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Earth Physics Branch
Direction de la physique du globe

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Seismological Service of Canada

THE IDENTIFICATION OF STRUCTURAL LINEARS
FROM LANDSAT IMAGERY IN NORTHWESTERN ONTARIO

by

Geo-analysis (1981) Ltd.,
1725 St. Laurent Blvd.,
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Ottawa, Ontario
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EARTH PHYSICS BRANCH OPEN FILE NO. 82-12

Ottawa, Canada

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ABSTRACT

A lineament study covering an area of 156,000 km^2 in northwestern Ontario has been completed from Landsat imagery. Mean lineament azimuths for seven geological subprovinces are: 069° (English River), 064° (Wabigoon), 078° (Quetico), 084° (Wawa), 060° (Lake Superior Basin), 058° (Port Arthur Homocline) and 183° (Nipigon Plate). A 1:1,000,000 compilation of the mapped linears shows many interesting apparent structural trends and domains of coherent deformational style.

Maps of lineament density and intersection frequency shows several areal minima. While some lows correspond to areas of thick glacial cover, 23 other areas appear to be regions of genuine low lineament density.

RESUME

Une étude de linéaments s'étendant sur une superficie de 156000 km^2 dans le nord-ouest de l'Ontario a été effectuée à partir des images Landsat. Les azimuths moyens de ces linéaments pour sept sous-provinces géologiques sont: 069° (English River), 064° (Wabigoon), 078° (Quetico), 084° (Wawa), 060° (bassin du Lac Supérieur), 058° (Homocline de Port-Arthur) et 183° (plaque Nipigon). Une carte des linéaments cartographiés à l'échelle 1:1,000,000 montre plusieurs directions structurales apparentes intéressantes ainsi que des domaines où le style de déformation est bien développé.

Les cartes de densité et de fréquence d'intersection des linéaments montrent plusieurs zones correspondant à des minima. Alors que quelques uns de ces minima correspondent à des régions recouvertes par une épaisse couverture glaciaire, 23 de ces zones semblent correspondre à des régions où la faible densité de linéaments est significative.

Report Prepared for
The Earth Physics Branch
Energy Mines and Resources
DSS File No: 15SQ.23233-0-1424

The Identification of Structural Linears from Landsat Imagery in Northwestern Ontario

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Table of Contents

		Page
1.0	INTRODUCTION	1
1.1	Study Area	1
1.2	Methodology	1
1.2.1	An Approach To Classification	5
1.2.2	Classification Method	7
1.3	Background Studies	8
2.0	GEOLOGY AND STRUCTURAL DOMAINS	12
2.1	Superior Province	12
2.1.1	The English River Belt	12
2.1.2	The Wabigoon Belt	13
2.1.3	The Quetico Belt	14
2.1.4	The Wawa Belt	14
2.2	Southern Province	15
2.2.1	The Port Arthur Homocline	16
2.2.2	The Lake Superior Basin	16
2.2.3	The Nipigon Plate	16
2.3	Surficial Geology	17
3.0	LINEAR TRENDS IN STRUCTURAL DOMAINS AND THEIR INTERPRETATION	19
3.1	Linear Trends and Orientation	20
3.1.1	Superior Province	20
3.1.1.1	The English River Belt	20
3.1.1.2	The Wabigoon Belt	22
3.1.1.3	The Quetico Belt	24
3.1.1.4	The Wawa Belt	26
3.1.2	The Southern Province	28
3.1.2.1	The Lake Superior Basin	28
3.1.2.2	The Port Arthur Homocline	30
3.1.2.3	The Nipigon Plate	32
3.2	Lineament Density	33

(cont'd) Table of Contents

		Page
3.3	Lineament Intersection Density	36
4.0	CONCLUSIONS	38
	APPENDIX I: Formulae for Mean, Standard Duration and Variance	

List of Tables

		Page
TABLE 1:	Imagery used in the study	4
TABLE 2:	Linear trends, English River Belt	21
TABLE 3:	Linear trends, Wabigoon Belt	23
TABLE 4:	Linear trends, Quetico Belt	25
TABLE 5:	Linear trends, Wawa Belt	27
TABLE 6:	Linear trends, Lake Superior Basin	29
TABLE 7:	Linear trends, Port Arthur Homocline	31
TABLE 8:	Linear trends, Nipigon Plate	34

