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PROSPECTING IN GLACIATED TERRAIN: AN APPROACH BASED ON GEOBOTANY, BIOGEOCHEMISTRY, AND REMOTE SENSING

J.R. Bélanger

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Colin E. Dunn
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Preface

Mineral exploration in large parts of Canada is difficult because the bedrock is blanketed by thick layers of glacially derived sediments and vegetation. One technique to overcome this, called drift prospecting, identifies anomalously high concentrations of minerals or elements and helps to identify the bedrock source of the anomaly. Dr. Bélanger has tested two other prospecting techniques, geobotany and biogeochemistry, in a large geochemical anomaly near Thetford Mines, Quebec. The chemical composition of the soils in this anomaly produces a wasting effect on certain deciduous trees, and this can be identified, particularly in spring and autumn, by remote sensing imagery. Studies such as this using state-of-the-art technology are designed to assist the mineral exploration industry. They also illustrate the complexity of our natural environment and the frailty of an ecological equilibrium where external disturbances or disruptions, including acid rain, can result in wasting processes such as the maple tree dieback in the Eastern Townships of Quebec.

R.A. Price
Assistant Deputy Minister
Geological Survey of Canada

Préface

Les épaisses couches de dépôts d'origine glaciaire et la végétation qui recouvrent le socle rocheux rendent difficiles les travaux de prospection minière dans plusieurs régions du Canada. La prospection des matériaux de transport glaciaires est un des moyens utilisés dans le but de surmonter ce problème; cette méthode permet de détecter des concentrations anormalement élevées de minéraux ou d'éléments et de retracer plus facilement le socle rocheux à la source de cette anomalie. M. Bélanger a aussi utilisé la géobotanique et la biogéochimie comme outils de prospection au sein d'une vaste anomalie géochimique située près de Thetford Mines, au Québec. La composition chimique des sols de cette anomalie affecte la croissance normale de certaines essences de feuillus cet effet peut être observé, particulièrement au printemps et à l'automne, au moyen d'images de télédétection. Les études faisant ainsi appel à une technologie avancée ont pour but d'aider l'industrie de la prospection minière. Les résultats mettent aussi en évidence la complexité du milieu naturel et montrent bien comment les perturbations écologiques causées par des phénomènes externes, dont les pluies acides, peuvent déclencher des processus délétères destructeurs tels le dépérissement des érables des Cantons de l'Est, au Québec.

R.A. Price, sous ministre adjoint,
Commission géologique du Canada

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Abstract

Prospecting based on geobotany, biogeochemistry, and remote sensing has been tested in a glaciated terrain environment. During the last glaciation, ultrabasic bedrock near Thetford Mines, Quebec, was deeply eroded by continental glaciers. The debris, enriched in nickel, calcium, magnesium, chromium, cobalt, and iron, was dispersed in the till down-ice from the source over an area exceeding 70 km by 15 km wide. The dispersal train had been studied previously as part of a drift-prospecting project, which provided information on the extent, element concentration levels, and mode of dispersion of the geochemical anomaly.

The geobotanical study, which was carried out between 1979 and 1985 and involved visual examination, inventory, and spatial distribution of plant species, shows that the geochemical anomaly influences the distribution and growth rate of plants and provokes chlorosis of leaves and dwarfism in certain species. The biogeochemical study, which consisted of chemical and chlorophyll analysis of leaf tissues, shows a close relationship between soil and plant chemistry and an inverse relationship between the concentration of heavy metals in plants and chlorophyll production.

The remote sensing study, based on the analysis of multidate Landsat imagery, confirms the botanical studies by showing the influence of the geochemical anomaly on vegetation patterns. This imagery is useful for monitoring late flush and early senescence of vegetation growing within the area of the geochemical anomaly. Airborne and field remote sensing (using a portable radiometer/photometer) confirm the anomalous behaviour of the spectral signature of vegetation affected by high concentrations of ultrabasic debris in the soil.

Résumé

La prospection basée sur la géobotanique, la biogéochimie, et la télédétection a été mise à l'épreuve en terrain glacié. Lors de la dernière glaciation, des affleurements de roche en place ultrabasique situés près de Thetford Mines, au Québec, ont été érodés par les glaciers continentaux, et les débris enrichis de nickel, calcium, magnésium, chrome, cobalt et fer ont été incorporés au till et répandus sur une distance excédant 70 km sur 15 km de large. L'étendue, les niveaux de concentration des éléments et la formation de la trainée de dispersion glaciaire ont été étudiés dans le cadre d'un projet de recherche en prospection minière à partir des matériaux de transport glaciaire.

L'étude géobotanique, axée sur l'étude de la répartition des espèces d'arbre, de la composition des peuplements et de l'aspect pathologique, démontre que l'anomalie géochimique influence la répartition et le taux de croissance des plantes et provoque la chlorose des feuilles et le rachitisme de certaines espèces d'arbre. L'étude biogéochimique, basée sur l'analyse chimique et la teneur en chlorophylle des feuilles, établit une relation directe entre la chimie du sol et celle des plantes, et une relation inverse entre la concentration des métaux lourds dans les plantes et la production de la chlorophylle.

L'étude par télédétection, faite à partir d'images Landsat, confirme les études géobotaniques en montrant l'influence de l'anomalie géochimique sur le développement et la répartition de la végétation; il est en effet possible d'établir un lien entre l'anomalie géochimique et un retard dans le développement des arbres au printemps et une sénescence précoce à l'automne. Les données de télédétection aéroportées et sur le terrain confirment le comportement anormal de la signature spectrale de la végétation affectée par la haute concentration de débris ultrabasiques dans le sol.

SUMMARY

This report sums up research aimed at developing a method of mineral prospecting in glaciated terrain based on remote sensing. The approach used is derived from glacial-drift prospecting, from geobotany and from biogeochemistry.

In glaciated terrain, bedrock is often covered over by a layer of sediments that were eroded and transported great distances by glaciers before being deposited. When the bedrock is covered with a thick layer of sediments, making prospecting difficult, mineralized formations can be identified by prospecting the glacial drift. The method consists of sampling and analyzing the glacial till to determine its chemical composition; when samples reveal abnormal quantities of certain minerals, more intensive sampling can be done to trace the geochemical anomaly back to its source, i.e., the mineralized zone from which the materials were eroded.

A second way of conducting mineral exploration consists in using geobotanical and biogeochemical methods to analyze the vegetation. Prospecting methods involving study of vegetation are based on the principle that plants have to draw their nutrients from elements present in the soil, and should therefore reflect the chemical composition of the soil around them. Geobotany studies the relationship between the soil and nature of vegetation, i.e., the composition of stands, the distribution of species and the pathological aspect; whereas biogeochemistry studies the chemical composition of plants in relation to the chemistry of the soil. Once the plant-soil relationship is established, a sampling method similar to glacial-drift prospecting is used to trace the geochemical anomalies back to their source.

The proposed method for prospecting based on remote sensing relies on the same principles as prospecting through study of glacial drift and vegetation. Remote sensing makes it possible to identify the various types of vegetation and to study their distribution and condition in the light of the same criteria as geobotanical studies in the field, but on a larger scale; and analysis of spectral signatures, particularly in the near-infrared region, makes it possible to identify certain conditions of pathological stress in plants, by detecting decreases in chlorophyll production; in this approach, remote sensing is similar to the biogeochemical methods.

The method was used to study a geochemical anomaly located in the vicinity of Thetford Mines, in southeastern Quebec. The anomaly was formed during the last glaciation, when continental glaciers, flowing southeast, eroded outcrops of ultrabasic rock from a serpentinized band lying on the Asbestos-Thetford Mines axis. The debris was incorporated into the glacial till, then deposited down-ice, forming a dispersal train that was traced as far as 70 km from the source. The geochemical anomaly has been studied within a project aimed at establishing the

SOMMAIRE

Le présent rapport fait le point sur des recherches visant à mettre au point une méthode de prospection minière en terrain glacié basée sur la télédétection. L'approche utilisée est dérivée de la prospection minière à partir des matériaux de transport glaciaire, de la géobotanique et de la biogéochimie.

En terrain glacié, la roche en place est souvent recouverte d'une couche de sédiments erodés et transportés sur de grandes distances par les glaciers avant d'être déposés. Lorsque la roche en place est recouverte d'une épaisse couche de sédiments, rendant la prospection difficile, il est possible d'identifier les formations minéralisées en explorant les matériaux de transport glaciaire: il s'agit d'échantillonner et d'analyser le till glaciaire pour en connaître la composition chimique. Lorsque les échantillons révèlent des quantités anormales de certains minéraux, on procède a un échantillonnage plus serré afin de remonter à la source de l'anomalie géochimique, c'est-à-dire a la zone minéralisée d'où les matériaux érodés proviennent.

Une seconde façon de procéder à l'exploration minière consiste à analyser la végétation en se servant des méthodes géobotaniques ou biogéochimiques. Les méthodes de prospection a l'aide de la végétation reposent sur le principe que les plantes doivent se nourrir des éléments présents dans le sol et devraient donc refléter la composition chimique du sol environnant. La géobotanique étudie la relation entre le sol et le type de végétation, c'est-à-dire la composition des peuplements, la répartition des espèces et l'aspect pathologique; la biogéochimie d'autre part étudie la composition chimique des plantes en relation avec la chimie du sol. Une fois que la relation plante-sol est établie, on se sert d'une méthode d'échantillonnage semblable a la prospection a partir des matériaux de transport glaciaire pour remonter a la source des anomalies géochimiques.

La méthode proposée pour la prospection minière à l'aide de la télédétection se base sur les principes de la prospection à partir des matériaux de transport glaciaire et de la végétation. La télédétection permet d'une part d'identifier les différents types de végétation et d'en étudier la répartition et la condition à partir de mêmes critères que les études géobotaniques sur le terrain, mais a une plus grande échelle. D'autre part, l'analyse des signatures spectrales, surtout dans la région du proche infrarouge, permet d'identifier certaines conditions de stress pathologique chez les plantes en détectant une diminution de la production de chlorophylle; dans cette approche, la télédétection s'apparente aux méthodes biogéochimiques.

La méthode a été utilisée pour étudier une anomalie géochimique située dans les environs de Thetford Mines, dans le sud-est du Québec. L'anomalie géochimique a été formée lors de la derniére glaciation, alors que des glaciers continentaux s'écoulant vers le sud-est, ont érodé des affleurements de roches ultrabasiques de la zone de serpentine située dans l'axe Asbestos-Thetford Mines et incorporé les débris au till glaciaire pour ensuite les déposer en aval formant une traînée de dispersion que l'on a retracée jusqu'à 70 km de la source. L'anomalie géochimique avait été étudiée dans le cadre d'un projet visant a établir les principes de prospection a partir des matériaux de transport glaciaire; l'étude avait révélé que le till glaciaire situé dans la région au sud de Thetford Mines et Black Lake était enrichi de métaux lourds, soit de nickel, cobalt, chrome, fer et magnésium, et ce à des concentrations pouvant atteindre vingt fois la normale.

principles of glacial-drift prospecting; the study revealed that the glacial till in the area south of Thetford Mines-Black Lake was enriched with heavy metals — nickel, cobalt, chronium, iron, and magnesium in concentrations as much as twenty times greater than normal.

The geobotanical study demonstrated that deciduous trees growing in areas of high content of ultrabasic debris generally showed signs of stress, characterized by premature senescence, rachitis, chlorosis of the leaves and premature loss of leaves in autumn. Certain species, such as sugar maple, only grow in soils with a low content of ultrabasic debris, and are thus absent from the area regarded as the centre of the geochemical anomaly. A few maple stands can be found inside the glacial dispersal train, but they are located on residual soils in areas protected from ultrabasic dispersal by the blocking effect of hills. The conifers seem to be less affected by the geochemical anomaly, and they are found on various types of soil, independently of the drainage slope or the maturity of the forest cover.

The biogeochemical study showed that there exists a direct relationship between nickel, iron, and magnesium content in the soil and in the plants: deciduous trees may accumulate as much as four times the normal level of these elements, whereas conifers do so to a far lesser degree. It has been established by biologists that such concentrations of nickel and magnesium are toxic to plants. Calcium, which is an essential element to plant growth, is deficient in the species of trees located in the glacial dispersal train; this deficiency in the trees shows a direct relationship with the high concentration of ultrabasic debris and a calcium deficiency in the soil. Samples of red maple and white birch suffering from chlorosis were analyzed by the Canadian Forestry Service and the results confirmed that the disease was caused by the toxic effect of a magnesium surplus and a calcium shortage. Analysis of the chlorophyll demonstrated that absorption by plants of elements linked to ultrabasic debris, along with calcium deficiency, slow down chlorophyll production in the different species of deciduous trees studied.

The remote sensing study demonstrated that the geochemical anomaly causes a change in the spectral signature of the trees because of a decrease in chlorophyll production, chiefly in deciduous trees. Analysis of satellite pictures taken at different times of the year showed that the geochemical anomaly is more visible at the beginning and end of the summer, as the trees growing inside the anomaly develop more slowly in the spring and cease chlorophyll production earlier in the autumn than the trees growing outside it.

L'étude géobotanique a démontré que les feuillus situés dans la région à forte teneur en débris ultrabasiques montrent généralement des signes de stress caractérisés par une sénescence prématurée, le rachitisme, la chlorose des feuilles et la chute prématurée des feuilles a l'automne. Certaines espèces comme l'érable à sucre ne croissent que sur des sols à faible teneur en débris ultrabasiques et sont ainsi absents de la région considérée comme le coeur de l'anomalie géochimique. On peut retrouver quelques érablières à l'intérieur de la traînée de dispersion glaciaire, mais celles-ci se trouvent sur des sols résiduels à des endroits protégés de la dispersion glaciaire par le relief. Les conifères semblent moins touchés par l'anomalie géochimique et on les retrouve sur différents types de sol indépendamment de la pente du drainage ou de la maturité de la couverture forestière.

L'étude biogéochimique a démontré qu'il existe une relation directe entre la teneur en nickel, fer et magnésium dans le sol et dans les plantes; les feuillus peuvent accumuler ces éléments jusqu'à des niveaux quatre fois plus élevés que la normale alors que les conifères accumulent ces éléments a un degré beaucoup moindre. Il a été établi par les biologistes que de telles concentrations de nickel et de magnésium sont toxiques aux plantes. Le calcium, qui est un élément essentiel à la croissance des plantes, est déficient chez les espèces d'arbres situés dans la traînée de dispersion glaciaire; cette déficience est en relation directe avec des taux élevés de débris ultrabasiques et une carence de calcium dans le sol. Des échantillons d'érables rouges et de bouleaux blancs souffrant de chlorose, ont été analysés par le Service canadien des forêts et les résultats ont confirmé que la maladie était causée par l'effet toxique d'un surplus de magnésium et d'une carence en calcium. L'analyse de la chlorophylle a démontré que l'absorption par les plantes d'éléments reliés aux débris ultrabasiques et la déficience en calcium ralentissent la production de la chlorophylle chez les différentes espèces de feuillus.

L'étude à l'aide la télédétection a démontré que l'anomalie géochimique provoque un changement dans la signature spectrale des arbres à cause d'une diminution de la production de chlorophylle, et ce principalement chez les feuillus. L'analyse d'images de satellite prises a différents temps de l'année a démontré que l'anomalie géochimique est plus visible au début et a la fin de l'été car les arbres situés au sein de l'anomalie géochimique accusent un développement plus lent au printemps et cessent la production de chlorophylle plus tôt à l'automne que les arbres situés à l'extérieur de l'anomalie.

INTRODUCTION

This study is part of a project entitled "Remote sensing applied to Quaternary geology", which was initiated at the Geological Survey of Canada (GSC) in 1978 to evaluate the contribution of remote sensing technology to geoscientific studies, in particular terrain mapping, mineral prospecting, and resource evaluation. Although the research is oriented primarily toward remote sensing techniques and methodologies, related disciplines, such as geology, geomorphology, and botany, are also involved. These disciplines are essential in understanding the relationship that exists between various environmental characteristics and the connection between geology and the spectral signatures.

The purpose of this report is to present an approach for mineral prospecting in glaciated terrain that establishes the link between the geology, geobotany, biogeochemistry, and remote sensing.

When interpreting remote sensing imagery (including aerial photography), geoscientists use information pertinent to their discipline extracted from an assembly of spectral signatures related to various phenomena located at the surface of the earth. Where bedrock outcrops, some interpretation can be done directly, provided that the spatial and spectral resolution of the imagery is fine enough to reveal the lithology and structure. However, where bedrock is masked by overburden and vegetation, direct interpretation is harder and often impossible.

In Canada, prospecting for minerals is further complicated as much bedrock is blanketed by sediments that were eroded and transported over large distances by continental glaciers during the last ice age (Fulton, 1984). Techniques have been developed to overcome the problem of prospecting in glaciated terrain. One method, called drift prospecting (Shilts, 1976), consists of sampling and analyzing glacial till for its mineral composition. When anomalously high concentrations of minerals are found, the till is sampled further to identify the bedrock source.

A second method of prospecting for minerals is through the study of vegetation. In glaciated terrain where soil is derived from transported material, botanical prospecting can be considered an extension of drift prospecting. The method is based initially on the plant-soil (drift) relationship and subsequently on the soil-bedrock relationship. Plant-soil relationships are determined generally through geobotanical and biogeochemical investigations. Geobotany is oriented toward the study of plant communities (e.g., composition, distribution, and pathology) whereas biogeochemistry involves the chemical analysis of vegetation.

Recent developments in remote sensing for the recording and processing of spectral signatures have spurred a new interest in this technique for mineral exploration. Reflectance values recorded in the invisible part of the spectrum, mainly in the infrared region, permit identification of various vegetation species, and detection of vegetation stress caused by local environmental conditions. Thus remote sensing techniques can be used to monitor geochemical anomalies.

The examples given in this report are based on the study of a geochemical anomaly located near Thetford Mines in the Eastern Townships of Quebec (Fig. 1). The anomaly was formed during the last glaciation when continental glaciers eroded ultrabasic rock outcrops and deposited the debris in till forming a dispersal train that can be traced for more than 70 km from the source. This anomaly was studied in detail by W.W. Shilts, Geological Survey of Canada, to evaluate the potential and develop the principles of geochemical exploration based on the dispersal of minerals in glacial drift (Shilts, 1973, 1975, 1976). The large size of the anomaly and the detailed analysis of the glacial till by Shilts provide an ideal context within which to test and develop an approach for mineral prospecting based on vegetation and remote sensing.

The first observations of the effects of the geochemical anomaly on vegetation based on remote sensing were reported by Bélanger et al. (1979). Further field and laboratory studies in 1981 showed the influence of the geochemical anomaly on local vegetation and confirmed the potential use of remote sensing for geobotanical and biogeochemical studies (Bélanger and Rencz, 1983). The current, more comprehensive study was done in 1984-85 to provide more detail on the influence the geochemical anomaly on vegetation and to develop an approach for mineral exploration based on the principles of drift prospecting, geobotany, biogeochemistry, and remote sensing.

Study Area

The study area is located in the vicinity of Thetford Mines, Quebec (Fig. 1). This area was chosen for the presence of a large till dispersal train, exceeding 800 km^2, on which it was possible to study several prospecting techniques (including the use of satellite imagery) and various types of bedrock, topography, drainage, vegetation cover, and land use. Centred on the geochemical anomaly, the study area extends over 1500 km^2 which allows comparison between normal background conditions and those found in the anomaly.

The study area lies in the northwestern part of the Appalachian structural province (Fig. 1). The bedrock is composed of a succession of lower Paleozoic metasediments and metavolcanic rocks oriented northeast-southwest, intruded by ultrabasic rocks (G of Fig. 1). The ultrabasic rocks (serpentinite, peridotite, and pyroxenite) occur within a serpentinized band forming an "asbestos belt" which extends over a length of 80 km (Harron, 1976). "Nickel makes up, on the average, 0.2 to 0.25 per cent of the ultrabasic rocks of the Thetford Mines area. Chromium, cobalt, iron and magnesium are also significantly enriched in the ultrabasic rocks compared to most other bedrock in the Appalachians" (Rencz and Shilts, 1980, p. 165).

