rocks thus clearly represent more of a liquid trend than a trend of fractionated crystals. The observation that abundant reaction took place between early formed cumulus crystals and intercumulus liquid in many MZ rocks implies no effective separation of crystals and liquid. This lack of separation would give rise to rocks whose chemical trends would have characteristics more truly representative of the liquid compositions.

A concept has been developed whereby the Fox River Sill is considered to represent a subvolcanic chamber that produced evolved liquids, that, in turn, periodically fed lava flows of the overlying volcanic formation (Scoates, 1981 and 1984). The relationship between fractionated crystals in the chamber and evolved liquid in the overlying lava flows can be illustrated in the CaO-MgO-$Al2O_3$ diagram where the trend of the volcanic rocks is the evolved liquid trend (Fig. 123). Thus, the control of olivine and clinopyroxene fractionation on the evolution of liquids is well illustrated. In a similar fashion, Anhaeusser (1977) has illustrated the importance of olivine,

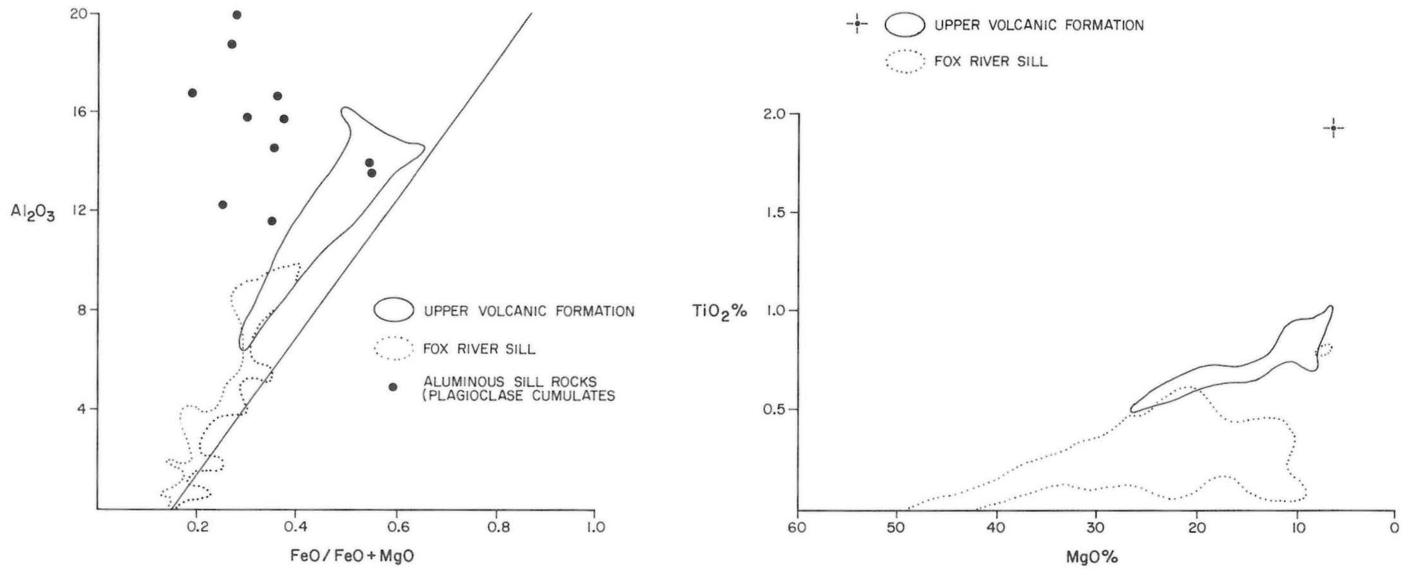


Figure 122: Chemical variation of Fox River Sill rocks and Upper volcanic formation rocks - binary variation diagrams.

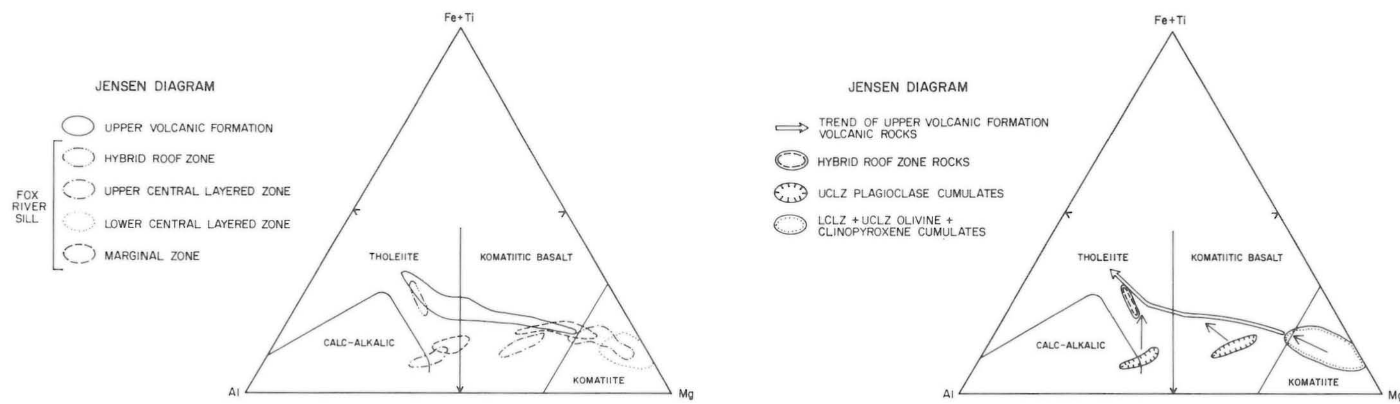


Figure 123: Chemical variation of Fox River Sill rocks and Upper volcanic formation rocks - ternary variation diagrams.

orthopyroxene and clinopyroxene fractionation in controlling the development of komatiite-type extrusives and associated tholeiitic basalt of the Archean, Roodekrans Greenstone Complex in South Africa.

JENSEN DIAGRAM

The overlapping and contiguous nature of Upper volcanic formation lavas and Sill rocks is clearly illustrated on the Jensen diagram, where LCLZ and UCLZ olivine $\pm$ clinopyroxene cumulate rocks extend the trend established by Upper volcanic formation rocks toward the Mg-corner of the diagram. Fields for UCLZ and MZ plagioclase cumulate rocks lie apart from the Upper volcanic formation field, and HRZ rocks define a field that overlaps the extension of the Upper volcanic formation field in the tholeiitic portion of the diagram. A relationship between fractionated crystals and evolved liquid can be illustrated on a simplified version of the diagram where the Upper volcanic formation field has been reduced to a line (evolved liquid trend), and where only LCLZ, UCLZ and HRZ fields have been plotted (Fig. 124). Fractional crystallization of olivine (+ clinopyroxene), that gives rise to the combined field for LCLZ and UCLZ olivine + clinopyroxene cumulates, drives the evolved liquid away from the Mg corner. Subsequent plagioclase fractionation (that gives rise to UCLZ plagioclase cumulate fields) combined with continued olivine fractionation, deviates the evolved liquid trend toward somewhat greater Fe-enrichment. Thus, the appearance of plagioclase as a liquidus phase in the main Sill magma appears to have had a substantial effect on the trend of Upper volcanic formation rocks. The close association of HRZ rocks with the termination of the evolved liquid trend suggests that these Upper volcanic formation rocks crystallized from liquid that was compositionally similar to HRZ rocks. The relationship between fractionated crystals and evolved liquid, that was previously described, utilizing the $CaO-MgO-Al_2O_3$ diagram where the effect of olivine and clinopyroxene fractionation on the evolved liquid was illustrated, is demonstrated on the Jensen diagram where the effect of olivine and plagioclase fractionation on the evolved liquid can be shown.

HRZ rocks appear to represent late-stage crystallization of magma contaminated by melted and partly melted Middle sedimentary formation roof rocks. High TiO_2 tholeiite, that has chemical characteristics similar to HRZ rocks, forms the uppermost part of the Upper volcanic formation succession. Thus, the magmatism-volcanism process apparently culminates with liquid of HRZ composition being expelled from the chamber to form lava flows.

OLIVINE-PLAGIOCLASE-QUARTZ DIAGRAM

The relationship between fractional crystallization in the Sill chamber and volcanism in the Upper volcanic formation is illustrated in the olivine-plagioclase-quartz diagram (Fig. 125). The diagram is the clinopyroxene projection of the quaternary system, olivine-plagioclase-quartz-clinopyroxene (Irvine, 1970a and 1979) that illustrates the general liquidus relations of subalkaline basaltic and related magmas at low pressure. Although Fox River volcanic rocks are demonstrably komatiitic, they display tholeiitic characteristics in being hypersthene and quartz normative and in displaying a trend toward Fe-enrichment in the standard AFM diagram (Scoates, 1981). Sedimentary rocks interpreted to have been less than 1 km thick formed the roof of the Sill during intrusion of magma. Consequently, fractional crystallization took place under low pressure conditions. The chemical characteristics of the volcanic rocks and the low pressure fractional crystallization of Fox River Sill magma suggest that utilizing a portion of the olivine-plagioclase-quart-clinopyrozene system for demonstrating relations among Fox River igneous rocks is not unreasonable. The plotted points are ratios of CIPW molecular norms.

The shape of the fields representing Lower and Middle zone Upper volcanic formation rocks demonstrates the dominance of olivine and clinopyroxene fractionation on derived liquids. Upper zone volcanic rocks are plagioclase-phyric, and the position of the field they define in the diagram is due to appreciable plagioclase fractionation. LCLZ and UCLZ olivine and clinopyroxene cumulates represent the fractionally crystallized products that contributed to the trend of Lower and Middle zone, Upper volcanic formation rocks. UCLZ plagioclase cumulate rocks represent the accumulation of fractionally crystallized plagioclase that in turn determined the position of Upper volcanic formation Upper zone plagioclase-phyric lavas. Thus, the relationship between the progressive change in liquidus minerals in the Sill magma, and the character of the evolved liquids, as demonstrated by the progressive chemical changes in the associated Upper volcanic formation lavas, is clearly illustrated.