List of Figures

Figure 1: Study Area divided up into 1:250,000 Map Sheets 2

Figure 2: Study Area showing the Location of the Imagery 3

Figure 3: Frequency distribution of photo lineaments by structural domains. (in pocket)

Maps

Map 1 to 9	(Airphoto lineaments maps of Northwestern Ontario)	(in roll)
Map 10	Lineament map of Northwestern Ontario	(in pocket)
Map 11	Contours of Lineament Density	(in pocket)
Map 12	Contours of Lineament Intersection Density	(in pocket)
Map 13	Zones of Low Lineament Density, in Relation to the Distribution of Surficial deposits.	(in pocket)

1.0 INTRODUCTION

Geo-analysis Ltd, under contract to the Earth Physics Branch, Energy, Mines and Resources Canada has undertaken the following interpretation and classification of linears using Landsat imagery in northwestern Ontario.

For this report the linears were mapped by M.A. Roed, and statistically assessed by Jacques Sauriol. The project was co-ordinated by Susan Ringrose. The authors wish to express their gratitude for the encouragement and constructive advice provided by Dave Forsyth of the Earth Physics Branch. This and the previous Report on North eastern Ontario have benefitted greatly thanks to Dr. Foryth's input.

1.1 Study Area

The area is bounded to the southeast by the Canada - United States border then from Lake Superior through north-eastern Minnesota. The eastern Boundary is demarked by a line extending from Black Bay on Lake Superior through Lake Nipigon and the western boundary by longitude 95°, located 11 km to the east of the Manitoba - Ontario border. The northern boundary lies at latitude 51°00' North. The extent of the study area is shown on Figure 1. The majority of the area comprises the Archean Superior geological Province which is subdivided into several minor Subprovinces. A portion of the Southern Province occurs on the northwest shores of Lake Superior. The Nipigon Plate is found to the west and south of Lake Nipigon.