The surficial formations are Pleistocene sediments related to the last glaciation (Chauvin, 1979). Although three tills have been identified, the two older ones, related to ice flow to the southeast and southwest, are found in only a few localities. Most of the region is covered by a till, deposited by continental glaciers that moved toward the southeast.

The topography, characterized by wide valleys and rolling hills, is strongly controlled by bedrock structures. The mean elevation ranges between 275-325 m a.s.l. with a series of parallel hills oriented southwest-northeast reaching altitudes of 650 to 700 m a.s.l.

The study area lies within the Great Lakes-St. Lawrence Forest Region (Rowe, 1972) and the vegetation comprises deciduous boreal forest. However, the original equilibrium has been disturbed by urbanization, mining and forestry industries, and agriculture. Existing vegetation associations and distribution reflect, in most part, the drainage conditions: white birch (*Betula papyrifera*), sugar maple (*Acer saccharum*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*) are found on well drained soils; red maple (*Acer rubrum*) and red spruce (*Picea rubens*) are found on a variety of soils; black spruce (*Picea mariana*), white cedar (*Thuja occidentalis*), and tamarack (*Larix laricina*) are found on poorly drained soils. Following wood cutting, aspen (*Populus tremuloides*), white birch, and white cedar are first to grow (Rowe, 1972; Bélanger et al., 1979).

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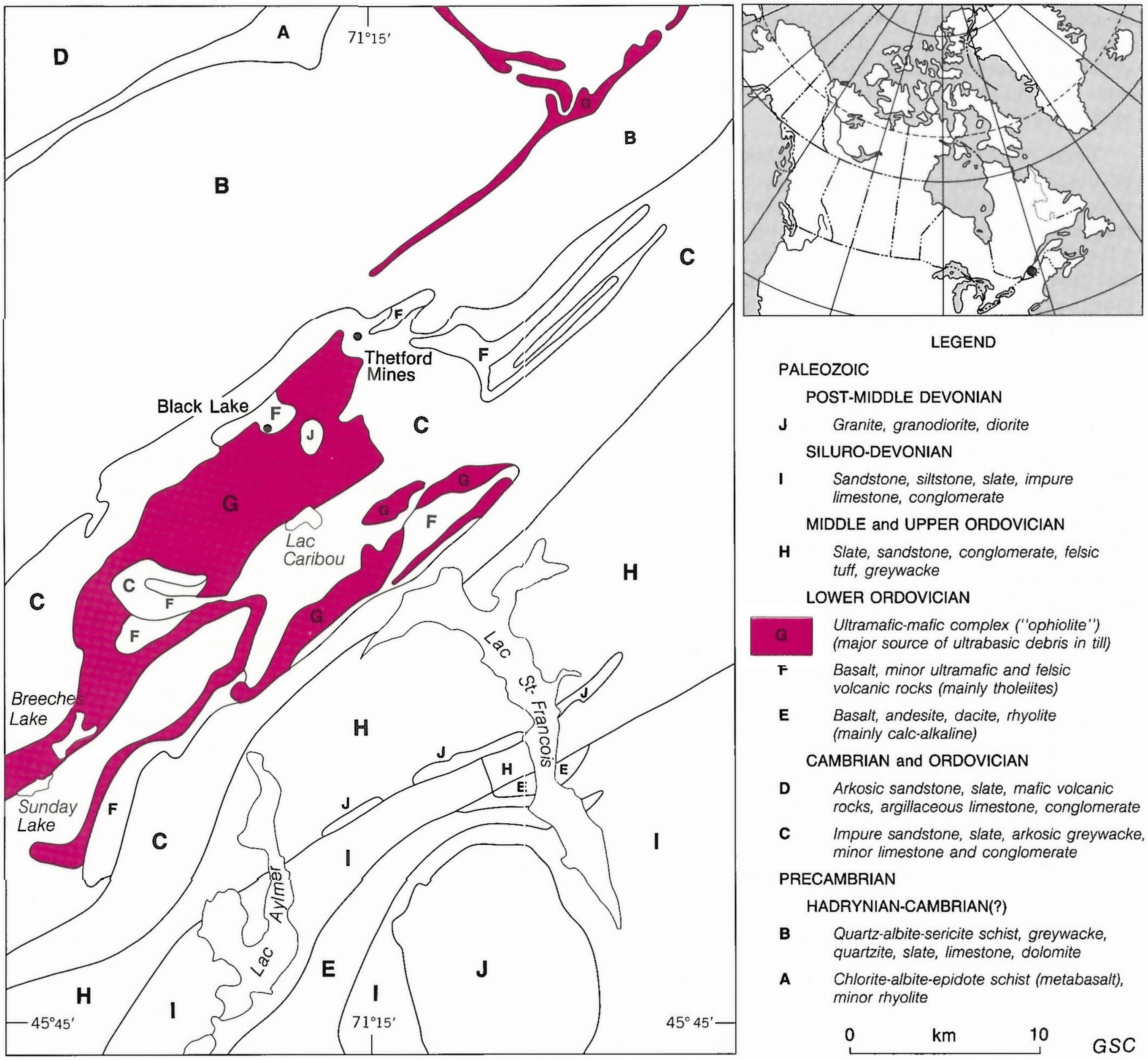

Figure 1. Location and geology of study area.

the chemical and chlorophyll analyses of the samples collected in 1984. C.E. Dunn and A.N. Rencz critically reviewed the report.

GEOCHEMISTRY

The geochemical anomaly was formed during the last glaciation, when continental glaciers flowing southeast deeply eroded the relatively soft rocks of the serpentinized band (G of Fig. 1). The chemically and mineralogically distinct ultrabasic debris eroded by glaciers was incorporated in the glacial till which deposited as a dispersal train that can be traced for at least 70 km, southeast from the source.

More than 1500 till samples were collected throughout the study area and were analyzed for trace elements. Most samples were collected from the oxidized and unoxidized (unleached) C horizon of the till. Some samples were collected in vertical profiles to study compositional variations that result from sedimentological, diagenetic, and weathering processes.

From the conclusions reached by Shilts four points can be observed. First, anomalously high concentrations of heavy metals, notably nickel, cobalt, chromium, iron, and magnesium in the < 2 μm fraction of till, can be found on a fan-shaped, well defined dispersal train extending southeast from the ultrabasic outcrop. The highest concentrations were found within 2 km of the source (> 2300 ppm for Ni, 2600 ppm for Cr, 80 ppm for Co) with concentrations decreasing with distance. Secondly, the similar dispersal patterns of nickel, cobalt, chromium, and magnesium (Fig. 2A-D) are typical of the patterns of all trace elements (related to ultrabasic rocks) studied. Table 1 shows the correlation between the concentrations of various elements in the till samples. The inverse relation between calcium and the other elements results from a dilution or "starvation" of carbonate rock debris (Fig. 3) in the till of the dispersal train created by preferential erosion of soft, carbonate-poor ultrabasic outcrops by continental glaciers which spread the debris down-ice from the source. Similar patterns of low concentration in the dispersal train were observed for lead, zinc, and manganese. Thirdly, the total concentration of trace elements in the < 2 μm fraction does not vary significantly between the oxidized and unoxidized zones of the till. The clay fraction of the till contains higher concentrations of nickel and magnesium as a result of preferential glacial comminution of the nickel-bearing phases of the ultrabasic rocks. Lastly, the topography influences the shape of the dispersal train by blocking the enriched till, causing anomalously low concentrations of ultrabasic debris on the leeside of the hills.

The magnitude of the geochemical anomaly, both in size and concentration of trace elements, along with the availability of detailed analysis of the surficial geology, provided an ideal context in which to pursue research in mineral prospecting based on botanical studies.

GEOBOTANICAL STUDY

In mineral exploration, geobotanical studies evaluate the precise relationship between the composition, form, and distribution of plant communities and environmental factors in undisturbed natural terrain. Their objective is the identification of anomalous plant communities related to mineralized bedrock (Cole, 1980). Geobotanical studies are carried out at three levels: 1) the nature and distribution of plant communities; 2) the nature and distribution of individual indicator plants; and 3) observation of morphological changes in vegetation (Brooks, 1983).

The literature (also surveyed in Cole, 1980 and Brooks, 1983) suggests that geobotanical studies are better suited for semi-arid regions, where anomalous plant communities are most likely to occur as a result of moisture stress. Favourable climate tends to nullify adverse effects of toxic elements in the substrate. A typical example of climatic influence on geobotany is that of the Canadian North, where semi-arid climate (and poor soil development) emphasize the relationship between the nature (petrography and granulometry) of surficial material and vegetation cover (Edlund, 1982; Bélanger and Hélie, 1984).

The natural vegetation of Thetford Mines area was classified by Marie-Victorin (1964) as deciduous boreal forest belonging to the "district Alléghanien"; "from the general Alleghanian flora, one must separate the florules... from the serpentine belt which occur in the counties of..." (counties located in the asbestos belt) "the magnesium silicates of the serpentine rocks have a definite influence on the vegetation. The flora of these magnesian terrains is generally poor in plant species and some species are definitely related to this type of substratum (*Adiantum pedatum, Pellaea densa, Festuca scabrella*). The adventitious flora growing on the Asbestos Mines tailings include allophilous plants: *Puccinellia distans, Rumex maritimus, Sonchus arbensis,* and *Spergularia aubra.*" (Marie-Victorin, 1964, p. 64).

The geobotanical study carried out in this project was oriented toward the nature and distribution of plant community and the morphology and pathology of the flora only. Indicator plants were not investigated for three reasons. First, in glaciated terrain, true indicator plants (Reeves et al., 1981) are nonexistent, as the flora is relatively new and accumulators and super-accumulators have not had time to develop over mineralized zones (Brooks, 1983, p. 258). The plant species, described as serpentine flora by Marie-Victorin, are allophyte plants, which are indicators of peculiar soils but which are not specific to the presence of any element. Secondly, the soils of glaciated terrain are formed of debris eroded and transported over many kilometres. The mineral debris incorporated in the soils is diluted and these soils can support a wide range of vegetation species compared to residual soils developed over mineralized bedrock. Thirdly, the study was also to establish the relationship between mineral exploration and remote sensing. The plant species endemic to the ultrabasic mineralization near Thetford Mines are restricted to ferns and grasses, which are hidden by taller vegetation and which are, therefore, not apparent on remote sensing imagery.

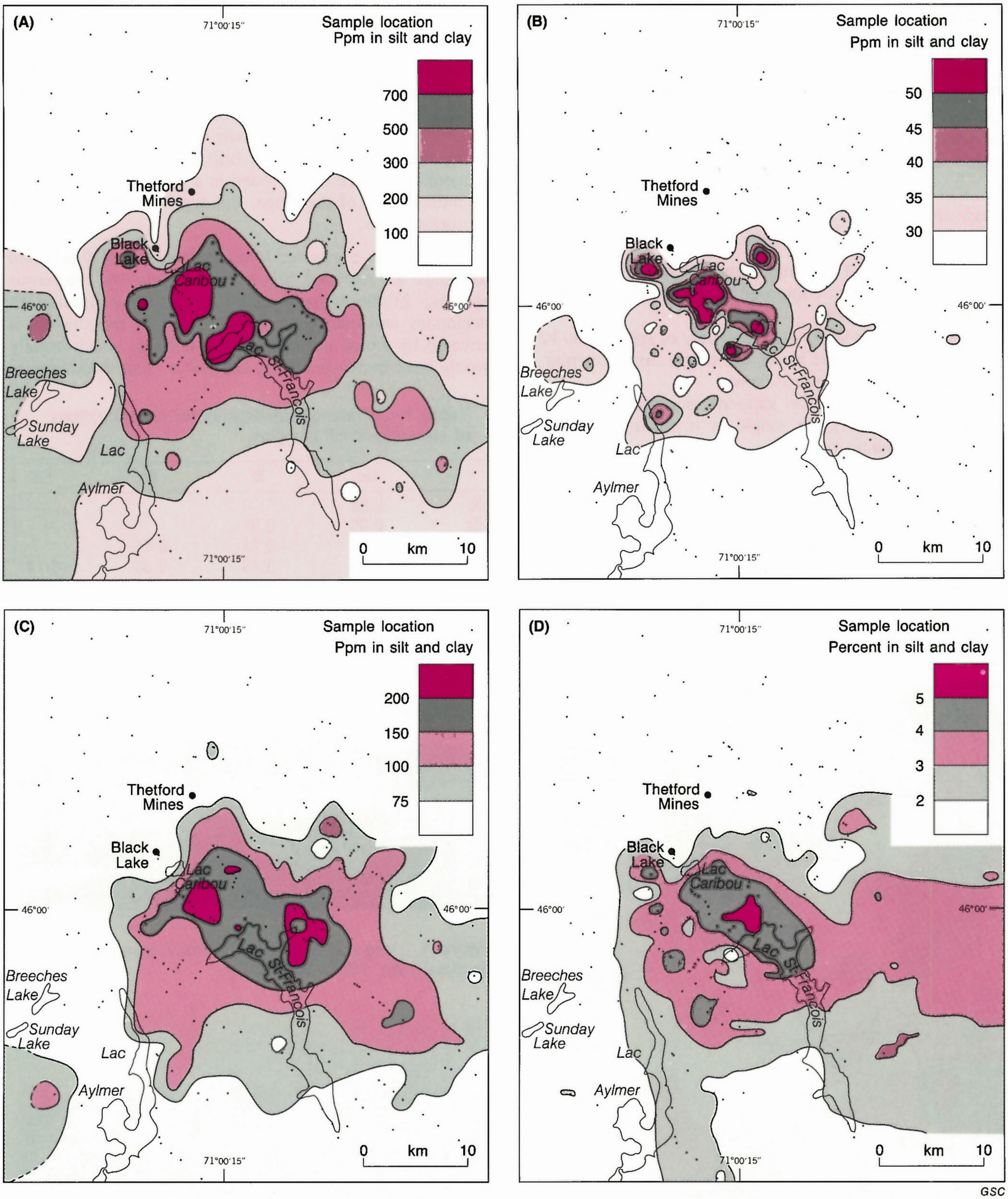

Figure 2. Dispersal patterns for trace elements in till: (A) Ni; (B) Co; (C) Cr; and (D) Mg.

Observations

The initial geobotanical study was made by A.N. Rencz of the Geological Survey of Canada in 1978 (Bélanger et al., 1979; Rencz and Shilts, 1980). Further field observations made by the author in 1981 and 1984-85 confirmed the observations made previously by Rencz, which are summarized in the following paragraphs.

Outside the dispersal train. Vegetation patterns are controlled by environmental conditions:

- low-lying areas of high moisture content are associated with conifer stands composed of black spruce, white cedar, and tamarack;
- on better drained soils, a wide variety of species can be found including white birch, red maple, aspen, poplar, and white and red spruce; and
- mesic upland generally supports deciduous species, mainly stands of sugar maple or a mixture of sugar maple and white birch.

Figure 4 illustrates a typical vegetation pattern in which flat terrain corresponds to agricultural land and hills covered by thin, well drained soils support deciduous trees, mainly sugar maple. Low-lying areas and some areas of regrowth after wood cutting are populated by coniferous species. Figure 5 illustrates a typical regrowth following woodcutting (red maple, birch, poplar, and spruce).

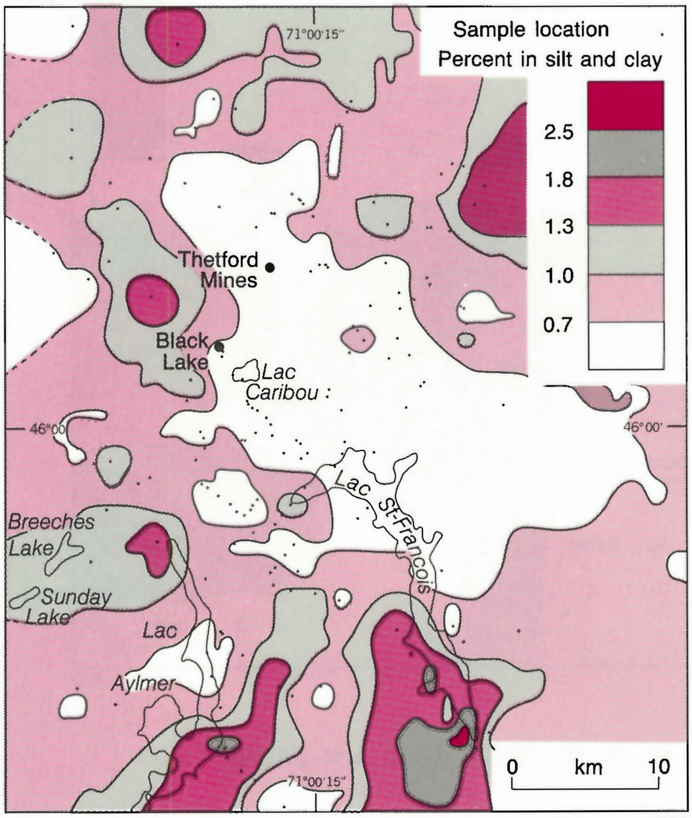

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Figure 3. Dispersal pattern for calcium in till.

Within the dispersal train. Environmental conditions play an important role but several anomalies can be found:

- sugar maples are restricted to soils of low ultrabasic content located outside the dispersal train but occasional stands are found within the dispersal train, in areas of thin soils usually protected from ultrabasic dispersal by the blocking effect of hills; and
- coniferous species are found in a wide variety of terrain independent of the slope, drainage, or maturity of the forest cover.

Figure 6 is a view of Mont Adstock: 1) flatlands and lowlands are covered almost exclusively by coniferous species; 2) the hillsides are covered by a mixture of deciduous and coniferous species; and 3) the summit is covered by alpine vegetation. The hillside, which usually would have been covered by deciduous "hardwood species

Table 1. Correlation coefficients for concentrations of elements in till samples

	Co	Ni	Cr	Ca
Ni	0.86			
Cr	0.85	0.91		
Ca	-0.20	-0.23	-0.15	
Mg	0.66	0.73	0.80	-0.14
		n: 380		

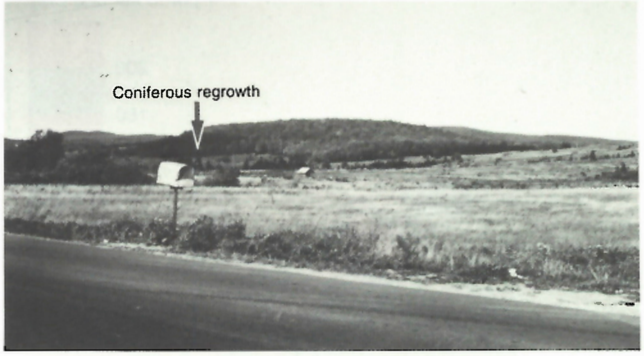

Figure 4. Vegetation pattern in study area, outside the dispersal train. (GSC 204335-O)

Figure 5. Forest regrowth following wood cutting, outside the dispersal train. (GSC 204335-L)

(maples and birches)," is populated by a mixture of deciduous and coniferous species in part because of the presence of ultrabasic debris in the soil and regrowth following wood cutting.

Core of the dispersal train. The vegetation is generally sparse, low, and composed mainly of alder (*Alnus*), willow (*Salix*), and various species of spruces, firs, and birches; the vegetation of these areas is classified by Rencz as scrub communities (Bélanger et al., 1979).

Figure 6. Vegetation pattern on Mount Adstock, within the dispersal train: 1) coniferous species; 2) mixed deciduous and coniferous species; and 3) alpine vegetation. (GSC 204335-N)

Figure 7. Shrub community located in the middle of the dispersal train. (GSC 204335-M)

Figure 8. Vegetation growing on thin, well drained soils in the middle of the dispersal train is little affected by toxic, ultrabasic debris. (GSC 204335-J)

Figure 7 shows a typical scrub community growing in Lac Caribou area, southeast of Thetford Mines.

On thin, well drained soils, the tree communities include mainly white birch, red maple, and poplar (Fig. 8). Vegetation growing in the core of the dispersal train usually shows signs of stress, such as dwarfism, early senescence, early fall foliage colouration, and chlorosis. Figure 9 shows a stand of white birch of about 40 to 50 years old. Despite the maturity of the stand, the trees have an average height of 10 m, as compared to 25 m under normal conditions. Trees in the foreground of Figure 9 show signs of early senescence and most of the leaves have already fallen, whereas outside the dispersal train leaves were still on the trees.