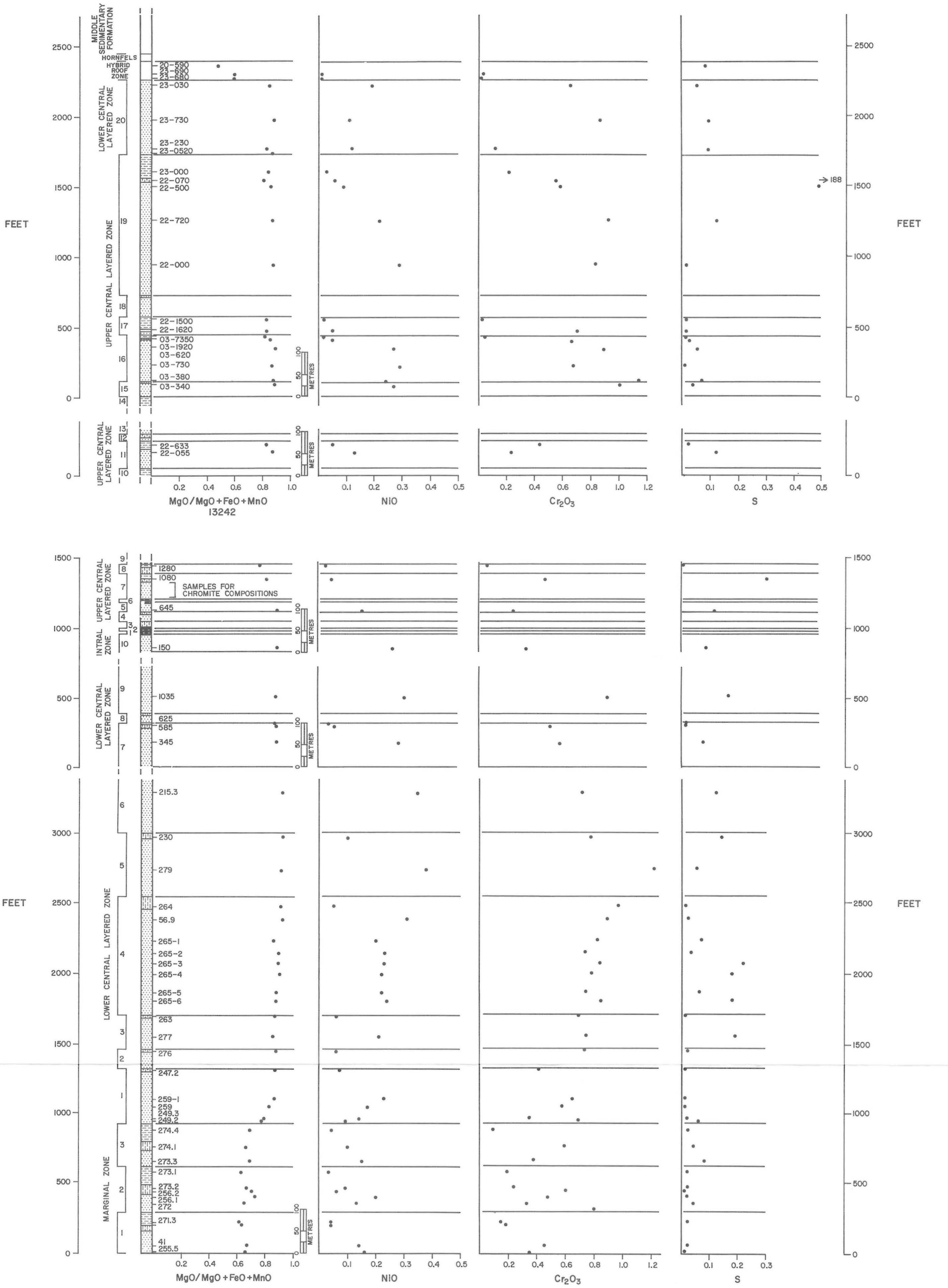


Figure 124: Jensen diagram.

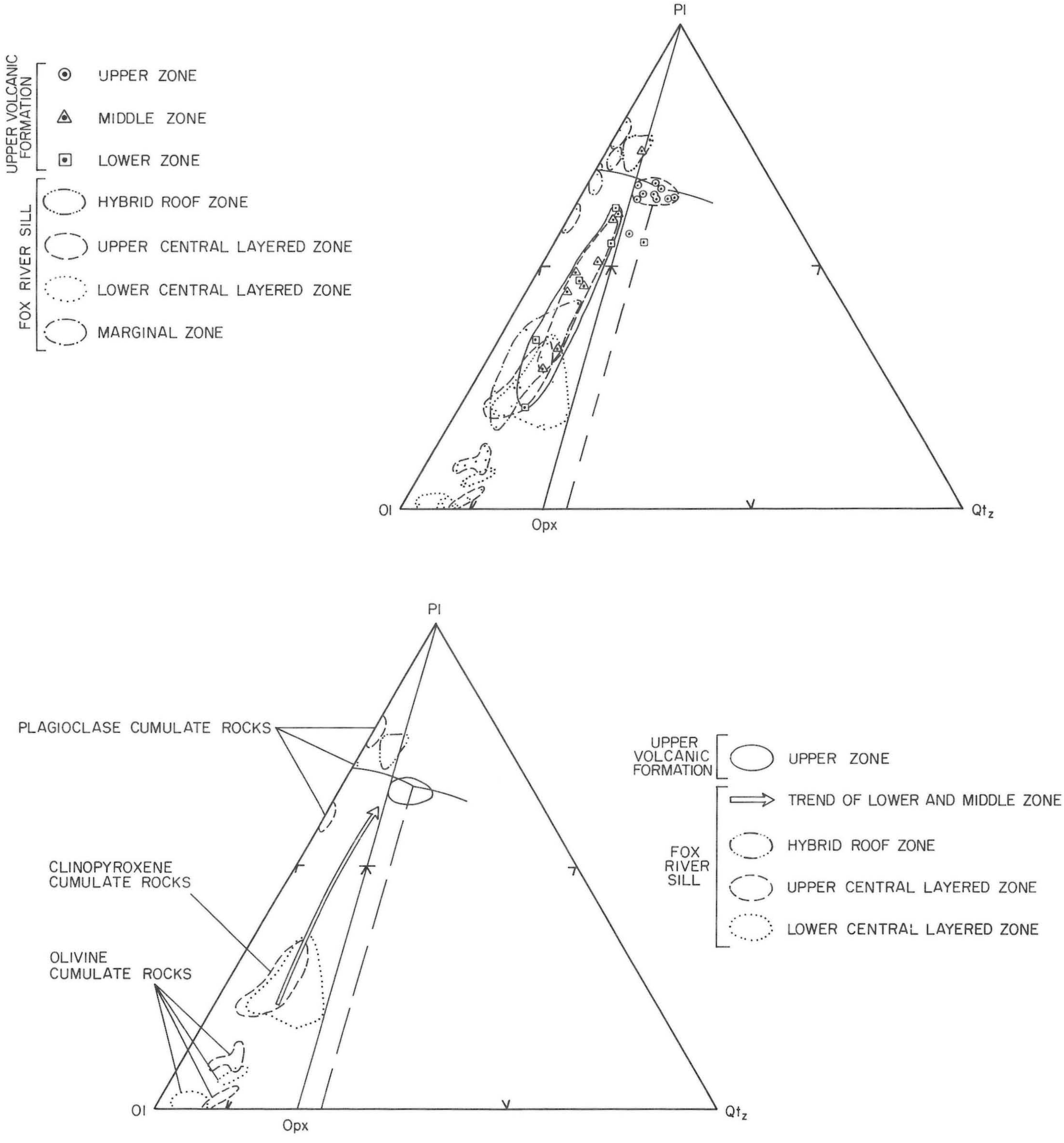


Figure 125: Olivine-plagioclase-quartz diagram.

The Fox River Sill consists of two lobes, each approximately 70 km long, that are separated by a gap of 10 km. Distinctive aeromagnetic anomaly patterns, east of the east lobe, indicate that the intrusion likely extends for a further 120 km, producing a probable overall length of 270 km. Thus, the west lobe of the Sill represents a portion of a much larger major stratiform intrusion. The Sill is slightly more than 2 km wide along the western portion of the west lobe.

Observation of shallower dips in LCLZ and UCLZ successions compared with the near vertical dip of MZ rocks as measured in the Great Falls outcrop area suggests that the intrusion may possess a lopolithic shape in cross-section (Fig. 126). The asymmetrical shape of ground magnetic anomalies associated with magnetic layers that are underlain and overlain by nonmagnetic layers implies northerly dips of the main layered series. In like fashion, the residual asymmetrical Bouguer gravity profile (Gibb, 1968) supports an overall northerly dip for the intrusion (Fig. 126).

The intrusion has been divided into four zones; from base upward these are: Marginal Zone (MZ-270 m)[1], Lower Central Layered Zone (LCLZ - 875 m), Upper Central Layered Zone (UCLZ - 925 m), and Hybrid Roof Zone (HRZ - 50 m). The intrusion is characterized, in part, by an overall predominant ultramafic composition, more than 75 percent of the Sill being composed of olivine-rich, olivine cumulate rocks (Table 13). LCLZ displays the most ultramafic character being composed of approximately 90 percent olivine-rich, olivine cumulate rocks (Table 13). UCLZ is slightly less ultramafic, being composed of approximately 75 percent olivine cumulate rocks (Table 13). MZ (as constituted in the Great Falls outcrop area on the Fox River) is the least ultramafic zone, olivine cumulate rocks compose slightly more than 40 percent of the zone (Table 16).

[1] Thicknesses were determined from the Great Falls outcrop area (MZ + LCLZ), from 462W section (LCLZ + UCLZ) and from 208W section (UCLZ + HRZ). Individual zones display a variation in thickness from place to place along strike.

Table 13:
Percentage† of olivine, pyroxene and plagioclase cumulate rocks‡ in the Fox River Sill

	Marginal Zone	Lower Central Layered Zone	Upper Central Layered Zone	TOTAL
Olivine cumulate	44.0	91.2	75.6	77.7
Pyroxene cumulate	18.2	8.4	8.2	9.6
Plagioclase cumulate	37.7	0.4	16.2	12.7

† Percentages are based on the thickness of layers in the composite stratigraphic section used to demonstrate stratigraphic chemical variations.
‡ HRZ rocks are not cumulate and therefore not included.

All zones, except the HRZ, are characterized by cyclic units that are essentially sequences of rocks composed of cumulus minerals that correspond to the order of appearance of phases crystallized from basic magma with decreasing temperature. Each cyclic unit is interpreted to represent the product of a separate fractionated magma batch. Variations in thickness of zones reflect variations in the number of layers and cyclic units within zones; however, it is probable that the Sill consists of at least 70 layers[2] and 35 cycle units.

[2] Layers less than 1 m thick have not been included. (Does not include small-scale rhythmic layers nor the macro-rhythmic layers of the MZ Banded Layer. Does not include grain size graded layers).