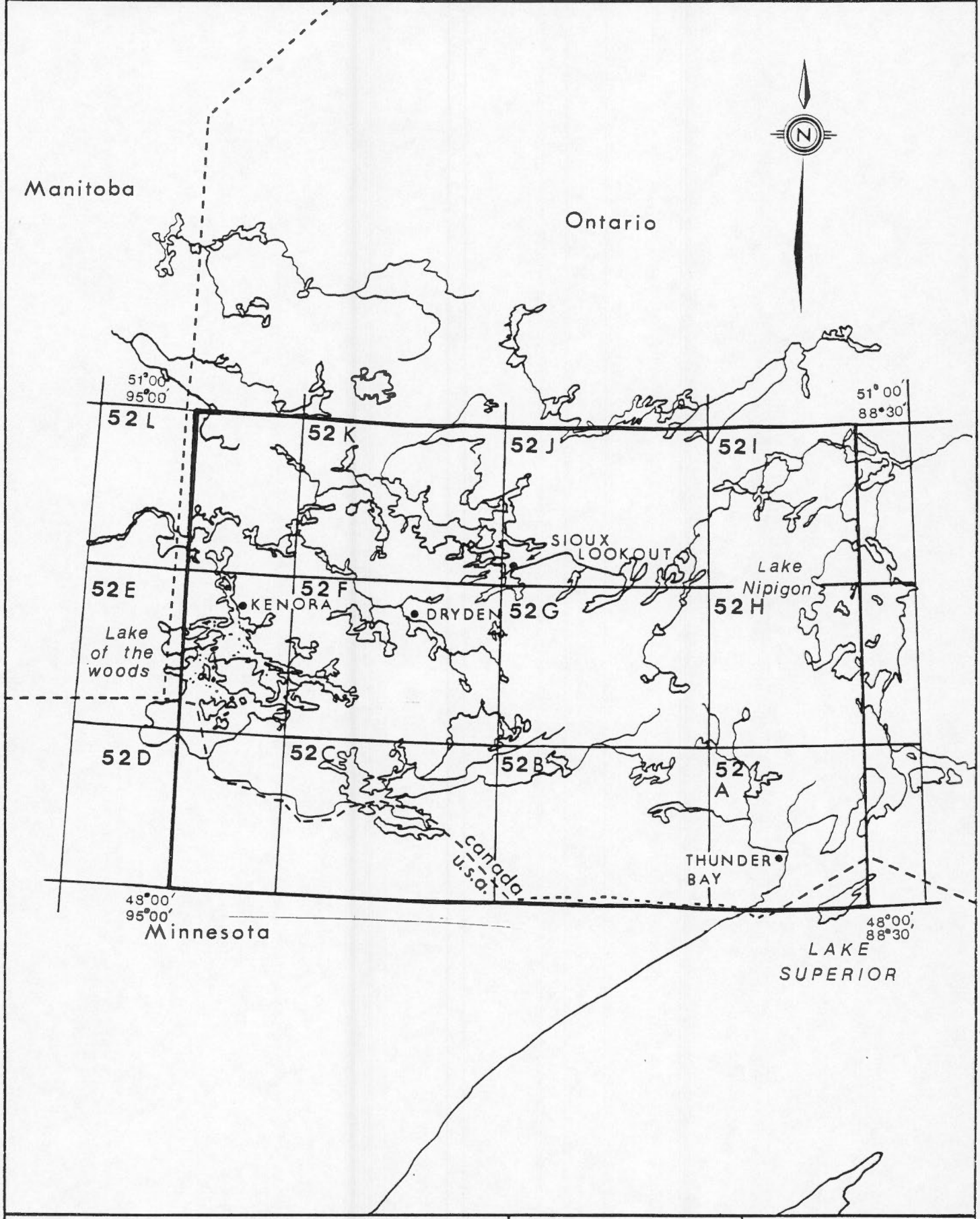

FIGURE 1: STUDY AREA DIVIDED UP INTO 1: 250,000 MAP SHEETS

SCALE 1:7,000,000	DATE Dec. 12 1980
DRAWN BY	APPROVED BY

Geo-analysis Ltd.