Discolouration (chlorosis) of birch leaves (Fig. 10) and of red maple leaves (Fig. 11) was also encountered in areas of high concentration of ultrabasic debris

Discussion

Although the geobotanical observations show that the geochemical anomaly in the glacial till influences the behaviour of the flora in the study area, the question

Figure 9. Dwarf and senescent birches located in the middle of the dispersal train, 28 August 1979. (GSC 204335-K)

remains: "Does the geobotanical study provide enough information to lead to the discovery of ore bodies?" To assess the importance of the geobotanical information in the present study, the following five points should be taken into consideration:

1) The source, extent, and nature of the geochemical anomaly near Thetford Mines are known. The geobotanical study was, therefore, limited to a specific area and the investigations were directed towards the toxic effect on vegetation of a known contaminant. Although this type of study is important to establish the influence of ultrabasic anomalies on vegetation, the same approach can hardly be used in mineral prospecting in which the unknown factors are the extent of the geochemical anomaly and the location of the ore body.
2) The indicator plants reported by Marie-Victorin (1964) are related to halophytic conditions, and are neither endemic to serpentinite-enriched soils nor are they accumulators of heavy metals. Therefore, they cannot be used as real indicators. The plant community study shows anomalies in plant associations and stress conditions related to scrub communities. Although these anomalies exist, it would be extremely difficult to relate them to any specific condition because of the interaction of characteristics such as drainage, soil thickness, or anthropogenic factors.
3) Sugar maple, which could serve as a negative indicator plant as it is restricted to soils having low concentration of ultrabasic debris, gives little information on the size or shape of the geochemical anomaly as its distribution does not correspond to the pattern of the dispersal train. The lack of correspondence results from the blocking effect of hills on the distribution of ultrabasic debris by glaciers and variation in soil thickness which permits sugar maple to grow in certain locations within the dispersal train.
4) Various pathological signs encountered in the vegetation are inconsistent. Chlorosis of leaves occurs only on certain individuals, which can be surrounded by unaffected trees of the same or different species. Dwarfed and senescent birches (Fig. 9) occur only in a few locations and the surrounding vegetation shows no similar pathological signs.
5) Less evident anthropogenic factors, such as the effect of acid rain on sugar maple, air pollution created by mine tailings (Fig. 12), and the use of tailings for road

Figure 10. White birch leaves discoloured because of high concentration of ultrabasic debris in the soil, 25 June 1984. (GSC 204542-A)

Figure 11. Red maple leaves discoloured because of high concentration of ultrabasic debris in the soil 25 June 1984. (GSC 204542)

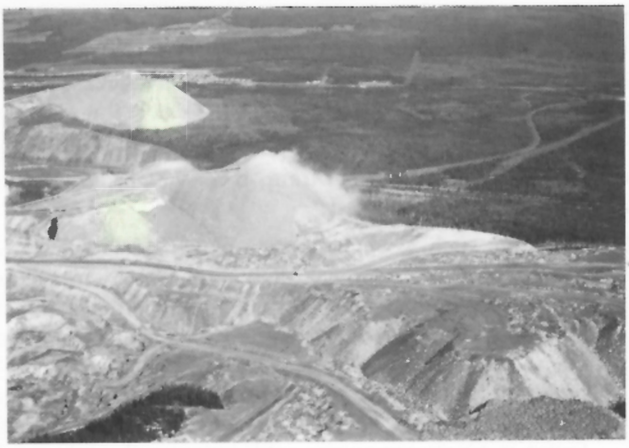

Figure 12. Mine tailings built around asbestoc open-pit mines. (GSC 204335-I)

fill, could also contribute to the degradation of vegetation near Thetford Mines, but a detailed study of those factors is beyond the scope of this study. It was observed, however, that the anomaly is oriented southeastward from the mineralized bedrock, whereas the prevailing winds are oriented northeastward, which indicates that the effect of windblown ultrabasic debris on vegetation is not as important as is soil chemistry.

A detailed study of the vegetation (such as detailed mapping of plant communities, including sociability, vitality, and periodicity) combining the various techniques described by Brooks (1983 p. 13) and using the entire flora might yield more conclusive results in locating geochemical anomalies. However, important factors to be considered in mineral exploration are the cost and time required to do such a detailed study. Considering the complexity of the study area, it is doubtful that a geobotanical study alone, based only on field evidence would be practical for an exploration company. It is, therefore, essential that the study be carried further using other techniques related to geobotany, such as biogeochemistry and remote sensing.

BIOGEOCHEMICAL STUDY

The study of plant chemistry to discover hidden ore bodies was reported as far back as 1938 (cf. Brooks, 1983, p. 109) and has gained importance in mineral prospecting with the advent of modern, multi-element analytical procedures. As Brooks reported in (1983, Chap. 12), extensive work by scientists such as Warren in Canada, Shacklette in the U.S.A., and Kovalevsky in the U.S.S.R. has permitted the establishment of the principles of biogeochemical prospecting and has proven their reliability in mineral exploration. Although the literature on biogeochemistry is fairly abundant, research in this field was done largely on residual soils of unglaciated terrain and the influence of glaciation on the dispersal of mineralized bedrock was either ignored or was mentioned only briefly. The purposes of the biogeochemical study in this project are:

1) to provide accurate quantitative information on the influence of the geochemical anomaly on the vegetation. The geobotanical study permitted a visual evaluation of till influence of the geochemistry on plant behaviour; the biogeochemical study attempts to substantiate the geobotanical observations by providing precise chemical information on the soil-plant relationship.
2) to study the possibility of using biogeochemical methods of prospecting in areas of glacial dispersal of an ultrabasic bedrock formation.
3) to evaluate the use of biogeochemical methods of prospecting in glaciated terrain by taking into consideration its practicality, cost effectiveness, and accuracy.

The biogeochemical study involved collection of vegetation samples throughout the study area, analysis of samples for trace element and chlorophyll concentrations, and comparison to plant and soil chemistry.

Collection of samples

The choice of samples was based on the following criteria:

- vegetation had to cover an area large enough to be visible on Landsat imagery;
- vegetation had to be present throughout the study area both on the geochemical anomaly and in the surrounding area; and
- samples had to come from various species to allow comparison or confirmation of the effect of the anomaly on plant chemistry.

Based on these criteria, five tree species were selected:

- *Acer saccharum* (sugar maple), hardwood deciduous, intolerant to high concentrations of heavy metal in the soil, based on the geobotanical study.
- *Betula papyrifera* (white birch), hardwood deciduous, tolerant but pathologically affected by the geochemical anomaly.
- *Acer rubrum* (red maple), medium hardwood deciduous, tolerant to many soil conditions, found equally distributed within and outside the dispersal train.
- *Populus tremuloides* (trembling aspen), softwood deciduous, tolerant to most soil conditions, not apparently affected by the geochemical anomaly.
- *Picea mariana* (black spruce), conifer, not visibly affected by the geochemical anomaly.

It was impossible to proceed by systematic sampling of the vegetation because of urban, mining, and agricultural activities; consequently, the sample distribution reflects a compromise between an even distribution and sites where at least three species are present, to permit a comparison between species.

The samples selected were leaves from deciduous species and needles from black spruce. Although Brooks (1983, p. 144) reported that it is not advisable to sample leaves of deciduous species because the element content varies considerably between budding and leaf fall, it was decided to use leaf samples for practical considerations (ease of sample identification in the field and laboratory, and of sample preparation) and for theoretical reasons (to monitor the variation of element contents throughout the growing season). The samples analyzed in this report were collected in September 1979, July 1980, August 1981, and May, June, and August 1984. Since the sample location differed from one year to another, the results were analyzed separately. During 1984, leaves from the same trees (and even from the same branches) were sampled three times to permit statistical comparison of the data. The soil type was similar at all sites, but the drainage, slope, and thickness differed because of the difficulty of selecting sites with identical conditions.

Sample Analysis

Chemical Analysis

All samples were first dried at 90°C until a moisture content of 5-10 % was obtained. Samples were then pulverized, to assure homogeneity, and sealed. The samples of 1978 and 1981 were sent to a commercial laboratory where they were prepared by dry ashing (2 g ashed at 500°C for 16 h) and were analyzed for trace elements with an atomic absorption spectrometer (AAS). The samples of 1980 were analyzed in a government laboratory using a similar technique. In 1984, samples were collected in duplicate; one set was sent to a government laboratory to be analyzed using a dry ash and AAS technique, and the other set was sent to a commercial laboratory to be prepared by wet ashing (2 g ashed using HNO_3, $HClO_3$, and HCL) and to be analyzed for trace elements by AAS and plasma emission (ICP-ES). The reason for using various techniques of preparation and analysis was to verify the accuracy of the techniques after some inconsistencies were observed in earlier analyses. To compare the plant response and possible interaction between known contaminants and other elements found at normal concentrations in the soil, chemical analysis included the elements related to the ultrabasic anomaly (nickel, chromium, cobalt, iron, and magnesium) plus calcium, copper, aluminum, and manganese.

Chlorophyll analysis

Chlorophyll analysis was performed on samples collected in 1981 and 1984. The 1981 samples were kept at about 5°C for three days before the chlorophyll analysis, whereas the 1984 samples were frozen immediately and kept on dry ice until the analysis. Chlorophyll was extracted using dimethylsulphoxide, and readings were taken at 645 nm and 663 nm for chlorophyll a and b using a spectrophotometer.

Discussion

Concentration of elements in plants

Range of values. Concentrations of some elements in vegetation sampled in June 1984 exemplify the range of values found near Thetford Mines (Fig. 13). Analysis both by commercial and by government laboratories using different techniques permitted a cross-verification and correction of the chemical analysis that was not available for the earlier surveys.

Background values were established for samples located outside the dispersal train, from which the following points can be observed:

1) Elements such as nickel, iron, and magnesium show background values lower than those found in plants located within the dispersal train, indicating a direct relationship between concentrations of an element in the soil and in the plants. Extreme values are commonly four times the background values for all deciduous species, whereas the higher concentrations found in black spruce are seldom larger than those of the background values.
2) Calcium and manganese show an inverse relationship, as the background values are higher in areas located outside the dispersal train. The lower calcium values correspond to lower concentrations of carbonate rock debris in the dispersal train as compared to surrounding areas (Fig. 3). This phenomenon is related to a dilution of carbonate rocks in the till as explained earlier in "Geochemistry".
3) Aluminum, copper, and chromium show no relationship to the geochemical anomaly, and background values do not differ from those found inside the dispersal train (except for red maple). The behaviour of aluminum and copper was anticipated as these elements neither were anomalously high within the dispersal train nor showed any interaction with other elements in plants sampled. The lack of absorption of chromium by plants is related, according to Rencz (Bélanger et al., 1979) and Lee (1977), to the low availability of chromium to plants, as its primary host mineral, chromite, is relatively stable in the soil-forming environment. Similarly, cobalt does not appear to accumulate in plant tissues in response to elevated levels in the soil. The reason for this lack of response of plants to cobalt in the soil is yet to be explained.

Regional study. Consideration of the influence of local conditions, such as slope, drainage, or type of soil, on the uptake of elements by plants, was omitted from the regional study on purpose to verify if a parallel exists between the geochemical anomaly and its biological response beyond local environmental factors. This approach was essential as the study covered a wide variety of terrain, and included the use of coarse resolution remote sensing data that are unsuited to detailed local studies.

Concentrations of elements in the species sampled in June 1984 were mapped and classified according to their relative value in showing regional patterns. The maps were rated from 0, for no regional pattern, to 3, for a clear regional pattern, to define which elements and species might best reveal the geochemical anomaly. Table 2 summarizes the analysis and Figure 14 A-D shows examples of regional maps.

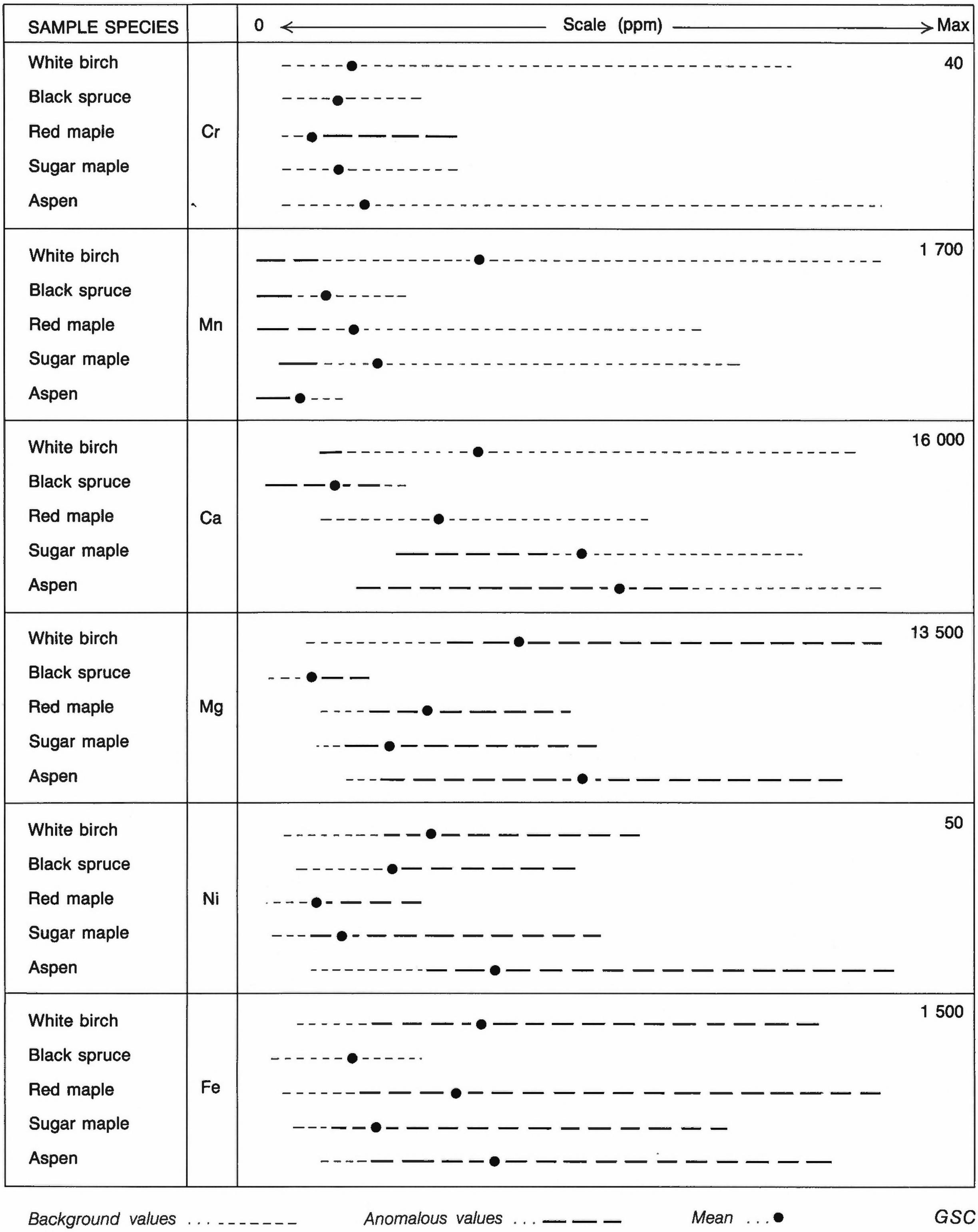

Figure 13. Range of values for concentration of elements in leaf samples, June 1984. Values are expressed in ppm dry weight.

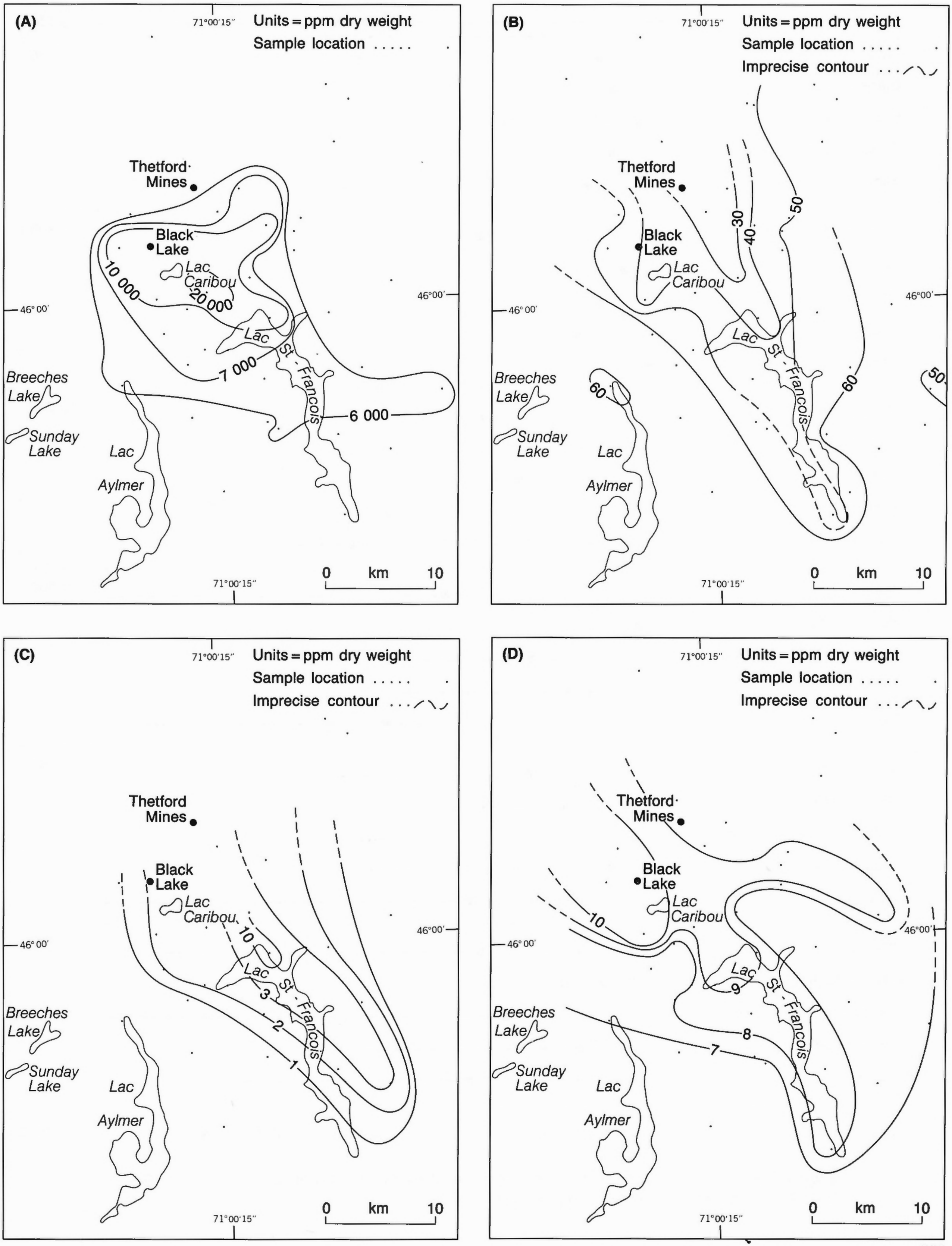

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Figure 14. Regional pattern of elements in vegetation: (A) Mg in white birch, Thetford Mines, August 1984; (B) Mn in aspen, June 1984; (C) Cr in red maple, June 1984; and (D) Cu in white birch, June 1984.