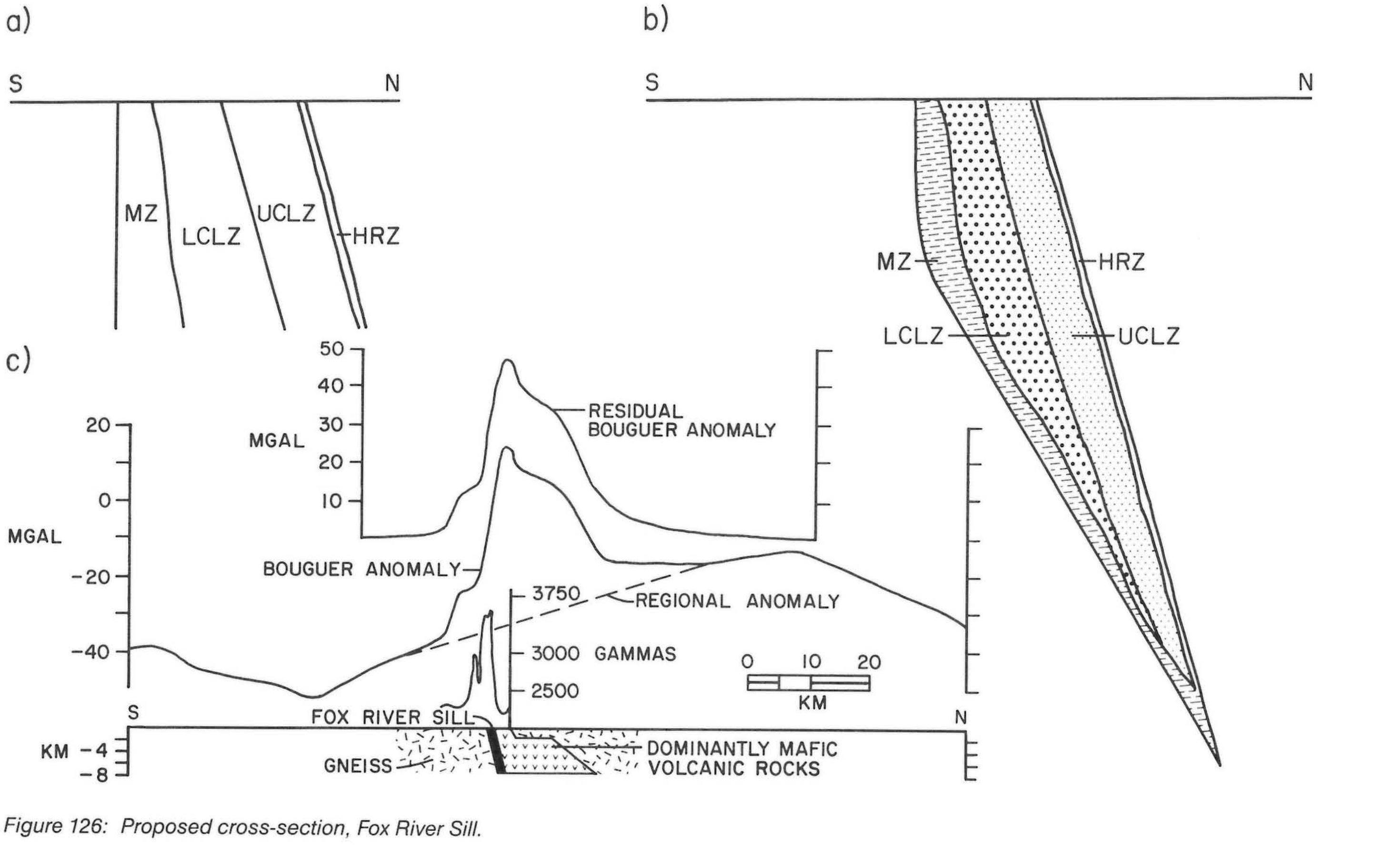


Figure 126: Proposed cross-section, Fox River Sill.

MARGINAL ZONE

The MZ of the intrusion is characterized by repetitions of olivine, clinopyroxene and plagioclase cumulate layers that constitute cyclic units. The number of cyclic repetitions is variable from area to area. The eastern and western extremities of the west lobe possess noncyclic MZ rocks, the former being olivine cumulate and the latter plagioclase cumulate. Non-cyclic olivine cumulate MZ rocks also occur at the 'pinch' portion of the pinch-and-swell structure. MZ repetitive cyclic units represent the fractional crystallization and consequent differentiation of successive intrusions of basic magma. Abundant reaction between cumulus phases (particularly olivine) and intercumulus magma, as noted in the well preserved textures, reflects the imperfect separation of liquid and crystals. This is caused by rapid cooling of the magma. The complete uninterrupted nature of the majority of cyclic units suggests an apparently "closed" system, whereby each intrusion of magma fractionally crystallized and differentiated without addition or subtraction of liquid. The poor separation of cumulus crystals and liquid, and the complete fractional crystallization and differentiation of successive magma intrusions are clearly illustrated in certain chemical plots.

The complete uninterrupted nature of MZ rocks is broken in 722E section by the Banded Layer composed of macrorhythmic, as well as small-scale rhythmic layers. Here, evidence of magmatic currents can be found in the bull's-eye patterns of olivine c-axis fabric diagrams, the substantial range of olivine compositions within the layer, the possible 'reworking' of poikilitic orthopyroxene crystals and the rhythmic layers themselves. The dimensions of the Banded Layer are not known, but it has some of the attributes of trough bands of the kind described from the Skaergaard Intrusion (Irvine and Stoeser, 1978). These are interpreted to have formed through successive density currents, each of which deposited a layer in the trough.

Non-cyclic MZ rocks are probably related to magmatic injections that postdate cyclic MZ rocks. These later injections, which are part of the main magmatic event, represent a much greater volume of magma than the injections that produced cyclic MZ rocks. Consequently, these injections would cover a larger area than cyclic MZ rocks, and locally would be in direct contact with rocks of the host Middle sedimentary formation. Cyclic MZ rocks represent a distinct, early event in the magmatic history of the Fox River Sill, whereas noncyclic MZ rocks may represent marginal phases of the later, main magmatic event.

Observation of changing dip within MZ cyclic units indicates that dip change was taking place during accumulation of MZ rocks. This may reflect progressive down-warping of the central part of the intrusion caused by successive magmatic impulses along the intrusion axis.

The presence of individual cyclic units with olivine cumulate rocks at the base indicates that crystallization proceeded, not from the contact inward, but from the top, with crystals accumulating from the bottom up. This suggests that at the time of formation of MZ rocks, the greatest heat loss was through the roof of the intrusion, not through the floor. Cyclic units that have olivine cumulates at the base of individual units are apparently uncommon in the marginal zones of other large stratiform intrusions. The Muskox and Stillwater intrusions have marginal zones that progressively grade from gabbro at the contact through to ultramafic lithologies into the intrusion. The Hartley Complex of the Great Dyke, Zimbabwe, possesses a 2 to 5 m thick norite that is considered to represent the basal unit of the complex (Wilson, 1982) and the Bushveld Complex has a marginal group composed of norite that apparently represents a Sill phase that preceded the main intrusion (Wager and Brown, 1968; Coertze, 1970). The disposition of marginal zone rocks in the Muskox and Stillwater intrusions implies crystallization from the contact inward due to excessive heat loss through the margins. In the Bushveld Complex, fine grained quartz norite that becomes coarser grained and less quartz-bearing upward (inward) also suggests simple crystallization of magma at the contact due to heat loss through the wall of the intrusion. The unique character of the marginal zone of the Fox River Sill as compared with marginal zones of other major stratiform intrusions is attributed to a different mode of origin.

Although the length of individual MZ cyclic units is unknown, their length to thickness ratio is large, possibly 100:1. Because the width of the intrusion is unknown their area to thickness ratio is unknown, although it can be assumed to be large. The reason these individual, thin, sill-like intrusions fractionally crystallized and differentiated rather than chilled to form uniform, fine grained mafic igneous rocks is unclear, but may be related to their environment of crystallization.

LOWER CENTRAL LAYERED ZONE

The LCLZ represents the lower half of the main layered series of the Sill. It is composed of a simple succession of cyclic units, each of which comprises a lower, relatively thick olivine cumulate (serpentinized dunite) layer, and an overlying, relatively thin clinopyroxene cumulate (olivine clinopyroxenite) layer. At least 10 such cyclic repetitions occur. Plagioclase cumulate rocks are rare, and are found only at the top of the zone where they form thin layers that cap cyclic units. Throughout the zone the assemblage of rocks is mineralogically simple, olivine and clinopyroxene being the predominant silicate phases. Chromite is an ubiquitous phase in the olivine cumulate layers throughout the zone.

The olivine cumulate-clinopyroxene cumulate cyclic units represent incomplete or beheaded cyclic units (Jackson, 1970). Complete cyclic units would possess a capping plagioclase cumulate layer caused by plagioclase ultimately following clinopyroxene as a liquidus phase. The absence of plagioclase cumulate rocks throughout most of the LCLZ succession suggests that plagioclase was prevented from becoming a liquidus phase by the influx of fresh basic magma into the chamber; this results in olivine replacing clinopyroxene as a liquidus phase. Each successive unit, therefore, is considered to represent the influx of a fresh magma batch into the chamber.

The intervals of successive size graded layers that characterize the thick olivine cumulate unit at the eastern end of the west lobe may represent deposition through the action of density currents, each of which may represent successive magmatic impulses. If such is the case, olivine was a suspended phase during intrusion in this part of the Sill. Each size graded layer could thus represent a magmatic cyclic unit similar to those represented by the olivine cumulate-clinopyroxene cumulate cyclic units.

The LCLZ succession represents accumulation of an enormous volume of olivine, derived through fractional crystallization of successive magma batches. Chemical variations indicate that the lower two-thirds of the LCLZ succession displays trends in MgO/MgO + FeO + MnO ratio, NiO and Cr_2O_3 that are reversed to what would be expected through fractional crystallization and normal differentiation of basic magma. Not only is a decrease in MgO/MgO + FeO + MnO ratio and a decrease in NiO and Cr_2O_3 abundance lacking with stratigraphic height, but also throughout most of the lower two-thirds of the zone MgO/MgO + FeO + MnO increases and NiO and Cr_2O_3 become progressively enriched with increasing stratigraphic height, including within individual cyclic units. One possible explanation is that this part of the LCLZ succession fractionally crystallized and accumulated from magma that progressively became more basic (ultrabasic) through almost continuous additions of fresh magma batches, each successive batch being more basic (ultrabasic) than the preceding batch.