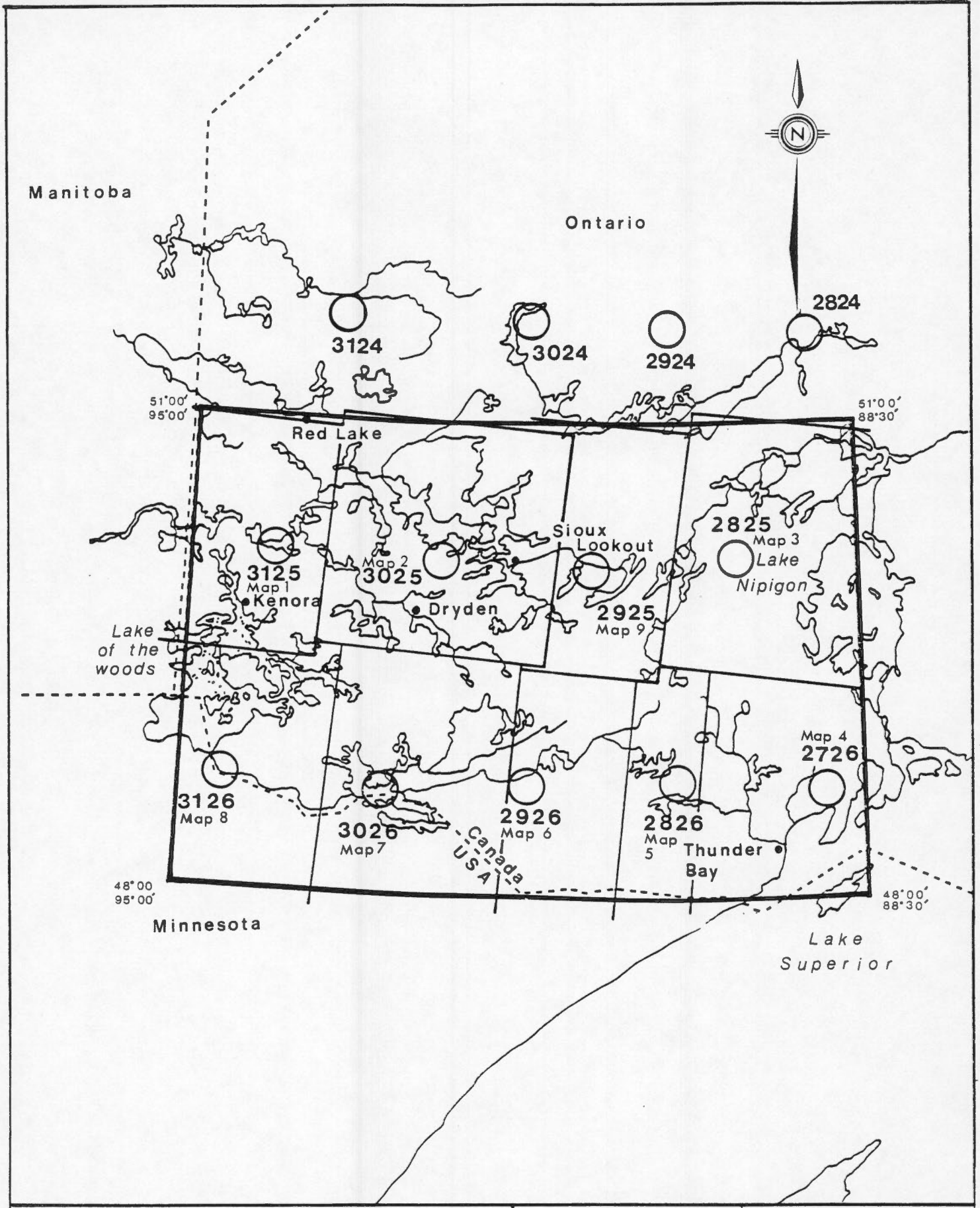

FIGURE 2: STUDY AREA SHOWING THE LOCATION OF THE IMAGE CENTRES

SCALE 1:7,000,000	DATE Dec. 12 1980
DRAWN BY	APPROVED BY S.R.

Geo-analysis Ltd.

1.2 Methodology

Landsat imagery was obtained directly from the Canada Centre for Remote Sensing via their facility in Prince Albert, Saskatchewan. The area is mainly covered by nine images which listed by track and row include 3125, 3025, 2925, 2825, 2725, 3126, 3026, 2926, and 2826 (Figure 2) except for a narrow belt on the northern margin of the study area. Generally the area covered by the entire image was required for the study. The imagery was carefully selected by comparing all available imagery for the area in the Canada Centre for Remote Sensing files. The most suitable imagery upon which the greatest number of linears could be clearly defined was flown during the winter months when the terrain was covered lightly with snow. The low sun angle at this time of year also assists in the discrimination of linear features. Pertinent information regarding the imagery used for this study is shown on Table 1. Nine prints were obtained and enlarged to a scale of 1:250,000 to facilitate precise and detailed lineament identification. The enlarged image gives a good overview of the structural domain under consideration. A problem stems from the track of the satellite which always passes overhead at a given location at the same time of day, such that the sun angle is held constant. This characteristic tends to emphasise linears which are oriented in a northeast - southwest direction. Awareness of this led the author to attempt compensation by not over weighing the significance of northeast - southwest oriented linears during this study. A comparison was also made at the 1:1,000,000 scale with imagery flown mainly during the summer months. The relatively high angle and heavy vegetation obscured some of the linear detail. Generally the same basic trends and features were obtained as those on the 1:250,000 imagery.

Table I: Landsat Imagery: North Western Ontario

Track & Row	Date	Image Number	MSS Band
27 - 26	Feb. 20, 74	E 1557 - 16152	7
28 - 26	Nov. 18, 74	E 1848 - 16131	7
29 - 26	Jan. 7, 76	E 11263 - 15564	7
30 - 26	Jan. 1, 79	E 21440 - 16120	7
31 - 26	Feb. 7, 79	E 21477 - 16190	7
31 - 35	Feb. 1, 75	E 10923 - 16265	7
30 - 25	Jan. 5, 73	E 1166 - 16364	7
29 - 25	Jan. 30, 75	E 10921 - 16152	7
28 - 25	Dec. 16, 72	E 1146 - 16252	7
*28 - 24	Feb. 11, 76	E 11298 - 15475	5, 6, 7
*29 - 24	Mar. 1, 76	E 11317 - 15522	4, 5, 7
*30 - 24	Feb. 22, 76	E 20396 - 16212	5, 6, 7
*31 - 24	Mar. 21, 76	E 11337 - 16023	4, 5, 7

(*) Refer to images to complete the study area to the north.