Table 2. Summary of ability of elements in leaves to reflect the geochemical anomaly. The classification is based on maps showing concentrations of elements in plants sampled in June 1984

Species	Cu	Ni	Cr	Mn	Fe	Al	Mg	Ca	Total
White birch	1	3	1	-3	2	0	2	0	12
Black spruce	0	1	0	-2	0	0	2	-1	6
Red maple	0	1	2	-3	1	0	3	0	10
Sugar maple	0	2	0	-3	0	0	3	-2	10
Aspen	1	3	0	-2	2	0	3	-3	14
Total	2	10	3	-13	5	0	13	-6	52

Legend: Correspondence with the dispersal train (geochemical anomaly)
0: No correspondence 1: Some (weak) 2: Good
3: Very good -: Inverse relationship (does not mean negative)

The following points generally confirm of the observations discussed earlier under "Range of values":

1) Copper, chromium, and aluminum show little or no relationship to the dispersal train.
2) Iron shows some correspondence, whereas calcium shows an inverse relationship to the dispersal train. The lack of consistent regional patterns makes these elements unreliable as indicators of an ultrabasic geochemical anomaly.
3) Nickel, manganese, and magnesium can be considered as the better indicators, although the inverse relationship of manganese is not fully explained.
4) Black spruce seems to be of limited use as a geochemical indicator.
5) Sugar maple, red maple, and white birch form an intermediate class as indicators, although the restricted distribution of sugar maple to areas of low ultrabasic concentration in soils makes this species less convenient as a sample medium.
6) Aspen shows the best aptitude as a biogeochemical indicator.

Comparison of uptake levels

Contrary to observed regional patterns of trace element concentrations (Fig. 14 A-D and Table 2) and the close relationship among elements in the soil (Table 1), the summary table (Table 3), showing correlations between elements in plants, indicates fewer strong relationships among element concentrations in the plants. The lack of correlation is more apparent at low concentration levels and the presence of a few abnormally (possibly erroneous) high values often gives some false high correlations caused by poor distribution of the variables (see * in Table 3).

The only constant, significant correlation found in this study is between iron and aluminum but no further investigation was done because neither element was encountered at high levels in the geochemical anomaly.

The information provided by the comparison of uptake levels of element by plants could be of importance when studying the influence of local environmental characteristics on the accumulation of elements by plants, but when

Table 3. Correlation coefficients of elements in leaf samples collected June 1984

	†	Ca	Mg	Al	Fe	Mn	Cr	Ni
Cu	WB	-0.27	0.22	-0.17	0.29	0.34	0.25	0.34
	BS	0.00	-0.26	-0.17	0.00	0.33	-0.15	-0.01
	RM	-0.15	0.07	0.03	0.03	0.03	0.07	0.09
	SM	-0.47	0.50	0.55	0.55	0.05	0.01	-0.29
	AS	0.03	0.26	-0.05	0.07	0.21	0.42	0.25
Ni	WB	-0.12	0.64	0.08	0.46	-0.38	0.34	
	BS	-0.22	0.40	-0.70	-0.39	-0.04	0.09	
	RM	-0.21	0.11	0.22	0.35	0.00	0.75	
	SM	-0.29	0.81	-0.11	0.03	0.37	0.84*	
	AS	-0.37	0.30	-0.22	0.00	0.31	0.31	
Cr	WB	0.03	0.05	-0.08	0.26	-0.11		
	BS	-0.26	-0.11	-0.08	-0.36	0.10		
	RM	-0.30*	0.02	0.62	0.77*	0.16		
	SM	0.13	0.60*	0.02	0.21	0.93*		
	AS	0.06	-0.11	-0.10	0.31	0.22		
Mn	WB	0.48	-0.41	-0.05	-0.11			
	BS	-0.15	0.17	0.37	-0.24			
	RM	0.50	0.07	-0.11	-0.16			
	SM	0.11	0.23	-0.08	0.04			
	AS	-0.05	-0.14	0.04	0.30			
Fe	WB	0.05	0.27	0.68				
	BS	0.03	-0.35	0.51				
	RM	0.15	0.05	0.97				
	SM	0.44	-0.16	0.97				
	AS	0.21	-0.28	0.83				
Al	WB	0.29	0.01					
	BS	-0.35	0.51					
	RM	0.28	-0.14					
	SM	0.40	-0.29					
	AS	0.29	-0.40					
Mg	WB	0.08						
	BS	-0.16						
	RM	0.19						
	SM	-0.33						
	AS	-0.48						

†Sample species	Size of population	Significance level 95 %	99 %
WB: white birch	n: 35	0.33	0.42
BS: black spruce	n: 31	0.35	0.45
RM: red maple	n: 23	0.42	0.53
SM: sugar maple	n: 18	0.47	0.59
AS: aspen	n: 37	0.33	0.42

* Correlation may be misleading because of uneven distribution.

__ (underlined) Confidence >95 %

looking for indicators that are detectable beyond local conditions, this type of study is of limited use, at least in the present context.

Plant-soil relationship

To verify the plant-soil chemical relationship, common to serpentine soils (Lyon et al., 1968), the concentration of elements in plants was compared to the concentration found in the soil; the soil concentration values are derived from the maps (Fig. 2). Correlation coefficients for element concentrations in soils and plants were calculated for the available soil analysis (Ca, Mg, Ni, Co, and Cr). It was found that a weak correlation exists for cobalt and chromium ($r = <0.3$), and slightly higher for nickel, calcium, and magnesium ($r = 0.30$ to 0.65, $n = 35$ to 40). The low correlation of chromium can be explained by the unavailability of this element to plants and the low correlation of cobalt can be explained by the low reliability of the chemical analysis when dealing with concentrations at the lower detection limit. Even if trend maps indicate similar patterns in the concentration of elements in soil and plants for magnesium, calcium, and nickel, statistical analyses based on site-specific data give results that are much less meaningful.

Correlations of nickel in soil and in leaf samples are plotted in Figure 15 A-E. The scattering of sample points along the regression line, especially at lower values, indicate a poor correspondence between soil and plant concentrations of nickel.

Results obtained in 1979 and 1980 showed closer correlations between soil and plant concentration levels of elements (Table 4), which can be explained by the selection of vegetation samples closer to the locations of soil samples in 1979 and 1980 than in 1984. In 1984, it was impossible to collect all vegetation samples close to previously sampled soils, because the area covered was larger than during previous years and sampling was oriented toward an even distribution of plant species throughout the study area.

Variations in plant chemistry

Concentrations of elements in plants can vary annually and seasonally (Egginton, 1983; Dunn, 1985) especially when the analysis is done on leaf tissue of deciduous species. In this study, discussion of variations in plant chemistry is essential because not only were the samples collected during different years and seasons but also the sample preparations, the chemical analysis, and the sample location varied from one survey to an other. Rather than comparing absolute values, which would be of limited use in the present context, the discussion is oriented mainly towards the capacity of each approach to detect the geochemical anomaly.

Technique

A first source of variation in the concentration levels of an element in plants is related to differences in the techniques used to prepare and analyze the vegetation samples. The techniques used, not only were governed by the availability of laboratory facilities, but also were designed to verify the consistency of results obtained from various methods.

Concentration values for 1979 samples are available for both dry and ash weights. Correlation coefficients between dry and ash weights were calculated for all species and elements, and scatterdiagrams were produced showing the regression between the two sets of data. Figure 16 is an example of the correlation between dry and ash weights for nickel in poplar. The close correlation, which is typical of all species, shows that it is possible to express values on either basis. The ratio of 1:26 (dry weight:ash weight) is consistent, with a slight decrease in the ash weight (1:33) at higher concentration levels. In this report all values are reported on a dry weight basis to facilitate comparison between various sets of data. Weight measurement errors were also encountered because of the small quantities of ash used for the analysis (cf. Method for chemical analysis).

A second source of variation in concentration levels is attributed to analytical instrumentation. To verify the accuracy and consistency of the methods used during the course of this program, samples collected during June 1984 were pulverized, homogenized, and dried before being split, sealed, and sent to the two laboratories; a government laboratory where they were prepared by dry ashing and analyzed by AAS, and a commercial laboratory where they were wet ashed and analyzed by ICP-ES.

Comparison of concentration levels shows excellent correlation between the two techniques for all elements analyzed (Table 5). Even though the absolute values vary,

Table 4. Correlation coefficients for cobalt, nickel, and chromium in soil and plants sampled in 1979 and 1980

Species	Co	Ni	Cr	n
Sugar maple	0.81	0.84	0.93	21
White birch	0.50	0.67	0.81	25
Yellow birch	0.27	0.53	0.38	11
Trembling aspen	-0.09	0.10	-0.07	25
Poplar	0.15	0.56	0.55	13
White spruce	0.50	0.26	0.40	24
Black spruce	0.28	0.21	0.52	7
Balsam fir	0.07	0.54	0.16	26

Table 5. Correlation coefficients for data obtained by AAS (dry ashing) and ICP-ES (wed ashing) of leaf samples collected June 1984

Species	Ca	Mg	Ni	Fe	Cu	Al	Mn	n
White birch	—	0.86	0.74	0.80	0.55	0.58	0.98	35
Black spruce	0.81	0.63	0.77	0.24	0.07	0.85	0.74	31
Red maple	0.89	0.91	0.90	0.97	0.93	0.93	0.96	23
Sugar maple	0.86	0.96	0.95	0.96	0.83	0.97	0.97	18
Aspen	0.61	0.83	0.97	0.81	0.62	0.97	0.98	37

— Not available

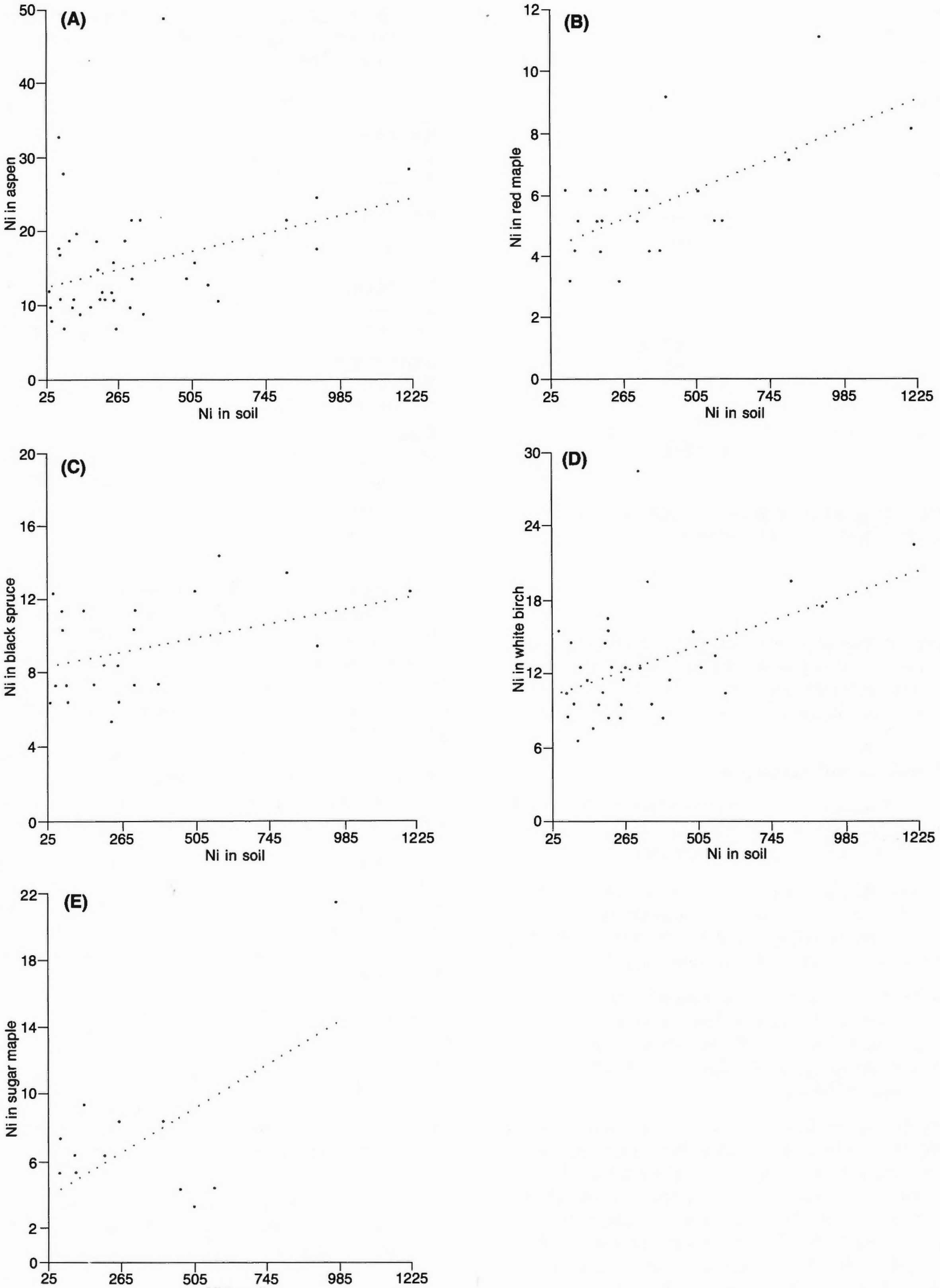

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Figure 15. Correlation between concentrations of nickel in soil and leaf sample collected in June 1984. Values are expressed in ppm dry weight.

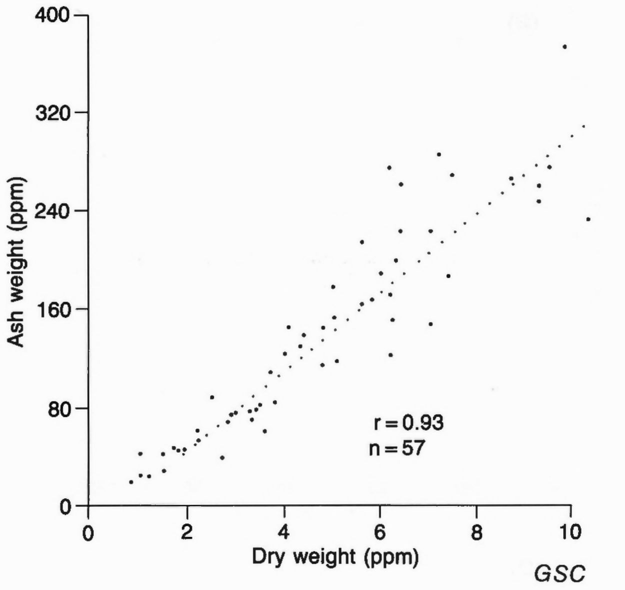


Figure 16. Correlation between dry and ash weights for nickel concentrations in poplar leaves.

in this case substantially, from one analytical technique to the other (Fig. 17) it is possible to compare the two sets of data (once normalized) because of the close correlation between the concentration values.

Seasonal and annual variations

Mean seasonal variations of concentration levels of elements for the five species sampled in 1984 are given in Figure 18, from which it is observed that:

1) Deciduous species have similar patterns of concentration levels during the growing season. Black spruce shows an inverse relationship for the first or last part of the season except for iron and aluminum.
2) Mean levels for calcium, magnesium, iron, and manganese increase throughout the growing season (except for black spruce) whereas nickel, copper, and aluminum decrease from May to mid-June and increase from mid-June to August.
3) Sampling leaves from the same trees and branches during May, June, and August permitted monitoring of the variation in uptake levels at each site. In spite of variations caused by local terrain conditions and inconsistencies in chemical analysis, correlation between the uptake levels for the three periods is generally good (Table 6). Correlations are similar for all species, including black spruce. The correlation between elements can be grouped into three categories: high correlation (Ca, Mg, and Mn: r=>0.7), good correlation (Ni, Fe, and Al: r=>0.5), and low to no correlation (Cr and Cu) mainly because of low concentration levels in plants.

Table 6. Correlation coefficients between samples collected in May and June, and June and August 1984

	Ca	Mg	Ni	Cu	Fe	Al	Mn	n
White birch								
May/June	0.78	0.68	0.45	0.20	0.00	0.00	0.90	35
June/August	0.70	0.93	0.65	0.30	0.30	0.47	0.95	35
Black spruce								
May/June	—	0.30	0.77	0.00	0.70	0.45	0.30	31
June/August	0.80	0.77	0.30	0.00	0.26	0.65	0.91	31
Red maple								
May/June	0.72	0.60	0.30	0.10	0.30	0.30	0.99	23
June/August	0.80	0.90	0.50	0.70	0.90	0.93	0.99	23
Sugar maple								
May/June	—	0.84	0.80	0.00	0.13	0.15	0.92	18
June/August	0.82	0.66	—	0.43	0.91	0.94	0.80	18
Aspen								
May/June	0.77	0.60	0.46	0.00	0.14	0.30	0.85	37
June/August	0.82	0.90	0.88	0.20	0.80	0.91	0.91	37

— Not available

Comparison of regional patterns (Fig. 14) shows similar concentrations for the three months surveyed (Table 7). The regional patterns confirm the statistical analysis by showing similar patterns of concentration values for May, June, and August. Thus, a biogeochemical study can be done at any time during the growing season for the species and elements analyzed, provided that sampling is done over a short period. Local variations in environmental conditions do not mask regional patterns, so, although local variations may exist from one survey to an other, the general pattern remains constant.

Comparison of absolute values for the different years was not possible as the samples were taken at different sites throughout the study area. The study was therefore carried out at the regional level by comparing patterns of concentration levels for samples collected in 1979, 1980, 1981, and 1984.

Tables summarizing the relative abilities of elements and species to reveal the geochemical anomaly were produced for every year surveyed (as in Table 7) and values were compiled (by adding the scores of each table) to produce Table 8. The values are normalized (compensated for null values) as some species and elements are not available for certain years. Analysis of the various surveys shows that:

1) Although sample location varied substantially from year to year, the patterns of concentration level of various elements and tree species are similar.
2) Deciduous species (white birch, sugar maple, trembling aspen, and red maple) are better indicators of the ultrabasic geochemical anomaly than are coniferous species. The 1981 survey, which included white spruce, balsam fir, and black spruce, showed similar behaviour for all coniferous species.

Table 7. Ability of elements and tree species to reflect the geochemical anomaly, based on regional patterns*

1984 Samples	Ca	Mg	Ni	Mn	Cr	Fe	Cu	Al	Total	Avg.
White birch										
May	-2	2	2		1	1	0	0	11	
June	0	2	3	-3	1	2	1	0	11	11.6
August	-2	3	3	-2	1	2	0	0	13	
Black spruce										
May	0	0	2	2	-2	0	0	0	6	
June	-1	2	1	-2	0	0	0	0	6	7.6
August	-2	3	3	-2	1	0	0	0	11	
Red maple										
May	-1	2	1	-2	0	0	0	0	6	
June	0	3	1	-3	2	1	0	0	9	8.6
August	-3	3	0	-3	1	0	1	0	11	
Sugar maple										
May	—	—	—	—	—	—	—	—	—	
June	-2	3	2	-3	0	0	0	0	10	9.5
August	-2	3	2	-1	0	0	0	-1	9	
Aspen										
May	—	2	1	-2	0	1	1	0	7	
June	-3	3	3	-2	0	2	1	0	14	10
August	-2	3	2	-2	0	0	0	0	9	
Total	-20	36	26	-32	9	9	4	-1		

* Correspondence of regional patterns with the geoghemical anomaly

0 = None

1 = some (weak)

2 = Good

3 = High

\- = Inverse to the anomaly (does not mean minus values)

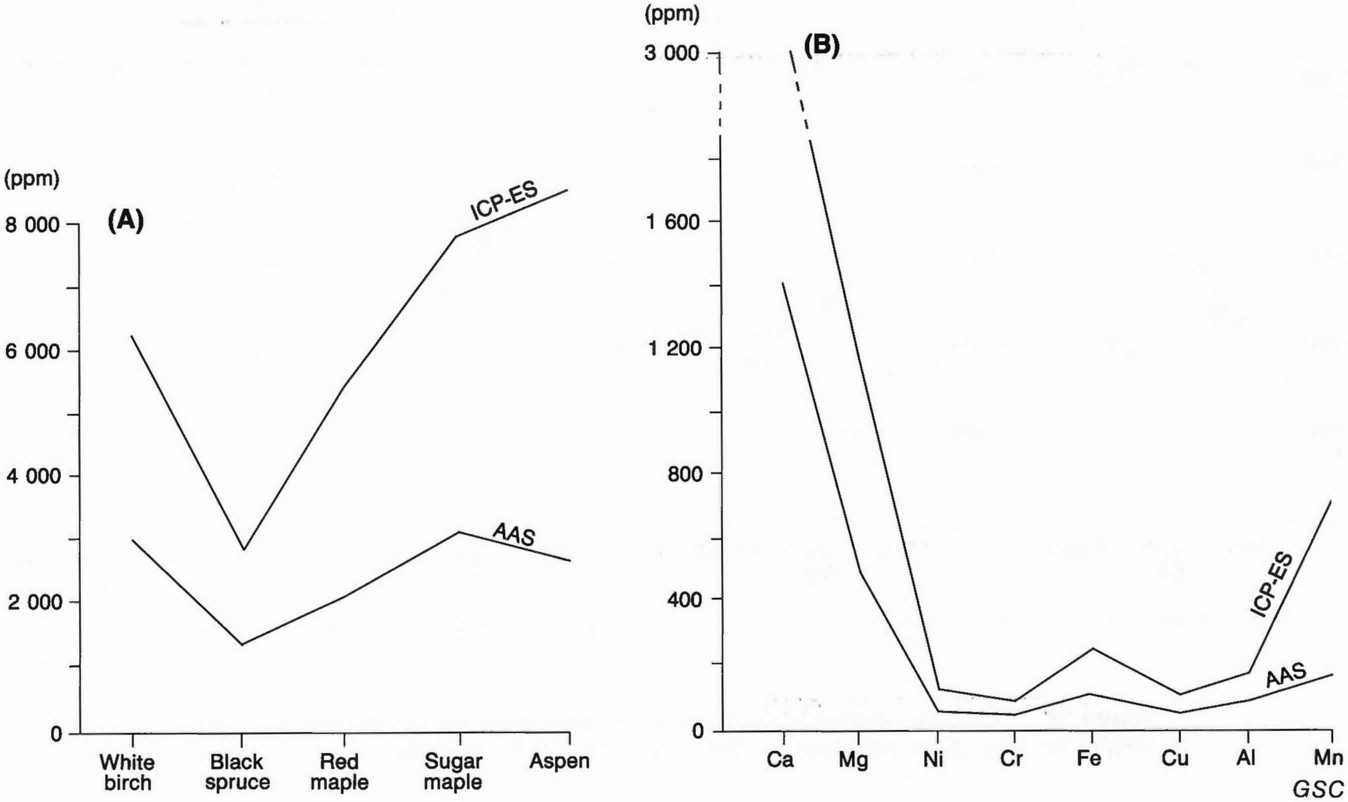


Figure 17. Examples of variations in concentration levels between AAS and ICP-ES, for vegetation samples collected in June 1984: (A) Ca in vegetation; and (B) element concentrations in black spruce. Values expressed on a dry weight basis.