There is evidence of depletion of Cr_2O_3 and NiO within individual cyclic units, after one-half to two-thirds of the zone was accumulated. Thus, during accumulation of the upper part of the zone, fractional crystallization and differentiation of magma produced depletion of Cr_2O_3 and NiO.

With a few exceptions, sulphur displays its greatest concentration at the base of cyclic units including those of the LCLZ. Concentration of sulphur at the base of macrorhythmic layers in the Jimberlana intrusion has been used to argue strongly for an origin of those layers by multiple injection of magma (Campbell, 1977). A similar interpretation is made here to support the concept of introduction of fresh magma batches into the chamber to account for the repetition of cyclic units.

The macrorhythmic units of the Jimberlana intrusion are associated with a reversal in mineral variation and in Ni-Cr trends (Campbell, 1977). These reversals are also accounted for by new influxes of magma that mix with the differentiated magma in the chamber making it more ultrabasic and raising its temperature. This results in repetitions of the mineral assemblage and the reversal in trends observed at the base of these units.

Jackson (1970) pointed out that the cumulus phases in the cyclic units in the lower part of the Stillwater ultramafic zone are progressively enriched in MgO with respect to FeO. He has also suggested that the same situation may occur in the Bushveld Complex and Great Dyke. Thus the lack of MgO-depletion (and consequent FeO-enrichment) in the lower zones of major stratiform intrusions may be the rule rather than the exception.

UPPER CENTRAL LAYERED ZONE

The UCLZ represents the upper half of the main layered series of the Sill. In contrast to the simple succession of cyclic units that compose the LCLZ succession, the UCLZ is composed of a variety of units. These units give rise to a number of different cyclic units, including those composed of olivine cumulate-clinopyroxene cumulate, olivine cumulate-clinopyroxene cumulate-plagioclase cumulate, clinopyroxene cumulate-plagioclase cumulate, olivine cumulate-plagioclase cumulate and olivine cumulate-orthopyroxene cumulate layers. In the western part of the intrusion the UCLZ comprises at least 20 such cyclic units composed of at least 40 layers.[1]

UCLZ olivine cumulate rocks possess more abundant postcumulus phases than their LCLZ counterparts. One of the distinguishing characteristics of UCLZ rocks is the relatively greater abundance of plagioclase. Plagioclase cumulate rocks cap many cyclic units, and plagioclase becomes a prominent postcumulus phase in olivine cumulate rocks. Orthopyroxene is a common although not abundant constituent, occurring as large poikilitic crystals and forming a zone of thin cumulate layers towards the top of the zone.

Lineate lamination of olivine and clinopyroxene c-axes, examples of grain size graded layers, and the presence of numerous cm-scale plagioclase cumulate layers interrupting an otherwise continuous succession of olivine cumulate rocks suggest deposition of crystals in magma current regimes.

The overall composition of UCLZ rocks is different from LCLZ rocks implying that the magma batches were significantly different in composition to those that produced the LCLZ succession. Disseminated chromite appears to be more abundant in UCLZ rocks as does disseminated sulphide, and these observations further demonstrate the compositional differences. The apparent abruptness of the LCLZ-UCLZ contact suggests that the change in magma composition represents a major event in the magmatic history of the intrusion.

Despite the greater abundance of plagioclase and orthopyroxene in the UCLZ succession and the greater abundance of postcumulus phases in UCLZ olivine cumulate rocks, these rocks display only slightly lower overall MgO/MgO + FeO + MnO ratio than LCLZ rocks. Within the UCLZ, this ratio displays a very slight decrease with stratigraphic height. The ratio displays a slight decrease from base to top of individual UCLZ cyclic units, and this is accompanied by depletion of NiO and Cr_2O_3. As previously noted, depletion of NiO and Cr_2O_3 within individual cyclic units begins approximately one-half to two-thirds the way up the LCLZ succession. Thus, although the LCLZ-UCLZ contact is the most dramatic, the change in character of individual cyclic units, whereby fractional crystallization is accompanied by normal differentiation of magma, occurs stratigraphically below this major contact.

The dramatic change in the character of the layered succession above the UCLZ-LCLZ contact likely represents a change in composition of successive magma batches. The greater abundance of sulphide is thought to reflect the change in magma composition. The increasing ratio of total pyroxene to olivine and plagioclase to olivine may also reflect the change in magma composition, but it may also indicate an increasing contribution of the overlying residual magma column to the liquidus phases that are possible during fractional crystallization of individual magma batches. The increasing contribution of the residual magma column may reflect smaller volumes of successive magma batches. A combination of these factors likely contributes to the change in character of the layered succession that takes place at the UCLZ-LCLZ contact.

HYBRID ROOF ZONE

The HRZ represents a heterogeneous suite of rocks that separates UCLZ cumulate cyclic units from contiguous hornfels derived from Middle sedimentary formation rocks. The zone consists of quartz- and granophyre-bearing Sill rocks, granophyre and aplite, and inclusions of Middle sedimentary formation rocks that have been largely converted to hornfels. Within the sedimentary roof rock sequence, a progression can be seen from hornfels to spotted hornfels that possess limited preserved devitrification textures, to melt rocks characterized by a dense cluster of dendrites and spherulites composed of fibrous quartz. Granophyre and aplite composed of interlocking albite crystals, with abundant quartz and granophyre, represent the end product of the progression. Thus, there seems little doubt that the quartz- and granophyre-bearing mafic rocks owe their origin entirely to contamination of Sill magma through melting of roof rocks.

HRZ rocks possess the lowest MgO/MgO + FeO + MnO ratios and contain the least NiO and Cr_2O_3 of the analyzed Sill samples.

ORIGIN OF LAYERS AND CYCLIC UNITS

Variations in major and minor element chemistry apparently dispel the notion that the Fox River Sill layered succession was derived through a simple continuous process of differentiation. However, despite the numerous cyclic repetitions, there is a gradual progressive decrease in the proportion of olivine to total pyroxene and olivine to plagioclase stratigraphically upward, suggesting the imprint of a grand scheme of differentiation. The major and minor element chemical variations, and repetitive cyclic units, on the other hand, suggest repeated injections of fresh magma batches into the chamber. These concepts are apparently conflicting, yet the intrusion seems to possess characteristics that suggest that it resulted from a combination of processes.

[1] Layers less than 1 m thick have not been included. (Does not include small-scale rhythmic layers, nor size graded layers).

Individual cyclic units composed of layers of cumulus crystals represent units whose character is predominantly controlled by the character of the injected fresh magma batches from which they were derived. The greater abundance of plagioclase in UCLZ rocks, as a postcumulus phase in olivine and clinopyroxene cumulate rocks, and as a cumulus phase forming plagioclase-rich cumulate layers that cap UCLZ cyclic units, may reflect some mixing of the overlying residual magma column with injected magma batches by the process of double diffusive convection. The large proportion of olivine cumulate rocks to plagioclase cumulate rocks in the UCLZ suggests that the contribution of the residual magma column to the fractional crystallization of individual UCLZ magma batches was relatively small. This may imply either that the volume of residual magma was relatively small or alternatively that it possessed a relatively basic composition. Estimating the volume of the residual magma column is complicated by the concept of periodic discharge of magma to the surface.

The thickness of individual cyclic units is interpreted to be a direct measure of the column or volume of magma that fractionated to produce the unit. The thick olivine cumulate layers that contribute to the thick cyclic units of the lower two-thirds of the LCLZ represent fractional crystallization of large volumes of magma. The thin olivine cumulate layers that form the base of the thinner cyclic units of the upper part of the LCLZ and the majority of the UCLZ represent fractional crystallization from much smaller volumes of magma. The change in minor element variation (Ni and Cr_2O_3) coincides with the change in thickness of cyclic units and consequently may simply reflect more extreme differentiation caused by fractional crystallization of smaller volumes of magma. As noted, the difficulty of estimating the volume of residual magma at any given time during the magmatic history of the intrusion is compounded by the probability that some of the magma reached the surface to form lava flows (Scoates, 1981).

DOUBLE DIFFUSIVE CONVECTION

Double diffusive convection (Turner and Gustafson, 1978; McBirney and Noyes, 1979; Irvine, 1980) is a process whereby a magma column becomes gravitationally stratified, so that it is subdivided into a number of horizontal layers. Heat and matter are transmitted in a step-like fashion through the magma column by diffusion across layer boundaries and by convection within layers. As Irvine (1980) pointed out, the important characteristic of double diffusive convection is that not only does it transfer heat from the bottom of the liquid column to the top (and sides), it also is a highly effective mechanism for mixing the contrasting initial liquids and transmitting other compositional changes.

The progressive change in mineralogical and chemical composition with stratigraphic height, noted in Upper volcanic formation lavas that overlie and are separated from the Sill by a few hundred metres of sedimentary rocks, suggests derivation of the lavas from a subvolcanic chamber in which differentiation was taking place. The Fox River Sill is considered as representing the chamber on the basis of the continuity of mineralogical and various chemical parameters between the flows and the Sill (Scoates, 1981). Thus, the lava flows of the Upper volcanic formation are considered to represent a succession of liquids derived from the chamber at different times in its evolution. The progressive and apparently uninterrupted mineralogical and chemical changes in lava compositions suggest that the liquids from which they were derived became progressively more evolved with time. The entire succession of rocks in the Sill (except the HRZ), however, is characterized by cyclic repetitions that imply repeated magma injections. Thus, the chamber appears to have consisted of magma that evolved with time, and periodic or successive introductions of fresh magma that produced the pile of fractionated crystals. These two liquids somehow must have been physically separated. The process of double diffusive convection could account for the necessary physical separation of evolved or differentiated residual liquid and the liquid undergoing fractional crystallization (Fig. 127). The diagram (modified after Irvine, 1980) illustrates an impulse of hot dense magma flowing laterally (parallel with the intrusion axis) along the floor of the intrusion, as represented by the top of the pile of accumulated crystals, and below the column of somewhat cooler, less dense residual magma.[1] The principal features of the intrusion, the cyclic repetition of groups of layers, is directly related to the fractional crystallization of the periodically introduced fresh magma batches. Within the column of residual magma . . . "composition effects associated with fractional crystallization at the bottom, liquid blending at intermediate levels, and contamination at the top are transmitted upward and downward (as appropriate) by the convection and diffusion" (Irvine, 1980). The processes of diffusion and convection would lead to progressively evolving liquid within the residual magma column. Periodic discharge of this liquid to the surface would give rise to progressively more evolved lavas of the kind represented by the Upper volcanic formation (Scoates, 1981). The progressive decrease of MgO/MgO + FeO and increase in TiO_2 with increasing stratigraphic height noted in Upper volcanic formation lavas (Scoates, 1981) suggests that homogenization of the residual magma column by double diffusive convection process was not accomplished.