1.2.1 An Approach To Classification

The linears were initially identified without regard for pre-existing geological survey information. In some cases boundaries of the major structural domains were clear and later confirmed by comparison with maps published by the Ontario Geological Survey. In other cases, the distinction was less clear and was made in a strictly interpretative fashion particularly in portions of the study area where the bedrock geology is obscured by thicknesses of glacial drift. Through these areas, the boundaries of structural domains are largely inferred.

In order to classify the lineaments in order of importance in each geological belt, a systematic statistical approach cannot be used since lineament occurrence does not readily lend itself to a methodical system of classification. A classification using trend 01 for the class with the highest frequency and 02 for the class with lowest frequency could not be used as a decisive parameter to attain a systematic classification. Some of the problems encountered in attempting this approach are enumerated.

1. The nature of the lineament population is such that not all linear features are equally exposed hence "frequency" of linears in an area of exposed shield has not the same connotation as "frequency" of linears in an area covered differentially by glacial sediment. The two areas cannot be statistically compared. A classification scheme could not be systematic throughout the entire geological belt.

2. The nature of the lineaments, and more significantly, the structures which they represent, tend to express a randomness induced by the curvilinear nature of the linears themselves and secondly the curvilinear nature of the geological belts in which the linears occur. If a reference point throughout each belt was based on the belt boundary then linears within the belt could all be oriented in space relative to the belt trend. This "degree of parallelism" is extremely difficult to quantify statistically, particularly where four contrasting trends are apparent within the belt.

3. Differential accentuation of lineaments occurs throughout the study area based on intrinsically geological para-

metres (mainly lithological differences) Sun angle, extent and localisation of erosion, and the orientation of the structures relative to Wisconsinian (or earlier) ice advance episodes. These factors tend to increase (or decrease) the visual dominance of linears in an area.

In general the lack of homogeneity of the lineament population and the absence of a constantly fixed reference point in space tends to make statistical analysis problematical. In fact detailed statistical analysis could lead to a higher degree of confusion rather than clarification insofar as it may provide an unrealistically simple picture of the geological complexity which confronts the observer.

1.2.2 Classification Method

Two combined parameters are used as a base to classify the linear trends. The parameter length is defined as the measured distance in kilometres of a linear or group of linears as observed by the scientist on the imagery. The second parameter is frequency orientation, and it is defined as the number of linears occuring in one azimuth (or average azimuth in the case of a curvi-linear lineament).

The prime factor for the classification of trends is the parameter length and second factor is the orientation frequency parameter. Therefore, in the event of there being two groups of linears of identical frequency of occurrence in their respective direction, the class with the maximum length is classified as the most important trend, or 01. Although rose diagrams were drawn to differentiate the different groups, overlap occurred as indicated by the frequency - orientation parameter shown on

Figure 3 (in pocket). This due to some extent on the subjectivity of orientation - frequency discrimination, but is also based on the curvilinear nature of the geological belts themselves, as indicated in the previous section (section 1.2.1). Moreover, the occurrence of overlapping in Figure 3 also illustrates the high variation (i.e. standard deviation) in the classification of the linear orientation, suggesting that the variable length is mutually exclusive with respect to the variable frequency - orientation.

The most important group of lineaments is that with the greatest occurrence of lineaments oriented in one direction or average direction, combined with the maximum length. This group is classified 01 for the geological belt in question and includes all lengths of linears oriented in the selected direction. The following groups (02, 03, 04) are defined arbitrarily based on a subjective assessment of orientation frequency and length.