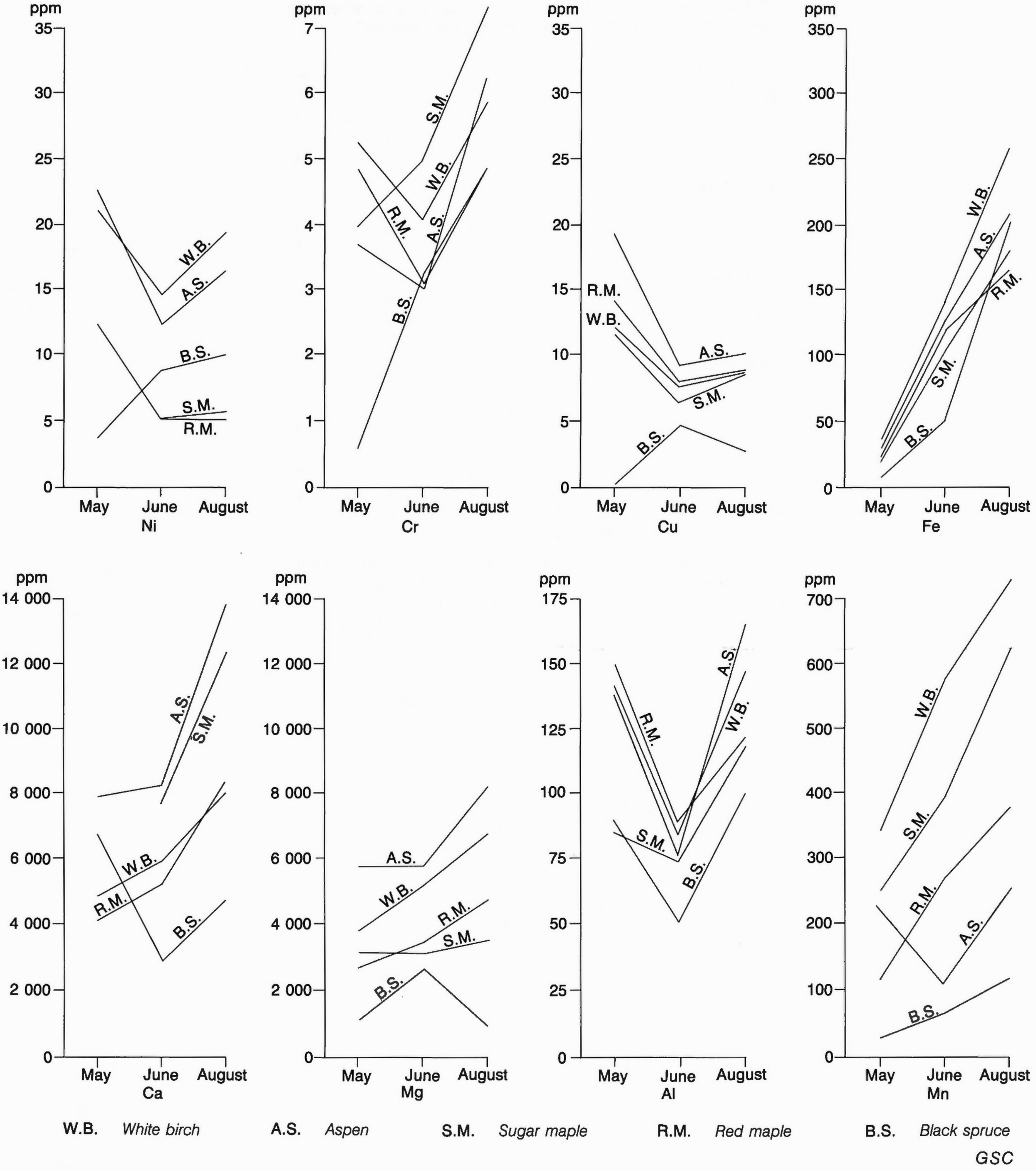


Figure 18. Seasonal variation in concentration of eight elements in plants; $\overline{X}$ ppm (dry weight) for May, June, and August 1984 (based on ICP-ES method).

3) Although sugar maple ranks second as an indicator, its uneven distribution (restricted to areas of low concentrations ultrabasic debris) makes it of limited value in drift prospecting.

4) Magnesium and nickel are considered better indicators of the dispersal train.

5) Manganese and, to a lesser degree, calcium are also good indicators, but show inverse reltionships with the ultrabasic component of the soil because of the dilution effect explained in "Geochemistry."

6) Chromium, although present in the ultrabasic debris cannot be used as agood biological indicator because the host mineral chromite is relatively stable in the soil, and is therefore not easily available to plants. The only regional pattern for chromium was for red maple sampled in June 1984 (Fig. 14C).

Effect of geochemistry on plants

The geobotanical study established the relationship between the geochemical anomaly and plant distribution. The biogeochemical study permits further analysis by monitoring the effect of plant chemistry on plant development. Bell et al. (1985) have shown that soils enriched with heavy metals provoke delay in leaf flush. Canney et al. (1969, 1979) reported that the onset of fall colours in deciduous flora may be hastened by toxic levels of heavy metals in the soil (early senescence). Because these factors can be detected on remote sensing imagery (Schwaller and Tkach, 1985), a study of leaf development and chlorophyll production was carried out throughout the study area. Investigations were made during May, June, and August 1984, by measuring leaf dimensions and by collecting duplicate leaf samples for chlorophyll and chemical analysis to study relationships between these characteristics. Chlorophyll analysis was impossible during May at several locations, because the leaves were just coming out or still in bud.

Regional patterns

Regional patterns described by leaf dimension (or new growth for black spruce) and chlorophyll content were graded using the same approach as for the chemical analysis and results are summarized in Table 9. The regional patterns show that early development of leaves (May) seems to be controlled more by topography than by geochemistry. No significant regional pattern was associated with the dispersal train in May (Fig. 19A). In early June and, to a lesser degree, in mid-August, the

Table 8. Evaluation of elements and tree species as indicators † of the geochemical anomaly, summarized from data collected in 1979, 1980, 1981, and 1984

Species	Ca	Mg	Ni	Mn	Cr	Fe	Cu	Al	Avg.	Average of Ca Mg Ni Mn Cr
White birch	45	80	84	88	30	55	0	0	47	65
Black spruce	30	68	70	66	9	0	0	0	30	48
Red maple	58	88	30	88	22	11	11	0	38	57
Sugar maple	76	100	71	66	0	0	0	18	41	62
Aspen	81	84	72	66	0	33	18	0	44	60
Average	58*	84	65	74*	12	19	5	3	40	58

†Values expressed as: 100 being excellent and 0 being useless as indicator
* Concentration in plants inverse to the geochemical anomaly.

Table 9. Summary of regional patterns of chlorophyll content and leaf dimension for May, June, and August 1984. The patterns are evaluated according to their ability to reveal the geochemical anomaly*

Species	MAY		JUNE		AUGUST	
	Chlorophyll	Leaf dimension	Chlorophyll	Leaf dimension	Chlorophyll	Leaf dimension
Sugar maple	—	1	2	2	3	1
Red maple	—	1	2	3	3	1
White birch	—	1	3	3	3	1
Aspen	—	1	2	1	2	1
Black spruce	—	1	2	2	3	1

* 0: No regional pattern
1: Weak regional pattern
2: Good regional pattern
3: Excellent regional pattern
—: No data available

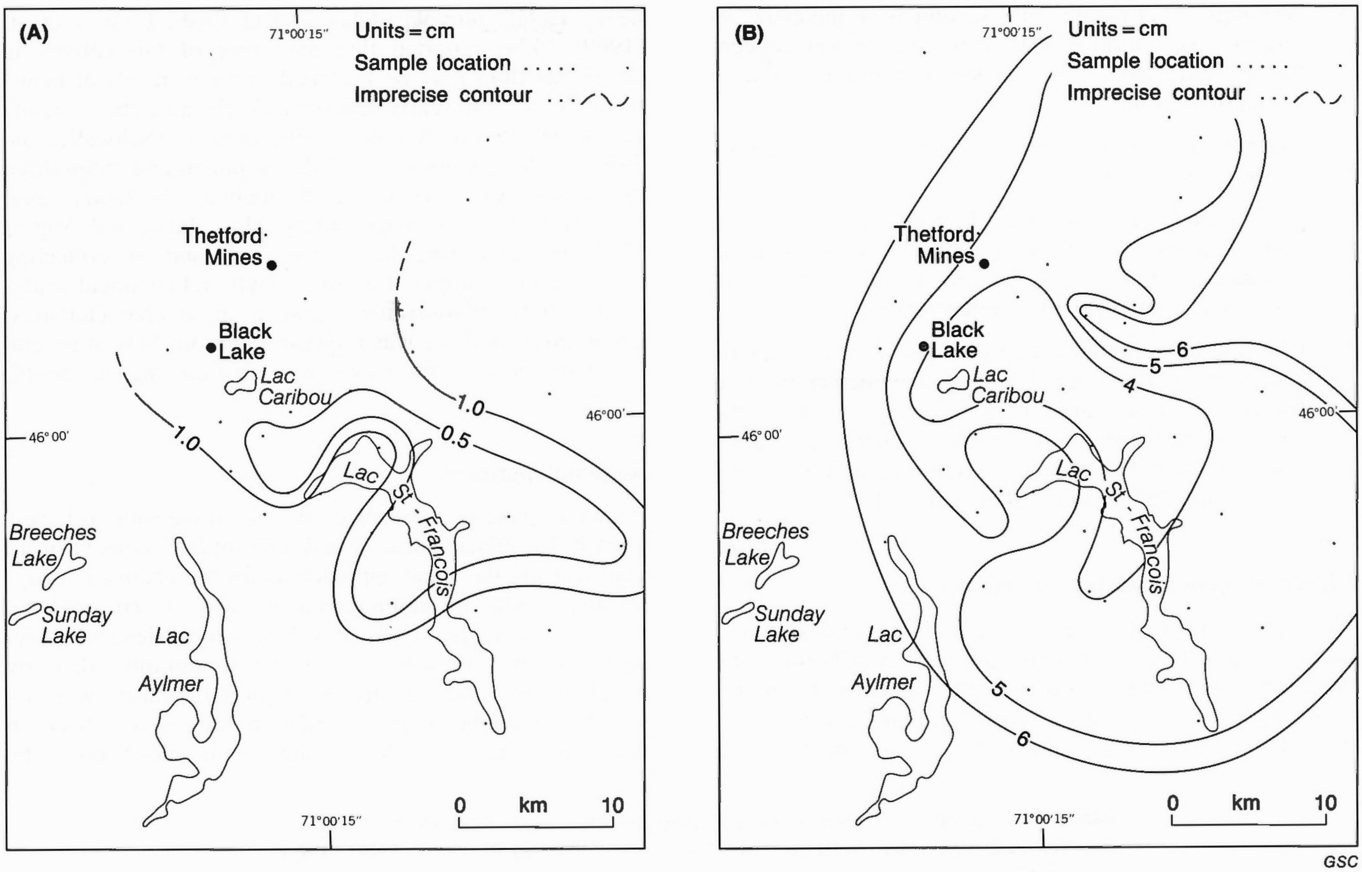


Figure 19. Leaf dimension patterns of white birch: (A) for May; and (B) for June.

influence of the geochemical anomaly on leaf dimension and chlorophyll production is more obvious (Fig. 19B). Figure 20 shows the significant relationship between chlorophyll production and leaf dimension for white birch and sugar maple in June.

Site data

Statistical analysis of the influence of heavy metals on leaf development and chlorophyll production gave no conclusive results for the 1984 samples, which seems to contradict earlier analysis (1979 and 1980) in which significant correlations were obtained for certain species (Table 10 and Fig. 21). An explanation could come from the method used for storing the leaf samples. In 1981 the leaves were kept cool but above freezing point, whereas in 1984 the leaves were frozen and, as the readings were taken, a rapid breakdown of chlorophyll was observed.

Samples of red maple and birch leaves collected in August 1984 showing discolouration (Fig. 10, 11) were sent to the pathology centre of the Canadian Forestry Service along with healthy samples collected outside the dispersal train, to be analyzed for possible causes of discolouration. The laboratory results were as follows:

1) Discoloration was not caused by micro-organisms or insects (pathological).
2) Chlorosis was related to physiological factors.
3) Numerous factors, such as microclimate, drainage, and analysis of other elements in soil and in vegetation, would have to be considered to give a complete diagnosis.
4) According to the chemical analysis, the problem was related to low calcium and excessive magnesium in the plants; the other trace elements analyzed were close to normal for the region. The calcium: magnesium ratio, which should be between 1 and 20 for healthy vegetation (Walker, 1954; Walker et al., 1955), was 0.49, 0.57, and 0.49 for birch, aspen, and red maple, respectively.

The regional patterns of calcium:magnesium ratios in birch, red maple, and aspen (Fig. 22A-C) indicate that the site yielding discoloured leaves is located close to the core of the dispersal train and corresponds to the lowest ratios found in the area.

Comparison of concentration values of various elements, chlorophyll, and leaf dimension for the discoloured samples from within the dispersal train to average values for samples outside the dispersal train (Table 11) yields the following observations:

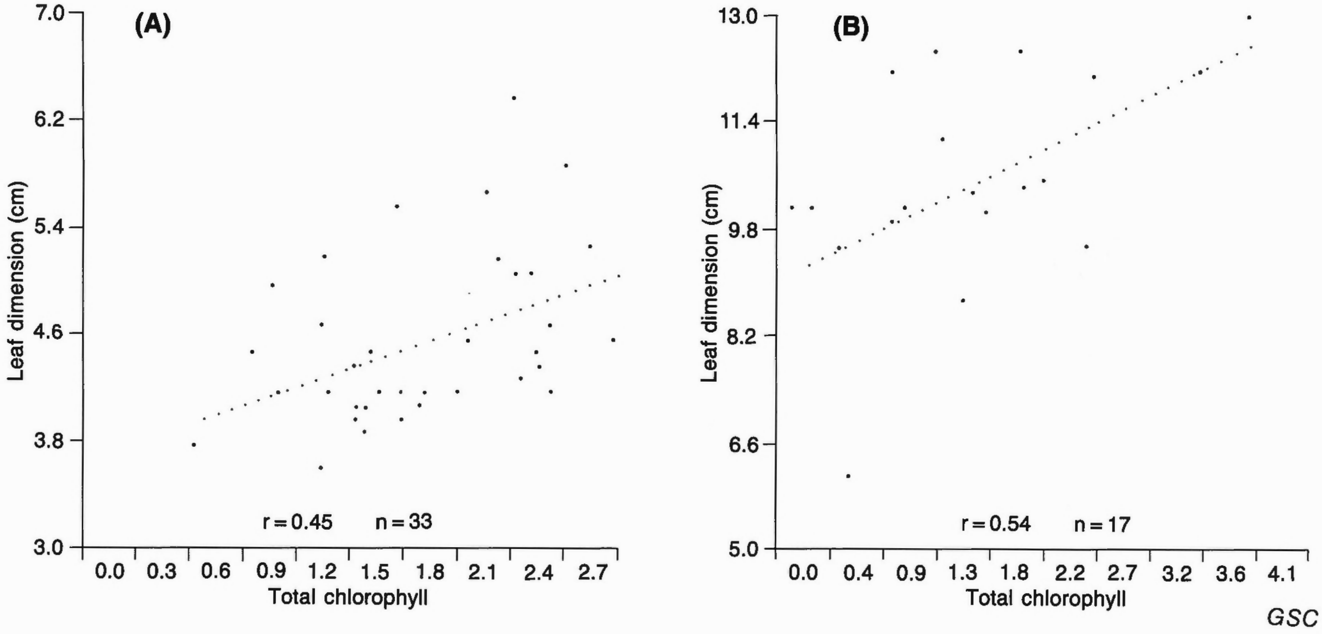


Figure 20. Correlation between leaf dimension and chlorophyll production for (A) white birch and (B) sugar maple. Samples collected on 10 June 1984.

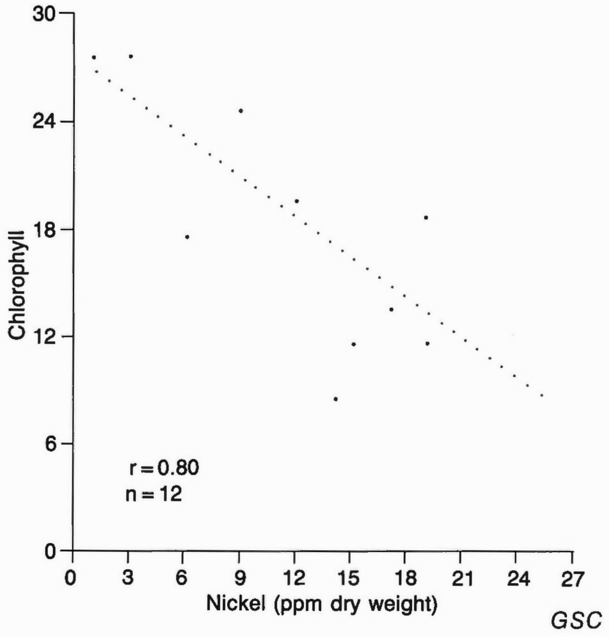


Figure 21. Correlation between nickel (leaves) and chlorophyll production in aspen collected in 1980.