Recently Irvine (1980, 1982) has suggested that cumulate layers in layered intrusions may be formed by lateral accretion rather than just by stratigraphic accumulation. The proposed mechanism involves a concept whereby whole sequences of cumulate layers form simultaneously by growing laterally into a stratified succession of magmatic liquid layers undergoing double diffusive convection.

MAGMATISM - VOLCANISM CONCEPT

The relationship between volcanism and magmatism as earlier proposed (Scoates, 1981) can be refined in light of the double diffusive convection concept. In the earlier proposal, a direct relationship between magma replenishment in the form of fresh magma batches entering the chamber and the flushing out of evolved magma that formed lava flows was considered likely. Successive influxes of magma would give rise to inflation of the chamber and a consequent increase in fluid pressure. Eventual rupture of the overlying sedimentary cover would result in discharge of magma to the surface. Thus, minerals on the liquidus at the termination of a cyclic unit within a certain zone of the Sill were compared with liquidus minerals of lavas in a certain zone of the overlying lava flows (Scoates, 1981). The relationship between influxes of fresh batches of magma and the column of cooler magmatic liquid that lies above is not likely as direct, and hence the compositional relationship between accumulating crystals at the floor of the intrusion and magmatic liquid at or near the top of the column of residual magma would be related by the rates of diffusion across layer boundaries in the stratified liquid column. The liquid that erupts to form lavas was likely derived from the upper part of the column of residual magma. The relationship between minerals on the liquidus at the termination of a particular cyclic unit in the Sill and liquidus minerals in the overlying time-equivalent Upper volcanic formation lava flow is not as direct, the latter reflecting the composition of the upper part of the residual magma column at the time of eruption.

[1] It appears that three, somewhat separate but related magmatic liquids were all evolving at any given time. Fractional crystallization of individual fresh magma batches leads to differentiation of those liquids. The overlying residual magma column is constantly changing composition through fractional crystallization of the underlying fresh magma batch, contamination by roof rocks at the top, and liquid blending at intermediate levels. The intercumulus magma that occurs within the pile of cumulus crystals differentiates as it crystallized, represents the third magmatic liquid.

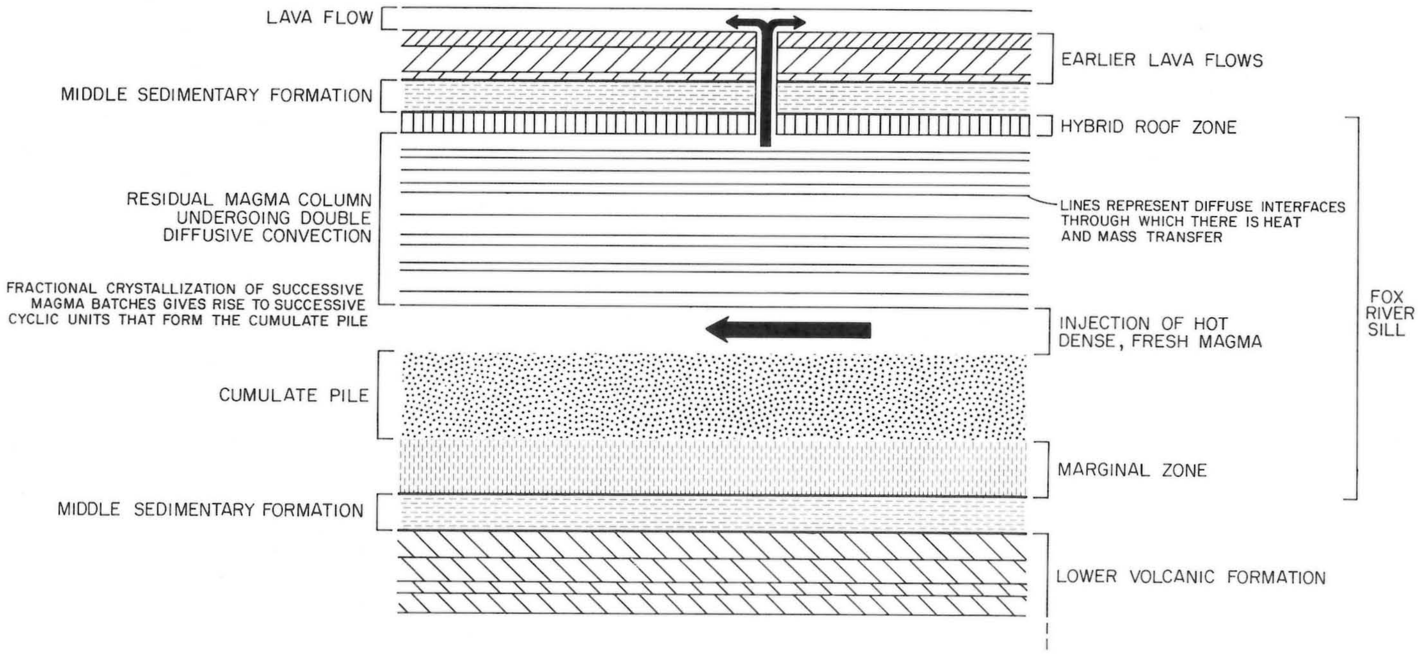


Figure 127: Sketch illustrating possible relationship between influx of fresh magma, residual magma column and eruption.

The composition of the upper part of the residual magma column in the Sill chamber at any given time is a function of the sum total of fractional crystallization, changes in composition through melting of roof rocks and the volume of liquid lost to volcanic eruptions. Changes in diffusion rates across layer boundaries in the stratified liquid would also play a significant role in the composition of the upper part of the column of residual magma. Loss of residual magma through eruption may contribute to a closer relationship between fractionating crystals at the floor of the intrusion and the composition of the overlying remaining residual magma. The conclusions reached in the previous evaluation of the relationship between magmatism and volcanism are not drastically changed by the concept of double diffusive convection, and are modified only by recognizing that the liquidus minerals of flows may not be directly related to minerals that are fractionally crystallizing in the Sill at a specific time. The liquidus mineral(s) of a lava at a specific stratigraphic position within the Upper volcanic formation reflects the result of fractional crystallization within the Sill prior to eruption, as well as other contributing factors.

Similar relationships between lavas and underlying magma chambers have been proposed. The recognition of evolved lavas along ocean ridges has led to the general hypothesis that these lavas formed through low pressure fractional crystallization of primitive magma in high level, open system magma chambers (O'Hara, 1977; O'Hara and Matthews, 1981). Huppert and Sparks (1980) stated that detailed pertological and geochemical studies of igneous rocks, together with geophysical investigations of active volcanoes, have provided persuasive evidence that many such magma chambers are periodically replenished by an influx of new and generally hotter primitive magma from depth. Sparks *et al.* (1980) stated that an implicit consequence of the periodically replenished magma chamber model is that many, perhaps most lava eruptions on the ocean floor are the consequence of influx of new magma into crustal chambers. They further stated that for the Icelandic volcanoes evidence indicates that influx of magma and eruption of lava are triggered by episodes of crustal rifting. Thus, in the case of the oceanic regime, there is ample evidence of a direct relationship between volcanism and fractional crystallization in underlying chambers of the kind postulated for the Fox River Belt.

Baragar (1977) has stated that large layered instrusions accompanying plateau basalt successions are magma chambers to which at least some of the variation in composition of surface flows can be attributed. Phinney (1970) has demonstrated the influence of fractionation in the Duluth Gabbro on the compositions of overlying Keeweenawan flows. The Muskox Intrusion of the Northwest Territories is assumed to be a model of the magma chamber that fed the Coppermine River basalts (Baragar, 1971). Wilson (1982) has suggested that the Great Dyke magma chamber may effectively have been an open system and acted as a feeder to surface volcanism.

This latter suggestion is the same as the concept relating the Fox River Sill to the lavas of the overlying Upper volcanic formation. The Fox River Sill, like other stratiform intrusions such as Rhum, Muskox, the Great Dyke and Stillwater, shows a cyclicity in the order of mineral crystallization. As Smewing (1981) pointed out, these cyclic units imply that the sequence of fractional crystallization was repeated many times. The most plausible hypothesis for their origin is by the periodic resetting of the magma composition by injections of fresh, unfractionated magma. This process also has a dramatic effect on the composition of lavas erupted from such a chamber as shown by O'Hara (1977), Dungan and Rhodes (1978) and Stern (1979).

SULPHIDE MINERALIZATION

Disseminated sulphide minerals are common accessory phases in parts of the MZ, UCLZ and HRZ succession, and are rare in LCLZ rocks. Pyrrhotite, pentlandite, chalcopyrite, pyrite, and heazlewoodite have been identified. Awaruite, a nickel-iron alloy, was identified in one LCLZ sample. In cyclic units, disseminated sulphide minerals occur in olivine and clinopyroxene cumulate layers and are more rare in plagioclase cumulate layers. An association in abundance between sulphide minerals and cumulus clinopyroxene has been recognized in some cyclic units, within which sulphide minerals are most abundant in clinopyroxene cumulate layers.

Marginal Zone

Sulphide minerals are common toward the top of the olivine cumulate layer of cyclic unit 1, 722E section where they constitute up to 5 percent of the rock. Disseminated sulphide forms up to 1 percent of the rock near the base of the overlying clinopyroxene cumulate layer. In the upper part of the plagioclase cumulate layer of cyclic unit 1, intercumulus sulphide minerals locally form 2 percent of the rock.

Sulphide minerals are sporadically distributed throughout the Banded Layer. In the lower two-thirds of the layer, sulphide minerals average less than 1 percent, whereas in the upper, homogeneous part of the layer, they constitute up to 5 percent of the rock and average 1 to 2 percent. They occur as bleb-like masses, and many possess cusp-shaped outlines. Intercumulus, bleb-like sulphides constitute up to 3 percent of the clinopyroxene cumulate layer of cyclic unit 2 in 722E section and compose up to 3 percent of a thin (less than 1 m) orthopyroxenite layer associated with the overlying plagioclase cumulate layer.

Sulphides are associated with a rusty weathering zone of gabbroic pegmatite that occupies a portion of the contact between the olivine and clinopyroxene cumulate layers of cyclic unit 3 in the Great Falls outcrop area. Chalcopyrite is the predominant sulphide mineral.