1.3 Background Studies

Regional lineament patterns have been studied in a number of areas using Landsat imagery both for the possible determination of seismic risk areas and for the location of zones of mineralisation.

A large region of high compressive stress has been delimited in eastern north America by Sbar and Sykes (1973). The authors consider that some form of earthquake prediction is possible from a combination of fault plane solutions for past earthquakes, in situ stress measurements and geological observations. In eastern North America most earthquakes occur in "unhealed" fault zones of Paleozoic or younger age, extended into the shield zone of western Quebec. Stress

build up in such zones may take place as a result of activity along pre-existing fault or plate boundaries. Hence, an analysis of the trend and significance of certain faults, and linears representative of faults is symptomatic of long-term fracturing trends and may be valuable in the prediction of possible future seismic risk.

Although the observed pattern of stress appears to be post Mesozoic in origin, the theory of present day compressive stress supports Voight's hypothesis that compressive stress observed within the north American plate may be generated by the same mechanism that drives the movements of large, lithospheric plates (Voight, 1969). Hence, in terms of earthquake prediction, if rupture were to occur it would take place either by renewed activity on old fault trends, particularly major faults, and/or at the junction of major crustal or structural plates, particularly where these are known to lie in a zone of compressive force, as illustrated by seismic activity along the Ottawa - West Quebec - Kirkland Lake Lake zone.

Work by Overby and Rough (1968, 1971) suggests that mapping structural features may provide reliable indication as to the orientation of the stress field. The relative age of surface structural features needs to be known before they can be used to define present directions of the stress field. Some insight into this can be inferred by a knowledge of the geological tectonic history of an area, including earth movements dating from earliest Precambrian to Quaternary time.

Hence, the mapping of macro surface features such as faults and fold trends as these are portrayed as lineaments, may provide important insight into the pattern of comtemporary stress and its possible resolution. Geological linear features,

based on structural fracture identification may well be indicative of potential and realised compressive stress patterns in northeastern North America, and by inference elsewhere on the continent.

A number of studies have previously been published on the use of Landsat imagery in the mapping of geological linear features. A number of studies have been published in International Symposia, for instance the Centre for Remote Sensing Information and Analysis (Ann Arbor, Michigan, 1974 onwards). Brockmann et al (1977) while working on structural mapping using Landsat images in Italy, determined that only regional information could be obtained at the scale of 1:1,000,000. At 1:250,000 the maximum limit of enlargement, folds, faults and other linears can be readily perceived without loss of resolution.

The study of structural lineaments has proved particularly valuable in areas of little or no vegetation. In the Zendan fault region of southern Iran, Iranpanah and Esfandiari (1980) mapped over 300 major and minor lineaments, Density of faults and lineaments mapped using Landsat images doubled those mapped by conventional means. Major identifiable lineaments included the axial planes of folds, high angle reverse faults, thrusts and underthrusts. The direction of horizontal compressional stress is postulated by analysis of the fracturing dynamics of the area. In Italy, Cassinis (1976) used Landsat and Skylab imagery to map significant lineaments in central Sicily and elsewhere. He concluded that the synoptic potential of space imagery is valuable because of the relatively high signal to noise ratio, otherwise obliterated in a confused geological picture.

A general literature review shows that lineament mapping has been used to provide information for earthquake detection, inter alia, in Alaska (Gedney, 1975), Italy (Barbier and Fanelli, 1976) the U.S.A. (Lamar and Merifield, 1975) Central Asia (Skaryatin, 1975) and France (Weber, Voight and Weeckstean, 1979). A study which relates structural lineaments to gravity, magnetics and seismicity has also been undertaken in the central U.S.A. by Smith et al, (1974).

Projects of direct relevance to this study include work by Chagaralamundi (1973) and Mussakowski (1973, 1974). Mussakowski mapped structural trends using Landsat imagery in eastern Ontario and western Quebec. In (1973), his work suggests that, in addition to structural lineaments and lithology, indication of foliation discernable on the imagery is of value especially in reconnaissance geological mapping. In 1974, Mussokowski defined more closely the terms lineament and mapped significant areas within the Grenville and Superior Provinces. Because of the abundance of data, a procedure was required to analyse the lineaments in terms not only of their total length and trend, but also of their density per unit area and intersection per unit area. These methods are discussed in more detail in a later section of this report.