Table 10. Correlation coefficients for chlorophyll production and concentration of elements in leaf tissues for samples collected in 1980

Species	Ni	Cr	Ca	Mg	n
Poplar	-0.78	-0.66	0.74	-0.52	13
Sugar maple	-0.14	-0.15	0.01	-0.25	17
Aspen	-0.48	—	0.52	-0.19	22
Balsam fir	0.30	—	0.45	-0.03	27

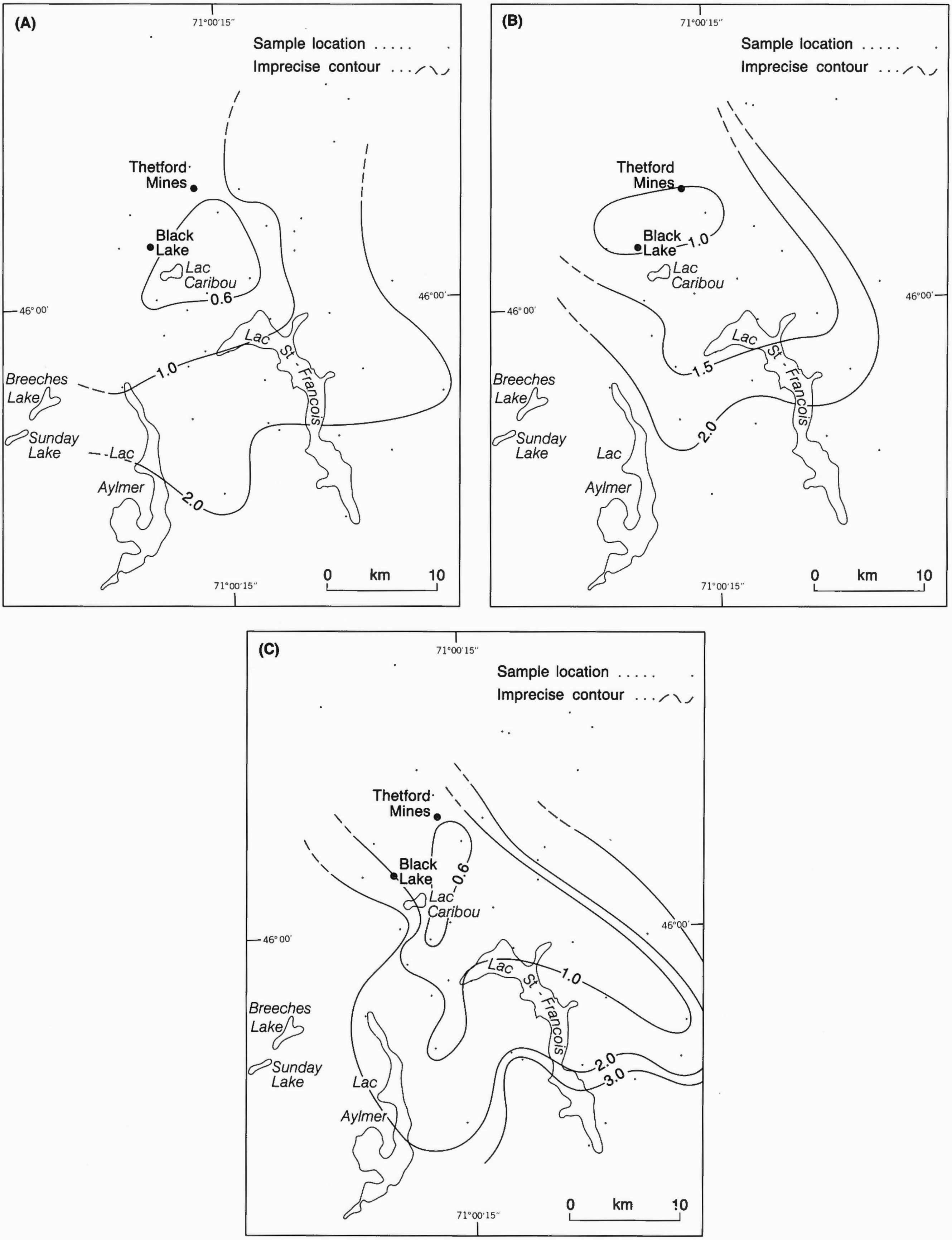
— No data available

1) Nickel, chromium, and iron are comparable to the background values.
2) Magnesium is substantially higher in the discoloured samples and, as pointed out before, manganese is lower than background values.
3) Calcium in the discoloured samples corresponds to the lowest value found in the study area.
4) Chlorophyll production of the discoloured samples is lower than background values whereas leaf dimension does not seem to be affected (except for white birch) by the chemical unbalance.

Study evaluation

The biogeochemical study permitted several points to be established with respect to the ultrabasic geochemical anomaly:

1) In glaciated terrain, where soils are derived from eroded and transported material, vegetation chemistry shows anomalous concentrations of nickel and magnesium and a deficiency in calcium and manganese that can be traced over an area far larger than the mineralized zone.
2) A direct correlation between soil and plant chemistry is difficult to obtain because of variations in local conditions, such as drainage, slope, type of soil, and microclimate, and in the ability of plants to absorb elements from the soil. Better results could be obtained by "weeding out" the original values and by using weighting factors based on environmental characteristics.
3) Maps showing regional patterns of concentrations of elements in plants closely outline the geochemical anomaly in the till and indicate its source.



GSC

Figure 22. Regional patterns of Ca/Mg in samples collected in August 1984: (A) white birch, (B) red maple, and (C) aspen.

Table 11. Comparison between chemistry and leaf dimension of discoloured samples with samples located outside the geochemical anomaly

		PPM dry weight						Chlorophyll	
	Discolouration	Ni	Cr	Mn	Fe	Mg	Ca	Dimension	(cm)
White birch	Yes	9	3	30*	199	6 530	3 172*	4.2	4.5
Outside[1]	No	9	3	1 300	135	4 000	12 000	4.7	6.0
Red maple	Yes	2	3	10*	86	7 200	3 454*	1.0*	13.0
Outside[1]	No	3	3	1 000	102	2 500	10 000	4.0	10.0

* Lowest value obtained for that species in the study area

[1] Average for samples located outside the geochemical anomaly

4) Yearly and seasonal variations in plant chemistry do not affect significantly the results of biogeochemical patterns although better results can be obtained from samples collected towards the end of the growing season.

5) In the mixed forest of the study region, leaves of deciduous species are better indicators of the geochemical anomaly than needles of black spruce.

6) Biogeochemical studies require more time and expense than geobotanical studies, but provide more detailed information on the size, location, source, and type of a geochemical anomaly. Geobotanical investigations describe pathological conditions of vegetation whereas biogeochemical studies provide precise quantitative information on the causes of plant disorder.

7) High concentrations (or deficiencies) of elements in soil and vegetation cause variations in the development of plants and in their chlorophyll production. These variations along with variations in plant distribution or segregation related to the ultrabasic geochemical anomaly serve as background information to the remote sensing study described in the following section.

REMOTE SENSING STUDY

Since the launch of Landsat in the early seventies numerous attempts have been made to use remote sensing imagery to monitor or discover ore bodies hidden by surficial geological formations (over-burden) and vegetation. Goetz et al. (1983) in their "overview of remote sensing applied to resource exploration" show the importance of the research done in this field and review the history, principles, and applications of remote sensing to mineral prospecting. A complete review of this literature in this case would therefore be redundant.

The major problem encountered in the use of space flight data to study geochemical anomalies is the difficulty of recording true spectral signatures of anomalous vegetation. In most cases the geochemical anomalies are too localized (< 2 km^2) and the variations in spectral signatures are too small to be detected precisely by a multispectral scanner (MSS). These problems are partly solved in this case as the ultrabasic dispersal train occupies a large area which permits study of the anomaly in various terrain conditions and vegetation types using Landsat imagery as well as airborne and field remote sensing. The problems encountered in this case study are related more to the difficulty of recording true spectral signatures of the vegetation because of coarse resolution of the pixels. This problem is common to all studies based on Landsat MSS date.

The study was carried out using a portable field radiometer, airborne data, and Landsat MSS to compare the efficiency of the three levels of remote sensing in detecting the geochemical anomaly. The portable radiometer-/photometer (SPECTRASPOT Tm) is equipped with five filters corresponding to a Landsat MSS bands 4, 5, 6, and 7, along with a blue filter (wavelenght 475 nm). Readings were taken in a laboratory under a controlled light source to avoid sunlight variations and the leaves were placed at a constant distance to assure that no background noise was recorded. Readings were taken for the June and August samples only, as the leaves collected during the May survey were too small to provide accurate readings.

The airborne flight was carried out on 18 August 1981, using a Daedalus 10-channel MSS plus infrared detectors. The flight altitude was 6 100 m above ground level, giving a pixel resolution of 6 m × 6 m. Four flight lines were required to cover an area equivalent to the study area described in Figure 23. Digitally corrected Landsat imagery (computer compatible tapes) was obtained for 10 June 1984, 29 August 1973, 5 August 1984, 4 September 1983, 24 September 1980, and 16 October 1984 to compare the evolution of spectral signatures during the summer and fall. It would have been preferable to use imagey all taken during the same year but that was impossible because of cloud cover.

Landsat MSS

Geobotany

The Landsat scene of 29 August 1973 is reproduced in Figure 23 to bring out the various spectral classes or "themes" recorded by Landsat MSS. The August 5 and 29 scenes show similar spectral classes, the August 29 scene is used in the examples because the image is of a better quality. Interpretation shows that the spectral classes are controlled mainly by the vegetation cover, which permits a study of vegetation distribution in relation to surficial geology.

The imagery shows a conspicuous tonal discontinuity that has northeastern and southwestern boundaries corresponding to the limit of the ultrabasic outcrops and their associated southeast-trending glacial dispersal train.

Reflectance values of various tree species taken from a Landsat scene of 26 June 1975 (Fig. 24), show that MSS band 4 (blue) and band 5 (red) cannot discriminate between various species, whereas bands 6 and 7 (near-infrared) are capable of separating several species that can be grouped into: coniferous (pine, spruce, fir, and cedar), alders, softwood deciduous (poplar, aspen), soft-hardwood (red maple, white birch), and hardwood deciduous (sugar maple, oak). The average chlorophyll content of species samples shows a direct relationship between chlorophyll content and reflectance values in the infrared bands (Fig. 25).

The shrub community located southeast of Thetford Mines-Lake is characterized more by a regional tonal pattern than by a precise spectral class. These shrub

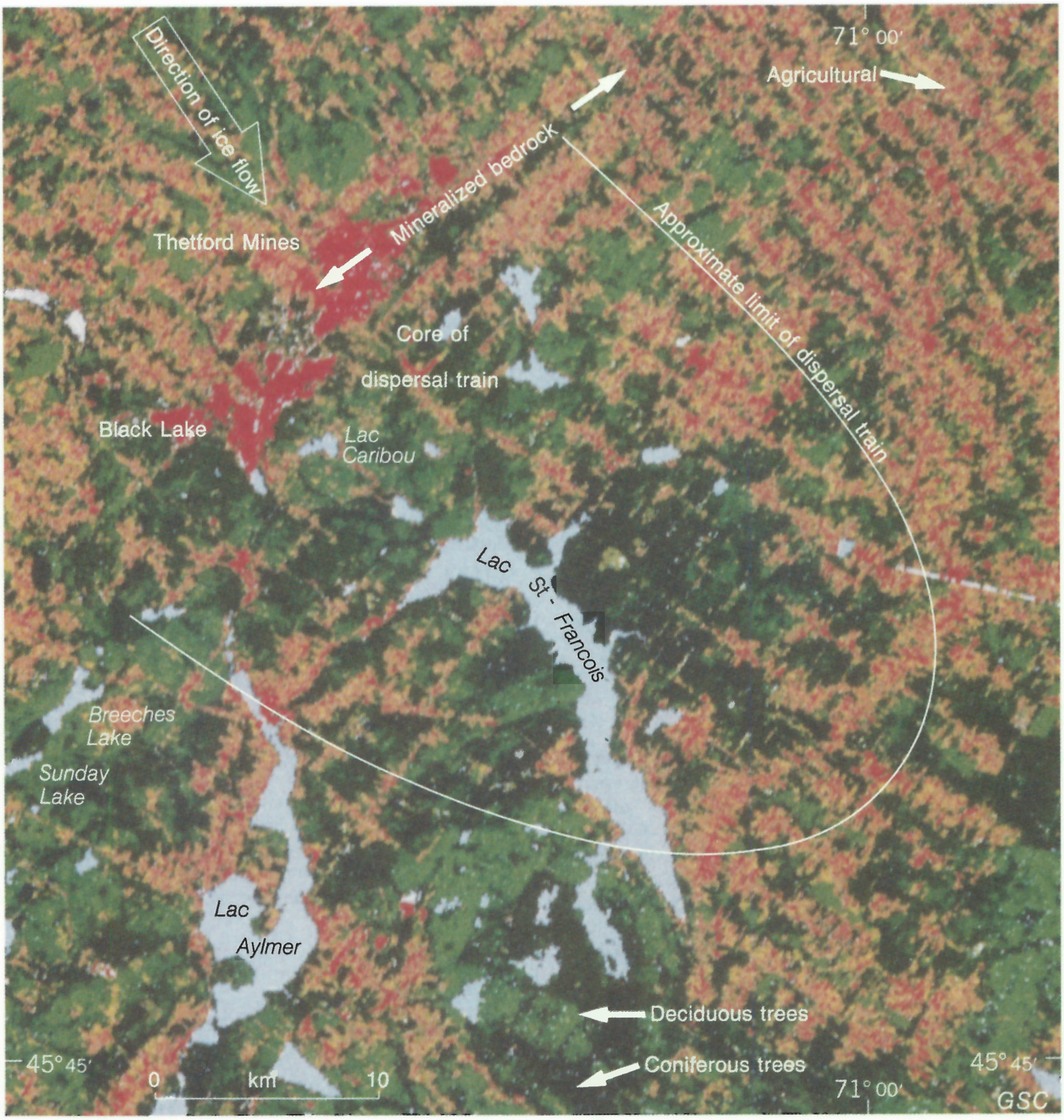


Figure 23. Interpretation of Landsat imagery of study area.

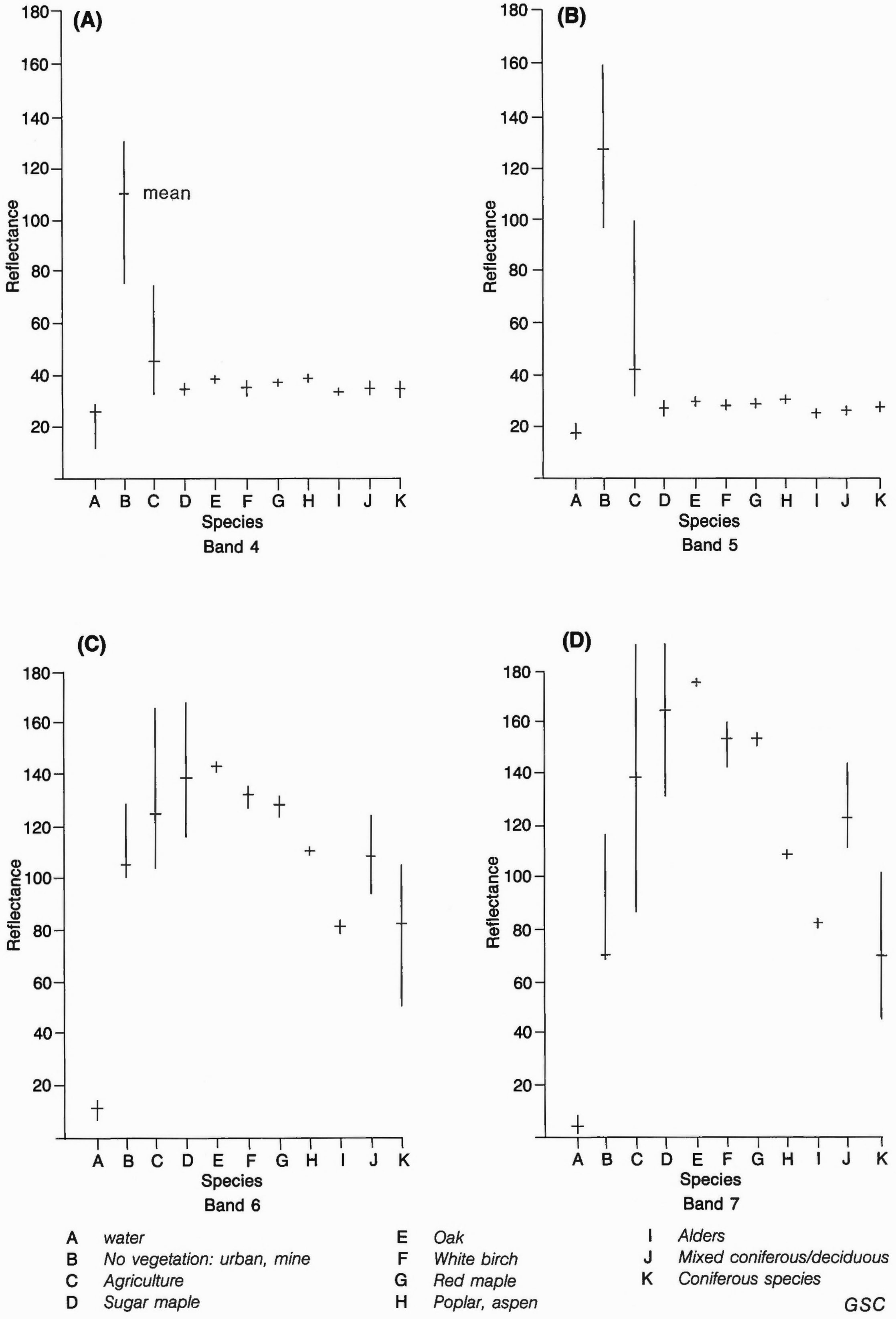


Figure 24. Reflectance of ground phenomena on Landsat imagery.

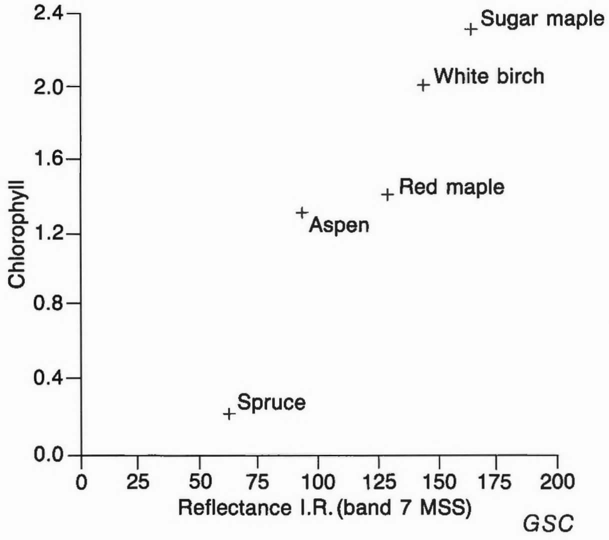


Figure 25. Comparison between chlorophyll production of tree species and reflectance values in band 7 (reflected infrared).

communities are hard to classify spectrally because they are composed of various species and usually have low chlorophyll production, which results in overlapping of several adjacent spectral classes.

The Landsat imagery shows that the deciduous species generally correspond to well drained soils and to thin soils on hills, except for the area of high concentrations of ultrabasic debris as noted in the section on "Geobotany". A typical example of a geobotanical anomaly is located on the hill separating Breeches Lake from Sunday Lake (southwest of Thetford Mines): usually hills having thin soils and similar relief (150 m) support hardwood deciduous species whereas the imagery shows a spectral class of coniferous species. Field verification showed that the hill corresponds to an ultrabasic rock outcrop and, even though a large portion of the hill is covered by deciduous trees, the Landsat imagery classifies the areas as coniferous species because of the low chlorophyll content of the local vegetation.

Multidate analysis

Although Landsat imagery can be used successfully to map vegetation, extensive field studies are required to identify anomalous vegetation patterns or spectral signatures. When exploring new areas, for which ground information is limited, single-date imagery is of limited use, because subtle changes in vegetation behaviour resulting from geochemical stress are not readily apparent. To overcome the necessity of extensive ground studies for geochemical exploration based on remote sensing, images taken at different dates can be used and the spectral signatures can be compared for variations from one season to another to detect anomalous changes.