Lower Central Layered Zone

Sulphide minerals are relatively rare in LCLZ rocks. They constitute 5 percent of portions of the clinopyroxene cumulate layer of cyclic unit 5 in the Great Falls outcrop area. Pyrrhotite forms disseminated crystals (less than 1 percent) associated with secondary magnetite in a few olivine cumulate rocks of 722E section. Irregular masses of interstitial pyrrhotite (about 1 percent) occur in the plagioclase cumulate layer of the uppermost LCLZ cyclic unit exposed in 1086E section. Disseminated ragged clots of sulphide constitute 1 percent of the olivine cumulate layer of the uppermost LCLZ cyclic unit 1, and the clinopyroxene cumulate layer of LCLZ cyclic unit 2 of drill hole 38541. Sparsely disseminated (less than 1 percent) brassy, pinpoint sulphide that occurs in olivine cumulate rocks of 64W section has been identified as pentlandite and heazlewoodite. Sulphide minerals are sparsely disseminated through the clinopyroxene cumulate layers of LCLZ cyclic units 1 and 2 that are exposed in drill hole 13221. Near the base of the olivine cumulate layer of the second cyclic unit exposed in drill hole 13237, sporadically distributed clots of sulphide constitute approximately 1 percent of the rock. The overlying clinopyroxene cumulate layer of the same cyclic unit contains clots of sulphide that make up less than 1 percent of the rock, as does the olivine cumulate layer of the next overlying cyclic unit. The olivine and clinopyroxene cumulate layers of the uppermost LCLZ cyclic unit exposed in drill holes 13231, 13234 and 13235 contain sporadically disseminated sulphide that constitutes up to 2 percent of the rock. In places the clinopyroxene cumulate layer contains intercumulus sulphide globules that compose up to 10 percent of the rock.

Upper Central Layered Zone

Sulphide minerals are common constituents of UCLZ rocks. Disseminated sulphides constitute in excess of 5 percent of all or part of 5 of the 6 olivine cumulate layers and in excess of 10 percent of some clinopyroxene cumulate layers of the lowermost UCLZ cyclic units exposed in drill hole 13231. The sulphides occur as cuspate masses, where their shape is controlled by the surrounding cumulus crystals, and as globule-like inclusions in clinopyroxene and/or orthopyroxene crystals. Clinopyroxene cumulate layers of cyclic units 8 and 9, also exposed in 13231, are sulphide-bearing and contain up to 5 percent disseminated sulphide. Sulphide minerals, which are rare throughout the olivine cumulate layer of the lowermost cyclic unit intersected by drill hole 38524 and make up 2 to 3 percent of the rock near the top of the layer, adjacent to orthopyroxene cumulate rocks. The overlying orthopyroxene cumulate rocks are sulphide-bearing, containing from 1 to 10 percent disseminated sulphides.

Sulphide minerals occur as rare globules (much less than 1 percent) in the olivine cumulate layers of the uppermost UCLZ cyclic units. One exception is the thick olivine cumulate layer of cyclic unit 5 exposed in drill hole 38522, that contains up to 5 percent disseminated sulphide near the top of the layer. The clinopyroxene cumulate layer of cyclic units 4 and 5, exposed in drill hole 38522, are sulphide bearing, with portions of the lowermost 6 m of the layer of cyclic unit 5 containing up to 10 percent intercumulus sulphide. The sulphides occur as cusp-shaped intercumulus masses and as globule-like inclusions in postcumulus silicate phases. The other exception to nonsulphide bearing olivine cumulate layers is the topmost UCLZ olivine cumulate layer, the uppermost 2 m of which is exposed in drill hole 38510. It contains sulphide globules that constitute up to 10 percent of the rock.

East of the pinch-and-swell structure, intercumulus sulphide forms less than 1 percent of the rock near the base of the olivine cumulate layer of the lowermost UCLZ cyclic unit exposed in drill hole 13219, and constitutes less than 1 percent of the rock near the base of the olivine cumulate layer of UCLZ cyclic unit 5 exposed in drill hole 13213.

Olivine cumulate rocks exposed in drill holes 13215, 13220, 13223, 13224, 13228, 13229, 13211, and 13232, north of 722E section contain widely disseminated sulphide minerals that constitute up to 3 percent of some rocks. The sulphide minerals occur as intercumulus phases with well developed cusp shapes, and some form rounded globules in serpentine pseudomorphs after olivine.

Sulphide ± magnetite ± serpentine veinlets are common throughout many of the olivine cumulate rocks of the UCLZ.

Hybrid Roof Zone

Sulphide minerals are locally significant as finely disseminated grains that constitute up to 5 percent of some rocks and that average less than 1 percent. Pyrite is the predominant sulphide mineral. This sulphide may have been derived from Middle sedimentary formation rocks that contain widely disseminated pyrite crystals.

Other Sulphide Minerals

Galena ± chalcopyrite veinlets have been observed in plagioclase cumulate rocks from three widely separated parts of the west lobe of the intrusion. One example represents an MZ plagioclase cumulate, the other two examples are UCLZ plagioclase cumulate rocks. The MZ example is approximately 22 km east of the UCLZ examples, which themselves are nearly 3 km apart.

The Pb in the galena may have been derived through contamination from the host sedimentary sequence or from some other unknown source. If this is the case, the widespread distribution of the veinlets laterally and stratigraphically suggests a source of Pb contamination that persisted through almost the whole course of crystallization of the Sill.

Alternatively, the Pb may have been derived locally, through breakdown of plagioclase feldspar. In each example the veinlets occur in rocks that have been extensively altered.

Summary

Sulphide minerals are widely disseminated through MZ, UCLZ and HRZ rocks and are relatively rare in LCLZ rocks. The local concentration of sulphide minerals at the base of many olivine cumulate layers suggests that the sulphide may have been an immiscible phase of the magma injection that gave rise to the cyclic unit to which the olivine cumulate layer belongs. A similar interpretation was made on the basis of the concentration of S at the base of many cyclic units. The concentrations of disseminated sulphides, associated commonly with clinopyroxene cumulate layers and rarely with plagioclase cumulate rocks, may represent sulphides derived through sulphur insolubility after a certain period of fractional crystallization of a magma batch had been accomplished.

Sulphide concentrations near the top of a clinopyroxene cumulate layer that is part of an olivine cumulate-clinopyroxene cumulate cyclic unit, may represent immiscible sulphide related to the magma impulse that gave rise to the next overlying cyclic unit. In this case the sulphide settles to the crystal-magma interface, and because the mass of crystals below the interface is unconsolidated, the sulphide continues to settle below the interface, displacing intercumulus magma upward. This mechanism was used to explain the sulphide concentration in the upper part of the uppermost LCLZ clinopyroxene cumulate layer in drill hole 13231.

Sulphide concentrations related to two distinct processes are interpreted as occurring in the stratiform succession that constitutes the Fox River Sill. Immiscible sulphide that accompanied many of the magma impulses settled to form concentrations at or near the base of cyclic units. Concentrations of this kind rarely produced disseminated sulphides in excess of 10 percent and commonly produced disseminated sulphides that composed from 1 to 2 percent of the rocks. Similarly, sulphide concentrations that represent insolubility of sulphur during fractional crystallization of a magma batch, rarely produced disseminated sulphides in excess of 10 percent of the rock.

The scarcity of outcrop and widespread distribution of drill holes indicates that only a very small portion of the Sill has been directly observed. The fact that some of the drill core had been reduced or telescoped to 15 cm samples representing approximately 3 m of core length interval, prior to examination, further reduced the proportion of Sill rocks directly observed. Thus, comments and conclusions based on examination and evaluation of available data should be constrained by the small proportion of the Fox River Sill that has been directly observed. The distribution of sulphide in the Sill indicates that, on the basis of the rocks examined, the UCLZ has the greatest sulphide concentration, followed by the MZ and LCLZ rocks possess the least sulphide concentration. The concentrations of sulphide in HRZ rocks appear to have been inherited by contamination from Middle sedimentary formation roof rocks.

This overall distribution of sulphide minerals is similar to the distribution of sulphide minerals in the Muskox Intrusion, where the core or lower part of the main layered series is almost barren of sulphides (Chamberlain, 1967). Sulphide minerals are sparsely disseminated along the margins of the intrusion and concentrations in chromite-rich horizons within the upper part of its main layered series.

Within the Bushveld Complex, minor quantities of disseminated sulphides are found throughout the whole sequence of layered rocks where it was found that they seldom exceed 2 percent by volume of the rock (Liebenberg, 1970). Abnormal concentrations of sulphide are known only from certain parts of the Basal Zone, from sulphide-bearing pegmatoids, from the Merensky Reef and from the mineralized anorthosites below the Main and Uppermost Magnetite Seams.

Sulphide minerals, which appear to be extremely rare in the Great Dyke, occur in the platiniferous zone of Pyroxenite Band No. 1 (Worst, 1960). The platiniferous horizon of the Dyke occurs a short distance below the base of the gabbroic rocks, wherever Pyroxenite Band No. 1 is exposed in the four complexes of the Dyke.

In the Stillwater Complex, concentrations of sulphide minerals have been noted in the Basal Zone and form sulphide-bearing layers, some of which have been traced along strike for several kilometres, in the Banded Zone. The Ultramafic Zone, which separates the Basal Zone from the Banded Zone, seems to be almost barren of sulphide minerals (Jackson, 1961; Page, 1979; McCallum *et al.,* 1980). A significant concentration of platinum group elements, termed the J-M reef, occurs in a horizon of sulphide-rich anorthositic rocks (plagioclase and plagioclase-bronzite cumulates) within the Banded Zone (Conn, 1979; Todd *et al.,* 1982; Bow *et al.,* 1982). The horizon, which is 300 to 400 m above the bronzite member of the Ultramafic Zone and it can be traced over a strike length of 39 km. The recent discovery of the J-M reef, which appears to be comparable to the Merensky Reef, has prompted Todd *et al.* (1982) to suggest that similarities of processes in the formation of large layered intrusions raises the probability that similar ore zones may occur in other stratiform intrusions.

It seems that the marginal zones and the upper portions of the main central layered series of major stratiform intrusions are sulphide bearing, whereas the lower, more ultramafic portions of the main central layered series are sulphide deficient. Abnormal concentrations of sulphide, some associated with concentrations of chromite, are particularly noteworthy for their platiniferous character.