Anomalous variations in vegetation biomass (density of green vegetation) throughout the growing season can be monitored using the biomass index (Canney et al., 1979). Delay in leaf flush (Bell et al., 1985), premature leaf senescence (Schwaller and Tkach, 1980) or a shift in the red-infrared reflectance values of stressed vegetation (Canney, 1969), such as the example of sugar maple (Fig. 26), can all be detected in multidate Landsat imagery.

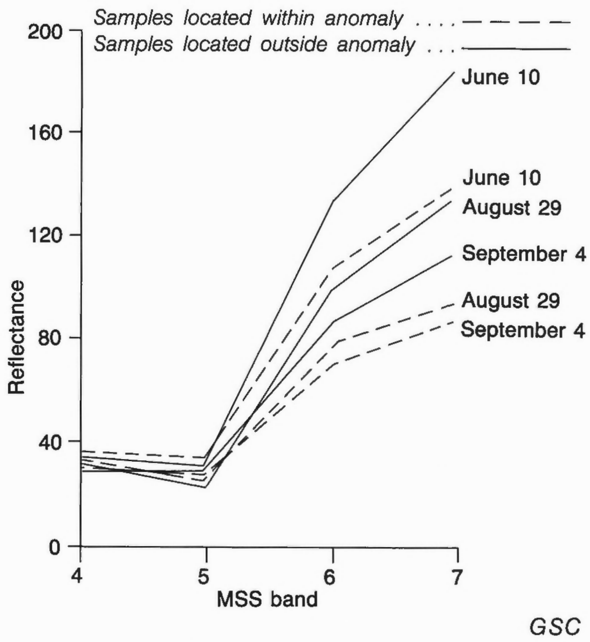


Figure 26. Example of variation in spectral signature of sugar maple samples located within and outside the dispersal train. Lower reflectance in the I.R. of samples located within the anomaly is a direct consequence of lower chlorophyll production.

Biomass index

Vegetation biomass and physiological conditions of vegetation can be monitored in remote sensing by comparing red to near-infrared reflectance values. The basic properties of infrared (I.R.) and red (R.) radiance with respect to green vegetation have been studied in detail by Tucker (1979, p. 130-131) who reported: "The red radiance exhibits the nonlinear inverse relationship between integrated spectral radiance and green biomass, while the near infrared component exhibits a nonlinear direct relationship." The relationship between the red radiance and green biomass results from strong spectral absorption of incident radiation by chlorophyll whereas in the near-infrared there is a lack of spectral absorption by green vegetation and a high degree of intra- and inter-leaf scattering in the plant canopy.

Several methods of calculating biomass index are used (such as adding bands before ratioing, and using the quadratic root) but Tucker found that the results were similar for the various techniques ($< 6\%$ variation). Because there is no scienfic basis for using more sophisticated transformation of the original I.R.: R. ratio, a linear ratioing is used for this project.

Figure 27A

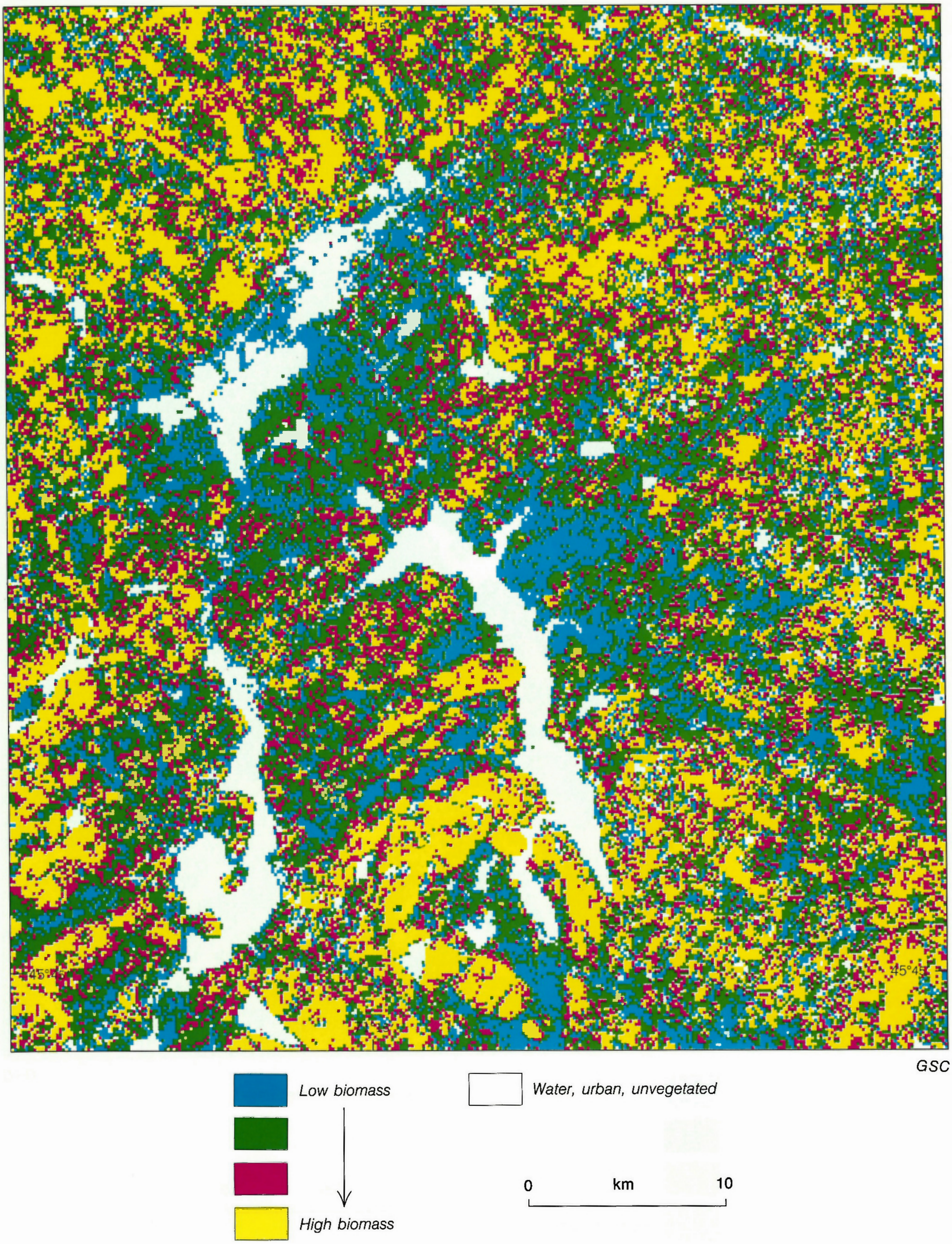


Figure 27. Biomass index maps: (A) for June 10, (B) August 29, (C) September 24, ans (D) October 16.

Figure 27B

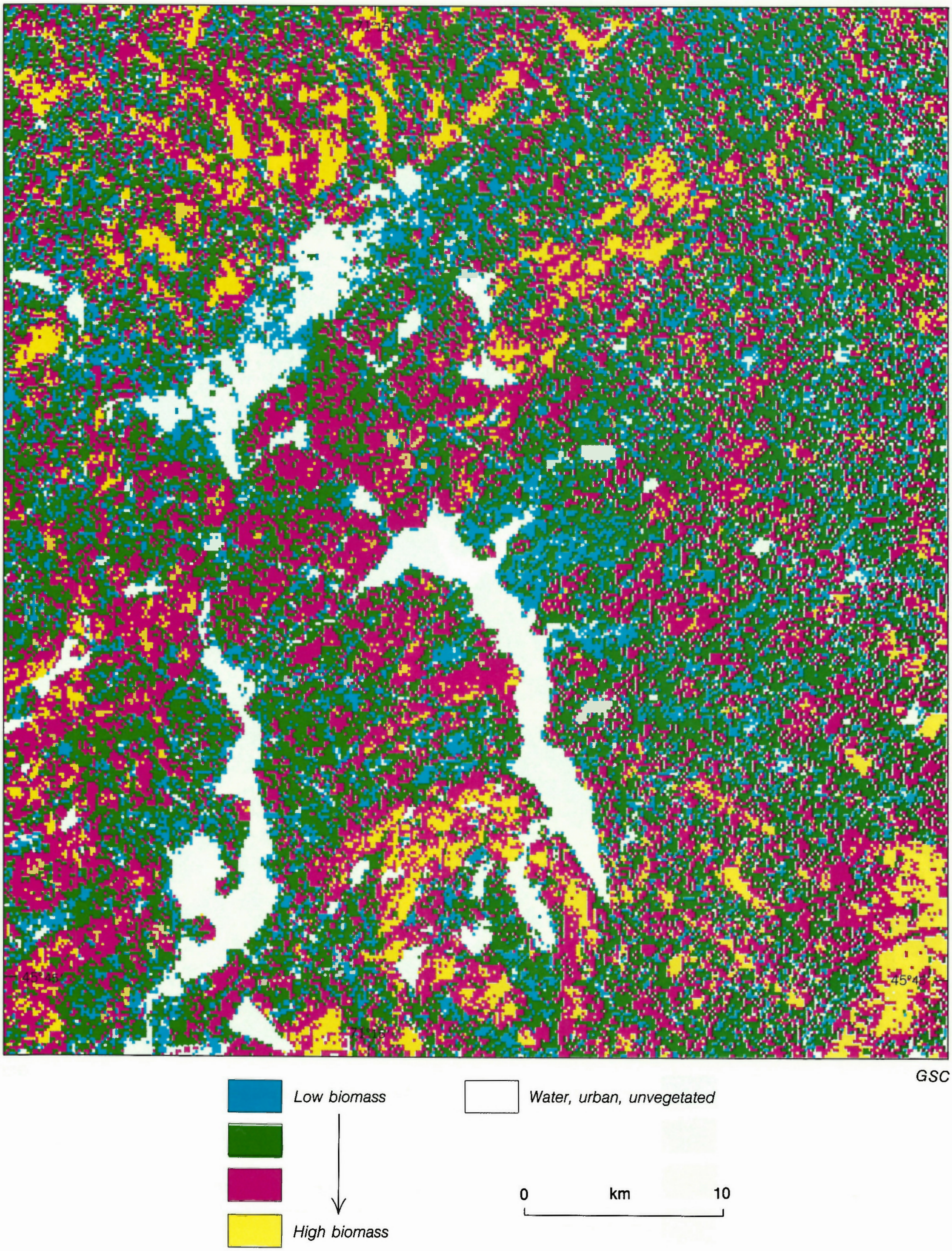
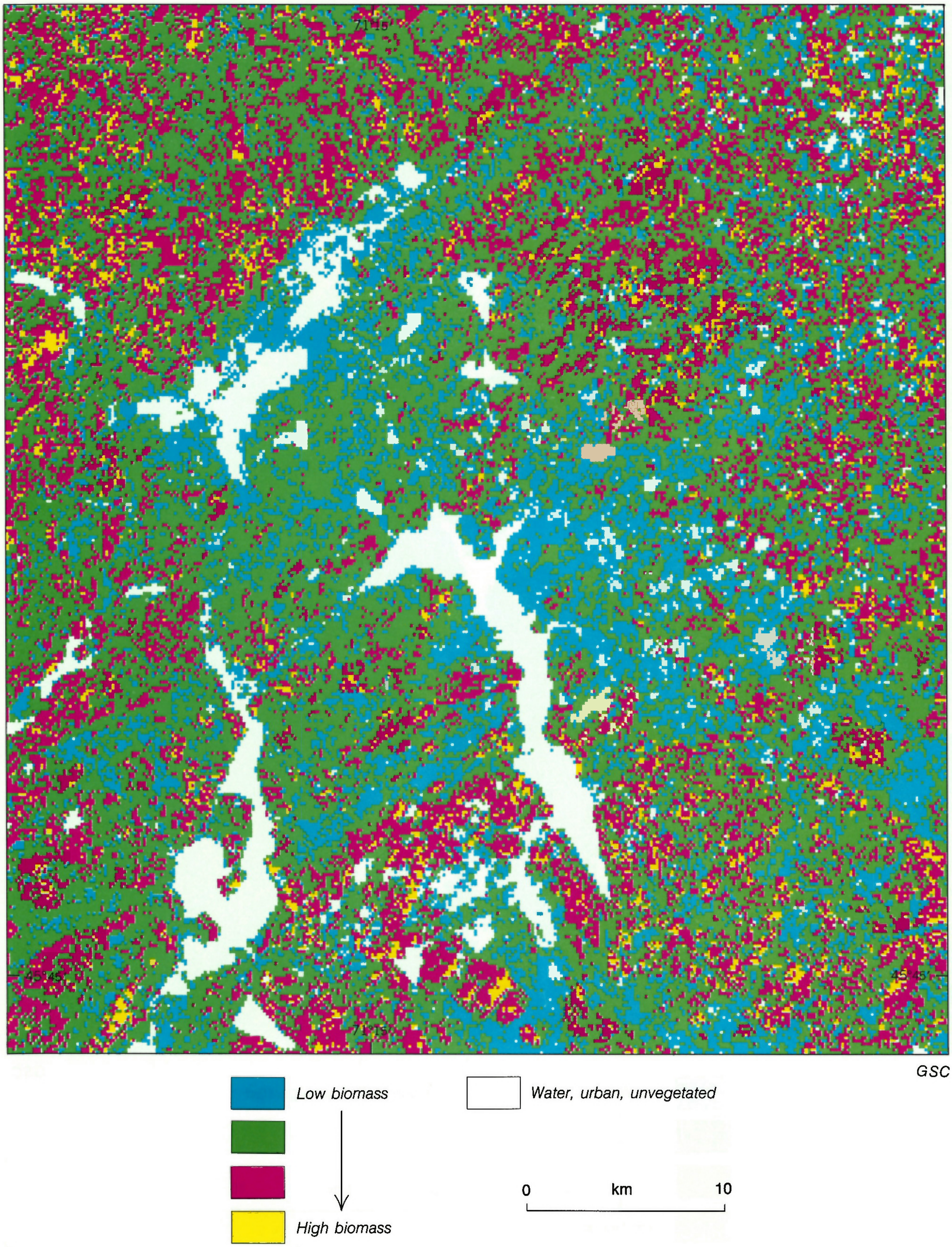

71°15'
45°45'
45°45'
71°15'
GSC
Low biomass
High biomass
Water, urban, unvegetated
0
km
10

Figure 27C


71°15'
45°45'
45°45'
71°15'
GSC
Low biomass
High biomass
Water, urban, unvegetated
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km
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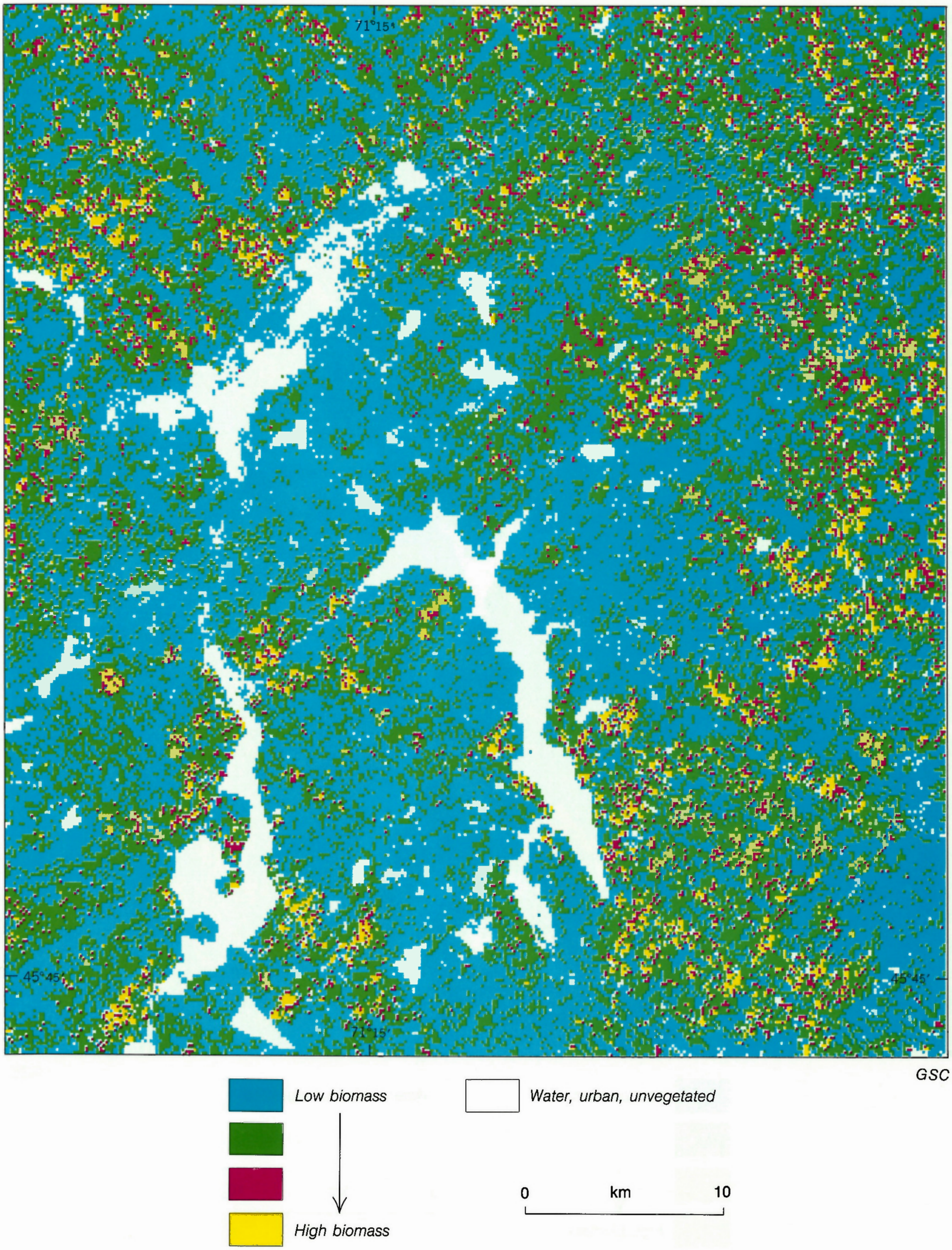
Figure 27D


71°15'
45°45'
45°45'
71°15'
GSC
Low biomass
High biomass
Water, urban, unvegetated
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10

Analysis of Biomass. In the Thetford Mines area, both a late flush and early senescence were observed during the field surveys. To monitor these changes, the biomass index was calculated for the Landsat scenes of June, August, September, and October according to the method described. Examples of biomass index maps for June 10, August 29, September 24, and October 16 are given in Figure 27A-D; scenes of August 5 and September 4 are not presented as they show patterns similar to the August 29 scene.

Vegetation stress is more apparent in early summer and early fall than at the peak of the growing season. On the June 10 scene, low-biomass vegetation is concentrated in the area southeast of Thetford Mines-Black Lake, corresponding to the dispersal train, whereas high-biomass vegetation (deciduous, hardwood) is almost absent from this area. On the August 29 scene, the tonal pattern disappears to reappear on the September 24 scene and, to a lesser degree, on the October 16 scene.

Vegetation stress can vitiate spectral signatures. The blue areas on the August 29 scene (see Fig. 27B) correspond to almost pure coniferous stands, which have a lower biomass index than mixed or deciduous stands; deciduous species are represented in red and yellow. On the October 16 scene, deciduous stands have generally lower biomass indices than coniferous stands because the leaves are gone yet the conifers are still producing chlorophyll. In the area immediately southeast of Thetford Mines-Black Lake, corresponding to high levels of ultrabasic debris, the vegetation shows a biomass index corresponding to: deciduous for August, predominantly coniferous for October, and mixed deciduous and coniferous for September and June.

Although a straight comparison of the biomass index is capable of bringing out tonal differences between the dispersal train and background conditions, this approach is insufficient to monitor vegetation types or chlorophyll content because local conditions, such as stress induced by a geochemical anomaly, can vitiate spectral signatures of vegetation. To monitor variations in biomass index and possible anomalous behaviour of certain species, scatter diagrams and corresponding maps were plotted to show the relationship between biomass for June versus August, August versus September, and August versus October.

The June/August scatter diagram (Fig. 28) is used to show the relationship between early, normal, and late vegetation flush. Early flush is characterized by relatively high production of chlorophyll in early June (index greater than 17) and average production of chlorophyll in August (index 12 to 18). Late flush corresponds to vegetation the biomass of which is low in June but high in August. High biomass index for both June and August correspond to hardwood deciduous species, such as sugar maple and birch, the spectral signatures of which are not affected by stress conditions. A map of late versus early and normal flush (Fig. 29) shows a close relationship between the dispersal train and late flush whereas early flush and high biomass index vegetation are located mainly outside the dispersal train.

On the August 29/September 24 scatter diagram (Fig. 30), vegetation having a high August and low September biomass has been identified as exhibiting early senescence, and vegetation with a high September biomass is identified as showing late senescence. The two classes are plotted in Figure 31, and show that early senescence vegetation is located mainly in the dispersal train area whereas the normal vegetation is concentrated mainly outside the dispersal train.

A comparison of biomass between August 29 and October 16 (Fig. 32) permits identification of coniferous and, deciduous species and of agricultural land, but gives little information on the health of the vegetation because all deciduous species have lost their leaves.

Airborne MSS

Although it was not possible to compare multidate data, because only one airborne flight was available, the airborne data were used to confirm the results obtained from Landsat analysis. A comparison of biomass indices show a close correlation between the August 29 scene and the airborne data (Fig. 33). The lack of precise correlation could result from the averaging of spectral signatures over a large area by Landsat compared to smaller pixel size for the airborne MSS, or could result from the difference between Landsat bands 5 and 7 and airborne bands 8 and 10 (red and infrared).

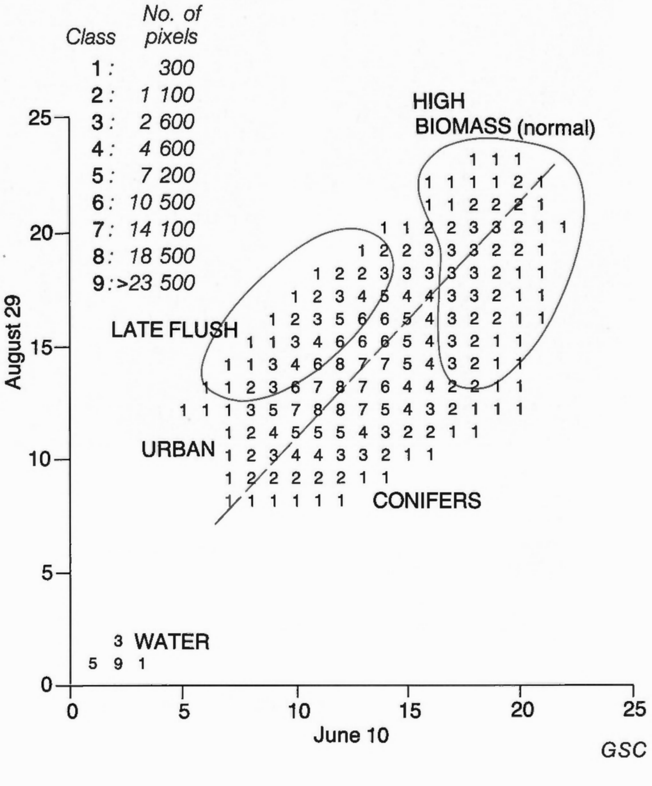

Figure 28. Scatter diagram comparing biomass for June 10 to August 29.

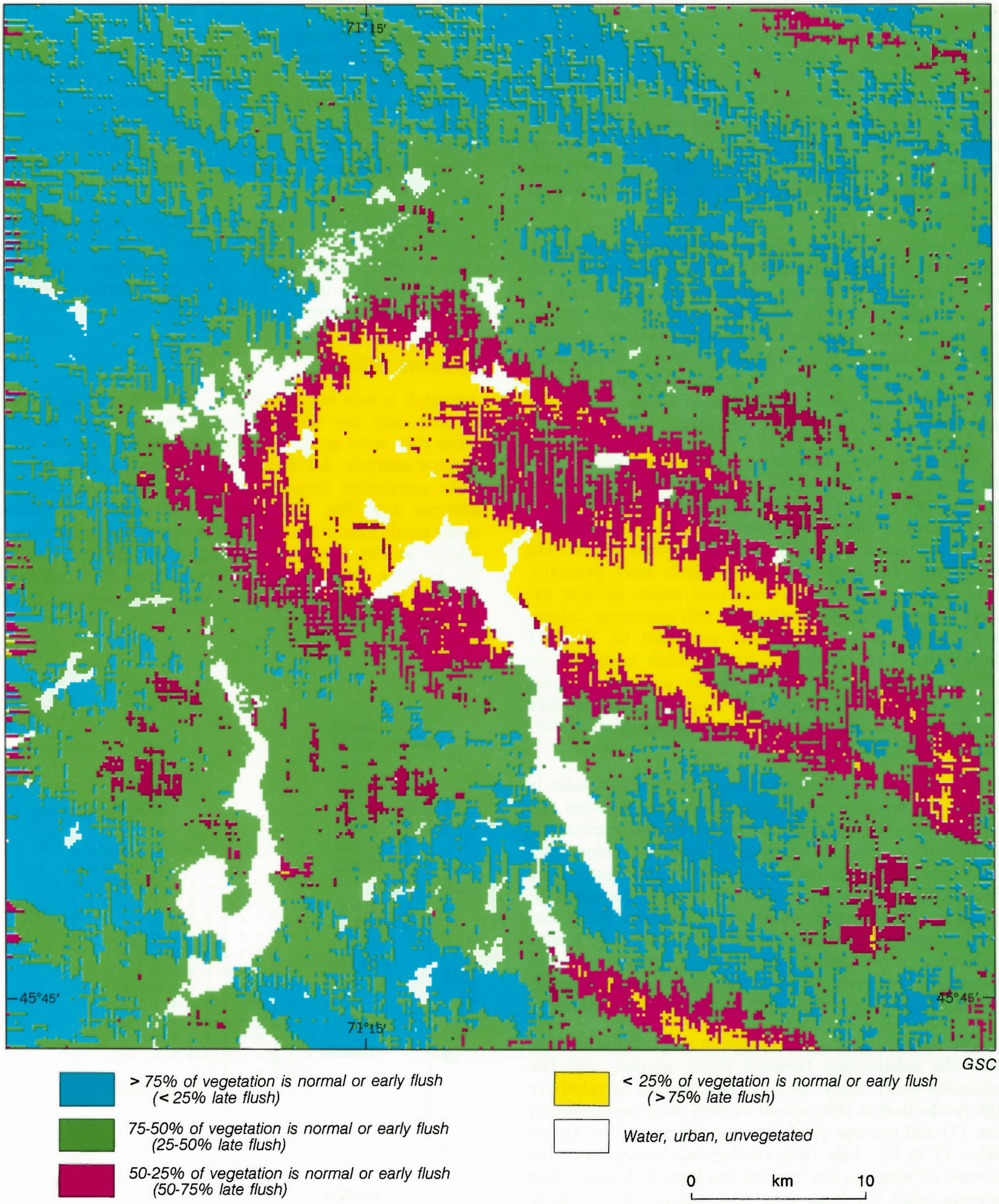

Figure 29. Regional pattern of normal versus late spring flush.

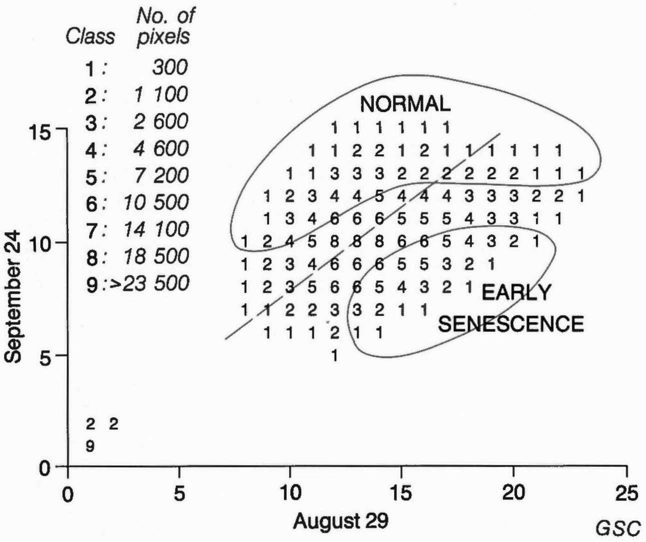

Figure 30. Scatter diagram comparing biomass for August 29 to September 24.

The major limitations of the airborne mission are related to the high cost of data acquisition, the difficulty (if not impossibility) of merging flight lines to form a continuous image or superposing images taken at different times, and the large volume of data to process (70 000 000 pixels × 11 channels to cover an area of 50 km × 50 km).

Airborne remote sensing can give a more accurate spectral signature than space flight data because of its better spectral and spatial resolution but the problems mentioned above make this approach impractical for use in large-scale exploration compared to Landsat data, especially if multidate analysis is required.

Field radiometer

For the field remote sensing study, the leaves were stored at cool temperature (2° to 5°C) during the day and readings were taken less than 8 hours after they were harvested. Attempts were made to freeze the samples at low temperature using dry ice to preserve the chlorophyll, but the leaves turned brown within a few seconds after the samples were placed under the radiometer at room temperature, making an accurate reading impossible. Readings were taken for the June and August samples only, as many of the leaves collected in May were too small to permit accurate reading.

Statistical analysis failed to show any significant relationship between spectral signatures and concentration of elements or chlorophyll production by plants. On the other hand, maps of biomass indices from the field radiometer show patterns similar to those obtained for Landsat data (Fig. 34). Red maple, aspen, sugar maple, and white birch showed better patterns in August than in June. As pointed out by Canney (1975) the acquisition of field remote sensing data is a time-consuming process and impossible at some sites, which makes this technique less than satisfactory when dealing with a large area. The lack of correspondence between spectral signature and concentration of elements could be caused by the lack of precision of the radiometer, but also shows the "complexity of the possible cause-effect relationships influencing vegetation canopy reflectance" as pointed out by Colwell (1974). Thus, it might prove difficult, if not impossible, to explain canopy reflectance if all the important environmental characteristics are not taken into consideration in detailed remote sensing studies.

CONCLUSIONS

The geochemical anomaly located near Thetford Mines provides an ideal target for testing botanical prospecting techniques, because of its large size, the high concentration of heavy metals in the soil, and the variety of vegetation cover. The study area also permitted an evaluation of remote sensing in diversified land use activities ranging from forestry and agriculture to mining and urban development. Even though the prime objective of this study was to evaluate remote sensing techniques in large-scale prospecting, the research led to the establishment of several general principles that can be applied in geobotany and biogeochemistry:

1) Soils enriched in ultrabasic debris influence the type and development of vegetation that grows in an area. Geobotanical studies can detect such anomalies but can be used only as preliminary research because they do not provide information on the chemistry of plants or soil.
2) Biogeochemical investigations can provide accurate information on soil geochemical anomalies and can be used effectively in geochemical exploration giving results similar to those produced by drift prospecting techniques.
3) Remote sensing can be used to monitor vegetation variation related to plant distribution, development, and pathological conditions. Field and airborne remote sensing offer good spectral and spatial resolutions but are expensive, time-consuming, and better suited for site information because continuous imagery for a

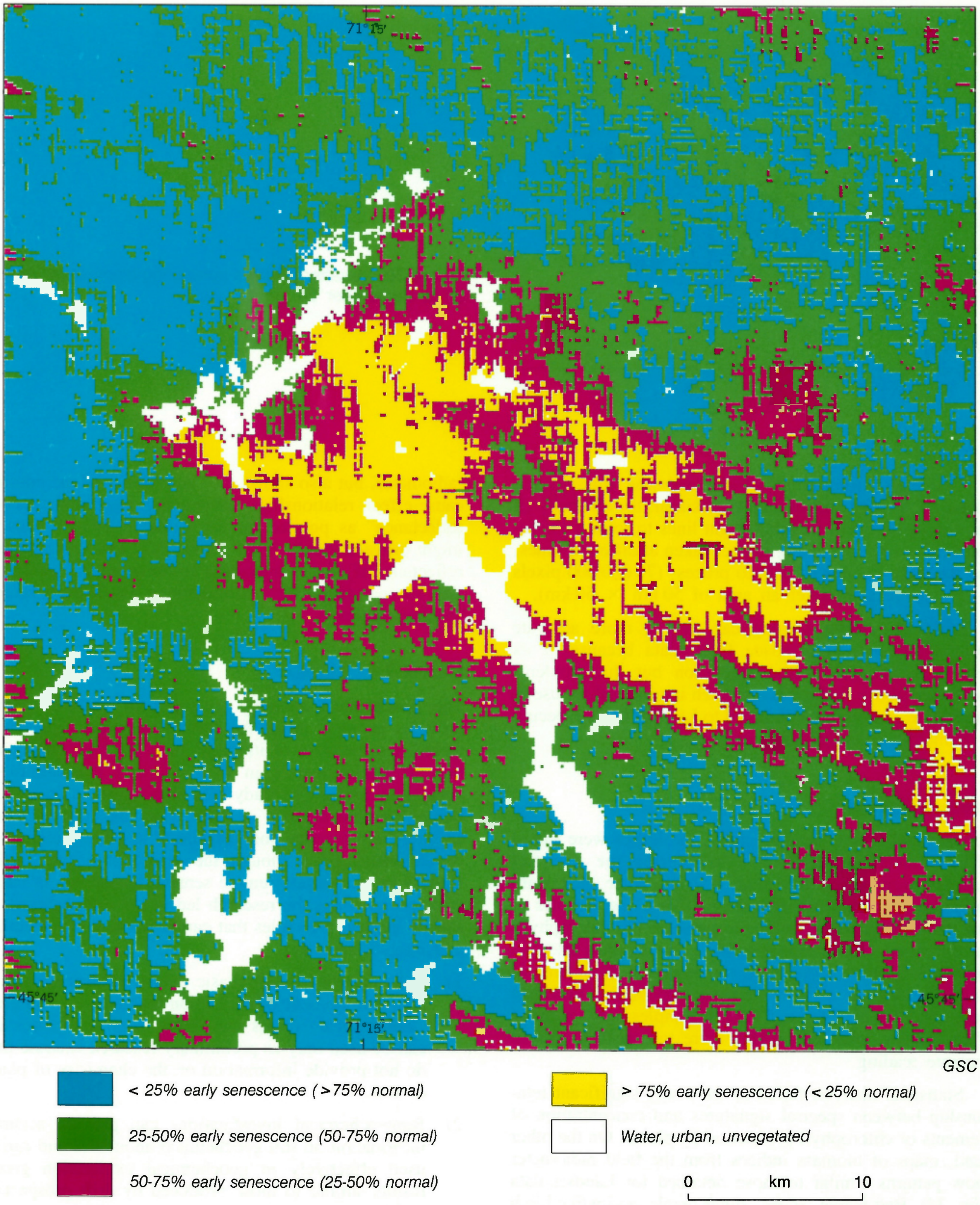

Figure 31. Regional pattern of normal versus early senescence.

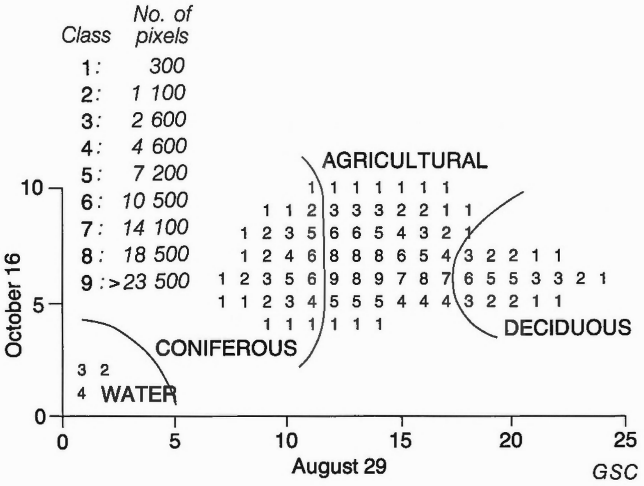

Figure 32. Scatter diagram comparing biomass for August 29 to October 16.

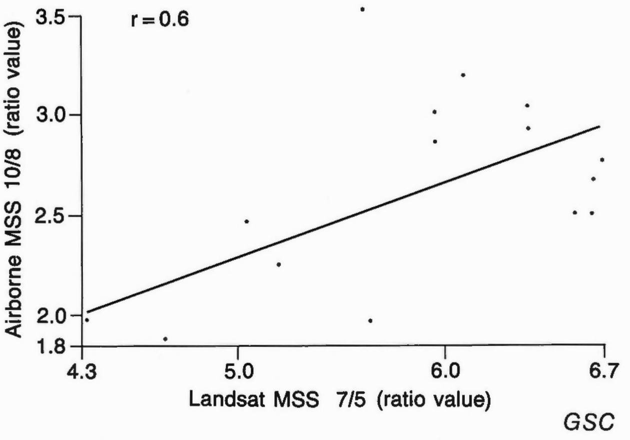

Figure 33. Biomass correlation between Landsat MSS (bands 7/5) and airbone MSS (bands 10/8).

large area is difficult to produce. Landsat multispectral data have coarser resolution but cover a large area, permitting the detection of anomalies in the vegetation at a regional level. Landsat also provides multidate imagery, at relatively low cost, which can be used to monitor the spectral evolution of vegetation revealing any anomalous spectral behaviour. The processing of Landsat (or remote sensing) data does not necessitate complex statistical analysis or mathematical algorithms to reveal vegetation anomalies. Processing, based on sound geobotanical, biogeochemical, and remote sensing principles, can provide information that can be related to ground conditions and is useful in mineral prospecting.

The recording of a larger part of the spectrum along with a better pixel resolution of the Thematic Mapper Scanners on Landsat IV and V will probably improve the detection of subtle and localized geobotanical and biogeochemical anomalies. For surveying a large area of glaciated terrain, a coarse pixel resolution (such as that of Landsat MSS) does not present a serious handicap because many localized, mineralized outcrops have been eroded and the debris spread out by glaciers forming mineralized dispersal trains much larger than the bedrock sources. Even with improvements to the new generation of sensors, the major problem in space flight remote sensing remains namely, the difficulty of obtaining several good-quality images (cloud free) over an area to permit the monitoring of vegetation during its full annual cycle.

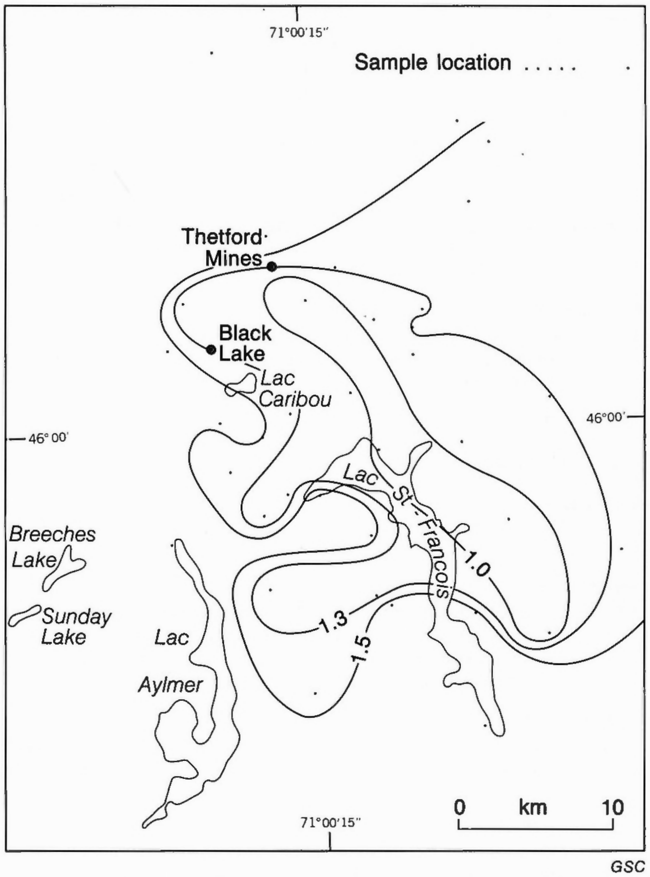

Figure 34. Biomass indices from the field radiometer.

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