All anomalous sulphide concentrations in stratiform intrusions should be carefully evaluated for their platinum group element content. The association of platiniferous horizons with major changes in the composition of the layered stratigraphic succession (Bushveld Complex, Stillwater Complex, and Great Dyke) and with concentrations of chromite (Bushveld, Stillwater Complex, and Muskox Intrusion) is particularly noteworthy. In the Fox River Sill, the lowermost UCLZ cyclic units adjacent to the LCLZ-UCLZ contact, as intersected by drill hole 13231, are characterized by an anomalous sulphide content. Four separate sulphide-bearing intervals have been detected, and the olivine cumulate layer of cyclic unit 7 contains up to 5 percent disseminated chromite. The LCLZ-UCLZ contact represents a distinct change in the character of the layered succession including the first noteworthy abundance of plagioclase cumulate rocks. This particular anomalous area would seem to represent the most significant sulphide concentration in the Sill, from the point of view of possible concentration of platinum group elements. However, as noted, all anomalous sulphide zones should be carefully evaluated.

CHROMITE

Chromite is a widely distributed primary cumulus phase of the intrusion. It is an accessory phase in all olivine cumulate rocks. Locally, it displays anomalous concentrations (more than 4 percent) as either heavy disseminations or more rarely as mm-scale layers.

Marginal Zone

Disseminated chromite is a ubiquitous cumulus phase in MZ olivine cumulate layers. It occurs as widely disseminated individuals and as clusters of crystals in intercumulus areas, where it occurs as inclusions in clinopyroxene, orthopyroxene and plagioclase. It constitutes up to 3 percent of the rock and averages approximately 1 percent. Anomalous chromite concentrations (about 2 mm) are associated with sulphide-bearing gabbroic pegmatite that occupies a portion of the contact between the olivine cumulate and clinopyroxene cumulate layers of cyclic unit 3, in the Great Falls outcrop area.

Lower Central Layered Zone

LCLZ olivine cumulate layers contain disseminated chromite in abundances that range from 1 to 4 percent, and it is estimated to average between 1 and 2 percent in the zone. Chromite layers observed in drill hole 38520 in an interval of broken core are 1.5 and 4 mm thick. The rock adjacent to the layers contains up to 10 percent chromite as dense clusters of crystals. Because of the broken nature of the core, the overall thickness of chromite-rich rocks is not known, although it likely does not exceed 10 cm. The chromite of the thickest chromitite layer exposed in drill hole 38520 contains 45.6 percent Cr_2O_3, is somewhat aluminous (17.3 percent Al_2O_3), and possesses a Cr:Fe ratio of 1.83:1 (Table 14).

Table 14: Chromite Analysis[1], 38520-394

SiO_2	0.14%
Al_2O_3	17.3
Fe_2O_3	7.11
FeO	15.6
CaO	nil
MgO	12.20
K_2O	nil
TiO_2	0.20
MnO	0.17
NiO	0.22
Cr_2O_3	45.6
Cr:Fe	1.83:1

[1] Analysis of hand-picked concentrate by Manitoba Energy and Mines Analytical Laboratory.

Chromite constitutes up to 10 percent of the rock over 4 cm in drill hole 13205. The extent of this chromiferous horizon is unknown because of the telescoped or skeletonized nature of the drill core but it is less than 3 m, the sample interval.

Millimetre-scale concentrations of chromite are associated with the contacts of some size graded layers in the olivine cumulate exposed in drill hole 38526.

Upper Central Layered Zone

Concentrations of disseminated chromite appear to be more abundant in UCLZ rocks and a number of chromiferous rocks (chromite more than 4 percent) have been observed. The chromite content in most UCLZ olivine cumulate rocks ranges from less than 1 to 3 percent and averages between 1 and 2 percent. Local concentrations that range from 5 up to 25 percent have been noted over thicknesses up to 5 mm, from 5 widely separated areas. All examples are from drill holes that were skeletonized or telescoped; thus a full evaluation of these chromiferous horizons is not possible.

Summary

The same constraint noted for sulphide minerals applies to evaluating chromite content in the Sill. The basic constraint relates to the fact that only a very small portion of the Sill has been directly observed and that some of the drill core had been reduced or telescoped to 15 cm samples representing approximately 3 m of core length interval; thus it is possible that concentrations of chromite noted in a sample of telescoped core might represent an interval of chromite concentration of several metres.

The potential for economic concentrations of chromite in the Sill is considered to be extremely high. Future work that would greatly assist in evaluation could involve a systematic examination of the Cr_2O_3-content and Cr:Fe ratio of chromite, and the variation of these parameters with stratigraphy and along strike of the Sill.

REFERENCES

Anhaeusser, C.R.
1977: Geological and geochemical investigations of the Roodekraus ultramafic complex and surrounding Archean volcanic rocks, Krugersdorp District; Transactions of the Geological Society of South Africa, v. 80, p. 17-28.

Baragar, W.R.A.
1977: Volcanism of the stable crust; in Volcanic Regimes in Canada; W.R.A. Baragar, L.C. Coleman and J.M. Hall (ed.); Geological Regimes in Canada, Geological Association of Canada, Special Paper No. 16, p. 377-405.
1983: The Circum-Ungava Belt of eastern Hudson Bay: geology of the Cape Smith region, in Current Research, Part A, Geological Survey of Canada, Paper 83-1A, p. 325-328.

Baragar, W.R.A. and Scoates, R.F.J.
1981: The Circum-Superior Belt: A Proterozoic plate margin?; in Precambrian Plate Tectonics, A. Kroner (ed.); Elsevier, Amsterdam, p. 297-330.

Bell, C.K.
1971: Boundary geology, upper Nelson River area, Manitoba and northwestern Ontario; Geological Association of Canada, Special Paper 9, p. 11-40.

Bell, Robert
1879: Report on the country between Lake Winnipeg and Hudson's Bay, 1878; Geological Survey of Canada; Report of Progress for 1877-78.

Bow, C., Wolfgram, D., Turner, A., Barnes, S., Evans, J., Zdepski, M, and Boudreau, A.
1982: Investigations of the Howland Reef of the Stillwater Complex, Minneapolis Adit area: stratigraphy, structure and mineralization; Economic Geology, v. 77, p. 1481-1492.

Brock, R.W.
1911: The Hudson Bay route (Observations made during a trip with His Excellency the Governor General); Geological Survey of Canada, Summary Report 1910, p. 14-22.

Campbell, I.H.
1978: Some problems with the cumulus theory; Lithos, v. 11, p. 311-323.
1977: A study of macro-rhythmic layering and cumulate processes in the Jimberlana Intrusion, Western Australia, Part I: The Upper Layered Series; Journal of Petrology, v. 18, Part 2, p. 83-215.

Campbell, I.H., McCall, G.J.H. and Tyrwhitt, D.S.
1970: The Jimberlana norite, Western Australia - a smaller analogue of the Great Dyke of Rhodesia; Geological Magazine, v. 107, p. 1-12.

Carmichael, I.S.E., Turner, F.J. and Verhoogen, J.
1974: Igneous Petrology; McGraw-Hill Book Company, New York.

Chamberlain, J.A.
1967: Sulphides in the Muskox Intrusion; Canadian Journal of Earth Sciences, v. 4, p. 105-153.

Clue, J.
1976: Fox River; in Report of Field Activities 1976; Manitoba Mineral Resources Division, p. 51-53.

Coertze, F.J.
1970: The geology of the western part of the Bushveld Igneous Complex; Geological Society of South Africa Special Publication 1, p. 5-20.

Coleman, R.G.
1977: Ophiolites - Ancient Oceanic Lithosphere; Springer-Verlag, Berlin-Heidelberg, 229 p.

Conn, H.K.
1979: The Johns-Manville platinum-palladium prospect, Stillwater Complex, Montana, U.S.A; Canadian Mineralogist, v. 17, p. 463-468.

Dimroth, E., Baragar, W.R.A., Bergeron, R. and Jackson, G.D.
1970: The filling of the Circum-Ungava geosyncline; in Basins and Geosynclines of the Canadian Shield; Geological Survey of Canada, Paper 70-40, p. 45-143.

Dungan, M.A. and Rhodes, J.M.
1978: Residual glasses and melt inclusions in basalts from DSDP Legs 45 and 46: Evidence for magma mixing; Contributions to Mineralogy and Petrology, v. 67, p. 417-431.

Elliott, W.D., Grandstaff, D.E., Ulmer, G.C., Buntin, T. and Gold, D.P.
1982: An intrusive oxygen fugacity study of platinum-carbon associations in layered intrusions; Economic Geology, v. 77, p. 1493-1510.

Evans, B.W. and Trommsdorff, V.
1970: Regional metamorphism of ultramafic rocks in the Central Alps: parageneses in the system CaO-MgO-SiO_2-H_2O; Schweizerische Mineralogische und Petrographische Mitteilungen, 50, p. 481-492.

Findlay, D.C. and Smith, C.H.
1965: The Muskox drilling project; Geological Survey of Canada, Paper 64-44.

Ford, A.B.
1976: Stratigraphy of the layered gabbroic Dufek intrusion, Antarctica; United States Geological Survey, Bulletin 1405-D, 36 p.

Francis, G.H.
1956: The serpentinite mass in Glen Urquhart, Invernesshire, Scotland; American Journal of Science, v. 254, p. 201-226.

Gibb, R.A.
1968: A geological interpretation of the Bouguer anomalies adjacent to the Churchill-Superior boundary in northern Manitoba; Canadian Journal of Earth Sciences, v. 5, p. 439-453.

Gibb, R.A. and Walcott, R.I.
1971: A Precambrian suture in the Canadian Shield; Earth and Planetary Science Letters, v. 10, p. 417-422.

Heaman, L.M., Machado, N., Krogh, T., Weber, W.
1986: Precise U-Pb zircon ages for the Molson Dyke Swarm and the Fox River Sill: constraints for early Proterozoic crustal evolution in northeast Manitoba, Canada; Contributions to Mineralogy and Petrology, 94, p. 82-89.

Hess, H.H.
1960: Stillwater igneous complex, Montana; Geological Society of America, Memoir 80.

Hoover, J.D.
1978: Petrologic features of the Skaergaard Marginal Border Group; Carnegie Institution of Washington, Year Book 77, p. 732-739.

Huppert, H.E. and Sparks, R.S.J.
1980: The fluid dynamics of a basaltic magma chamber replenished by influx of hot, dense ultrabasic magma; Contributions to Mineralogy and Petrology, v. 75, p. 279-289.

Irvine, T.N.
1965: Sedimentary structures in igneous intrusions with particular reference to the Duke Island ultramafic complex; in Primary Sedimentary Structures and their Hydrodynamic Interpretation; G.V. Middleton, (ed.); Society of Economic Paleontologists and Mineralogists, Special Publication 12, p. 220-232.
1970a: Crystallization sequences in the Muskox intrusion and other layered intrusions, 1. Olivine-pyroxene-plagioclase relations; South Africa Geological Society, Special Publication 1, p. 441-476.
1970b: Heat transfer during solidification of layered intrusions, 1. Sheets and sills; Canadian Journal of Earth Sciences, v. 7, no. 4, p. 1031-1061.
1975: Crystallization sequences in the Muskox intrusion and other layered intrusions - II. Origin of chromitite layers and similar deposits of other magmatic ores; Geochimica et Cosmochimica Acta, v. 39, p. 991-1020.
1977: Origin of chromitite layers in the Muskox intrusions and other stratiform intrusions: a new interpretation; Geology v. 5, p. 273-277.
1979: Rocks whose composition is determined by crystal accumulation and sorting; in The Evolution of Igneous Rocks, Fiftieth Anniversary Perspectives; H.S. Yoder Jr., (ed.); Princeton University Press, Princeton, New Jersey, p. 245-306.
1980: Magmatic density currents and cumulus processes; in The Jackson Volume; Irving, A.J. and Dungan, M.A., (ed.); American Journal of Science; v. 280A, p. 1-58.
1982: Terminology for layered intrusions; Journal of Petrology, v. 23, Part 2, p. 127-162.

Irvine, T.N. and Smith, C.H.
1967: The ultramafic rocks of the Muskox Intrusion, Northwest Territories, Canada; in Ultramafic and Related Rocks, Wyllie, P.J., (ed.); John Wiley and Sons, Inc., New York, p. 38-49.

Irvine, T.N. and Stoeser, D.B.
1978: Structure of the Skaergaard trough bands; Carnegie Institution of Washington, Year Book 77, p. 725-732.

Jackson, E.D.
1961: Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana; United States Geological Survey, Professional Paper 358.
1967: Ultramafic cumulates in the Stillwater, Great Dyke and Bushveld intrusions; in Ultramafic and Related Rocks, P.J. Wyllie, (ed.); John Wiley and Sons, New York, p. 20-38.
1970: The cyclic unit in layered intrusions - a comparison of repetitive stratigraphy in the Stillwater, Muskox, Great Dyke and Bushveld Complexes; South Africa Geological Society, Special Publication 1, p. 391-424.

Jackson, E.D., Green, H.W. and Moores, E.M.
1975: The Vourinos ophiolite, Greece: cyclic units of lineated cumulates overlying harzburgite tectonite; Geological Society of America Bulletin, v. 86, p. 390-398.

Jensen, L.S.
1976: A new cation plot for classifying subalkalic volcanic rocks; Ontario Division of Mines, Miscellaneous Paper 66.

Liebenberg, L.
1970: The sulphides in the layered sequence of the Bushveld Igneous Complex; in Symposium on the Bushveld Igneous Complex and Other Layered Intrusions; D.J.L. Visser and G. von Gruenewaldt, (eds.); Geological Society of South Africa, Special Publication Number 1, 1970, p. 108-207.

Lofgren, G.
1971a: Spherulitic textures in glassy and crystalline rocks; Journal of Geophysical Research, v. 76, no. 23, p. 5635-5648.
1971b: Experimentally produced devitrification textures in natural rhyolite glass; Geological Society of America Bulletin, v. 82, p. 111-124.

Manitoba Mineral Resources Division
1979: Geological Map of Manitoba, scale 1:1 000 000, Map 79-2.

McBirney, A.R. and Noyes, R.M.
1979: Crystallization and layering of the Skaergaard intrusion; Journal of Petrology, v. 20, Part 3, p. 487-554.

McCallum, I.S., Raedeke, L.D. and Mathez, E.A.
1980: Investigations of the Stillwater Complex: Part I; Stratigraphy and Structure of the Banded Zone; American Journal of Science, v. 280A, p. 59-87.

Merritt, C.A.
1925: Bigstone and Fox Rivers area, northern Manitoba; Geological Survey of Canada, Summary Report, 1925, Part B, p. 27-30.

O'Hara, M.J.
1977: Geochemical evolution during fractional crystallization of a periodically refilled magma chamber; Nature, v. 266, p. 503-507.

O'Hara, M.J. and Matthews, R.E.
1981: Geochemical evolution in an advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber; Journal of the Geological Society of London; v. 138, p. 237-277.

Page, N.J.
1979: Stillwater Complex, Montana - Structure, mineralogy and petrology of the Basal Zone with emphasis on the occurrence of sulphides; United States Geological Survey, Professional Paper 1038, p. 69.

Page, N.J., Riley, L.B. and Haffty, J.
1972: Vertical and lateral variation of platinum, palladium, and rhodium in the Stillwater Complex, Montana; Economic Geology, v. 67, p. 915-923.

Page, N.J., Shimek, R. and Hoffman, C.
1972: Grain size variations within an olivine cumulate, Stillwater Complex, Montana; United States Geological Survey, Professional Paper 800-C, p. C29-C37.

Phinney, W.C.
1970: Chemical relations between Keweenawan lavas and the Duluth Complex, Minnesota; Geological Society of America Bulletin, v. 81, p. 2487-2496.

Potter, R.R.
1962: Gods River map-area, Manitoba; Geological Survey of Canada, Paper 62-8.

Quinn, H.A.
1955a: Knee Lake, Manitoba; Geological Survey of Canada, Paper 55-8.
1955b: Mineral prospects of the Knee Lake map-area, Manitoba; Precambrian, v. 28, no. 5, p. 10-27.

Sato, M. and Valenza, M.
1980: Oxygen fungacities of the layered series of the Skaergaard Intrusive, East Greenland; American Journal of Science, v. 280A, p. 134-158.

Scoates, R.F.J.
1969: Ultramafic Project; in Summary of Geological Fieldwork; Manitoba Mineral Resources Division, Geological Paper 4/69, p. 90-101.
1973: Ultramafic Rocks Project; in Summary of Geological Fieldwork 1973; Manitoba Mineral Resources Division, Geological Paper 2/73, p. 11.
1975a: Fox River Greenstone Belt (West), 53 M 15, 16; Manitoba Mineral Resources Division, Preliminary Map 1975G-1.
1975b: Fox River Greenstone Belt (East), 53 N 11, 12, 13, 14; Manitoba Mineral Resources Division, Preliminary Map 1975G-2.
1975c: Ultramafic Rock Project; in Summary of Geological Fieldwork; Manitoba Mineral Resources Division, Geological Paper 2/75, p. 22-23.
1977: Structures and textures of Paleohelikian(?) volcanic rocks of the Fox River area, northeastern Manitoba; Geological Association of Canada, Program with Abstracts 2, p. 47.
1981: Volcanic rocks of the Fox River Belt, northeastern Manitoba; Manitoba Mineral Resources Division, Geological Report GR81-1, 109 p.
1984: The Fox River Sill, northeastern Manitoba: a subvolcanic intrusion; Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, v. 9, p. 103.

Scoates, R.F.J. and Macek J.J.
1978: The Molson Dyke Swarm; Manitoba Mineral Resources Division, Paper 78-1, 53 p.

Smewing, J.D.
1981: Mixing characteristics and compositional differences in mantle-derived melts beneath spreading axes: evidence from cyclically layered rocks in the ophiolite of North Oman; Journal of Geophysical Research, v. 86, p. 2645-2659.

Smith, C.H.
1962: Notes on the Muskox Intrusion, Coppermine River area, District of Mackenzie; Geological Survey of Canada, Paper 61-25, 16 p.

Sparks, R.S.J., Meyer, P. and Sigurdsson, H.
1980: Density variation amongst mid-ocean ridge basalts: implications for magma mixing and the scarcity of primitive lavas; Earth and Planetary Science Letters, v. 46, p. 419-430.

Springer, G.D.
1946: Geology of the Knee Lake area-Gods Lake division; Manitoba Mines Branch, Preliminary Report 46-1.

Stern, C.
1979: Open and closed system igneous fractionation within two Chilean ophiolites and the tectonic implication; Contributions to Mineralogy and Petrology, v. 68, p. 243-258.

Streckeisen, A.
1976: To each plutonic rock its proper name; Earth-Science Reviews, 12, p. 1-33.

Thomas, M.D. and Gibb, R.A.
1977: Gravity anomalies and deep structure of the Cape Smith fold belt, northern Ungava, Quebec; Geology, v. 5, p. 169-172.

Todd, S.G., Keith, D.W., LeRay, L.W., Schissel, D.J., Mann, E.L. and Irvine, T.N.
1982: The J-M platinum-palladium reef of the Stillwater Complex, Montana: 1; Stratigraphy and petrology; Economic Geology, v. 77, p. 1454-1480.

Turner, J.S. and Gustafson, L.B.
1978: The flow of hot saline solutions from vents in the sea floor - some implications for exhalative massive sulphide and other ore deposits; Economic Geology, v. 72, p. 1082-1100.

Vermaak, C.F. and Lees, C.A.
1981: Bushveld and kindred complexes; in Precambrian of the Southern Hemisphere; D.R. Hunter (ed.); Elsevier, Amsterdam, p. 599-618.

Wager, L.R. and Brown, G.M.
1968: Layered Igneous Rocks; Oliver and Boyd, Edinburgh and London, 404 p.

Wager, L.R., Brown, G.M. and Wadsworth, W.J.
1960: Types of igneous cumulates; Journal of Petrology, 1, p. 73-85.

Wager, L.R. and Deer, W.A.
1939: Geological investigations in East Greenland, Part III: the petrology of the Skaergaard intrusion, Kungerdlugssuag, East Greenland; Meddelelser om Gronland, v. 105, p. 1-352.

Weiblen, P.W. and Morey, G.B.
1980: A summary of the stratigraphy, petrology, and structure of the Duluth Complex; American Journal of Science, v. 280A, p. 88-133.

Wicks, F.J., Whittaker, E.J.W. and Zussman, J.
1977: An idealized model for serpentine textures after olivine; Canadian Mineralogist, v. 15, p. 446-458.

Wilson, A.H.
1982: The geology of the Great "Dyke", Zimbabwe: the ultramafic rocks; Journal of Petrology, v. 23, Part 2, p. 240-292.

Worst, B.G.
1960: The Great Dyke of Southern Rhodesia; Southern Rhodesia Geological Survey, Bulletin No. 47.

Wright, J.F.
1932: Oxford House area, Manitoba; Geological Survey of Canada, Summary Report 1931, part C, p. 1-25.