2.0 GEOLOGY AND STRUCTURAL DOMAINS

The bedrock geology of the study area can be subdivided into major structural domains based on work by Goodwin et al (1972), Stockwell, (1964) and Stockwell et al (1969). The following is a summary of structure and lineament trends, included here as background information and taken directly from the 1:253,440 Ontario Geological Survey maps (see References). Within the study area, the Superior Province is subdivided into the English River Belt, the Wabigoon Belt, the Quetico Belt and the Wawa Belt. The southern province is divided into the Lake Superior Basin, the northeastern limb of the Port Arthur Homocline and the Nipigon Plate. The structural Provinces and belts are defined in terms of gneissic and schistose structure,bedding, formational boundaries and the crest lines of positive magnetic anomalies. All the Superior Province Belts are Archean in age and were folded and metamorphosed initially during the Kenoran orogeny (Goodwin et al, 1972).

2.1 Superior Province

The geology of four subprovinces within the study area are discussed individually below in some detail.

2.1.1 The English River Belt

Within the Superior Province, the English River Belt is composed mainly of easterly trending structures formed within the highly metamorphosed sediments and their granitised equivalents. Magmatic and granitic rocks range in composition from quartz diorite to granite and occur as elongated masses parallel to trends within adjacent meta-sediments.

Structures in the English River Belt, include major faults, at 090° - 100° with a secondary fault system ranging between 025° and 040°. Of major significance is the Minnis Lake Fault which is oriented between 030° - 040°, and separates predominantly granitic lithologies to the north from metasediments and metavolcanics to the south.

A series of fold lineaments also occur in the belt. The long axial trend of these lies mainly at 045° - 050° and 090° - 135°. The otherwise straight lineaments trend in similar directions to the folds and faults. These vary throughout the belt between 025° - 040° predominantly with some linears oriented between 090° - 115°.

2.1.2 The Wabigoon Belt

The Wabigoon Belt consists mainly of curved structures which occur within granite rich batholithic intrusions and adjacent metavolcanics and metasedimentary strata. In the study area, the Wabigoon Belt extends from Lake of the Woods to Lake Nipigon. Major faults appear to correspond with topographic features, such as lower Manitou Lake, and range in direction between 035° and 040°. A major fault associated with a magnetic anomaly occurs at 070°. Other major faults in this vicinity lie at 090°. A series of curved linears representing folds were noted. These occur as two separate sets throughout the Belt with a long axis orientation between 070° - 090° and 010° - 030°. Numerous

straight linear features are mapped as occurring within the Belt. Almost 50% (of a total of 30) were found to have an orientation between 050° and 030°. Of the remaining linears, 25% are oriented between 110 - 150° and 25% between 060 - 090°. Although these correspond in part to major faults and fold features, the actual lineament orientation appears much more varied.

2.1.3 The Quetico Belt

The Quetico Belt is composed of easterly trending structures occuring within highly metamorphosed sediments, migmatites, granitised gneisses or massive granitic rocks of approximate granodioritic composition. The Quetico Belt is characterised by linear structures that trend easterly in contrast to the curvilinear structures in granitic terrains, particularly to the south. Major faults include the Knife Lake fault which trends at 040°. Faults which trend at 060° also mark the southern boundary of the Belt. Minor faults are oriented between 150 - 170°. A series of minor folds follows trends parallel to the major faults (25%) and the long axial trend of major folds (50%).
(50%).

2.1.4 The Wawa Belt

The Wawa Belt is similar to the Wabigoon Belt in that it consists of curved structures which occur within granitic rich batholitic intrusions and adjacent metavolcanics and metasediments. The Wawa Belt comprises a zone in which intrusions prevail with relatively little mapped structural occurance. Three major faults at around 080° appear to delineate the zone of contact between the Wawa

and Quetico Belts. Only two sets of minor lineaments were otherwise noted at around 100° and 155°.

2.2 Southern Province

Within the study area the southern Province is subdivided into the Port Arthur Homocline, the Lake Superior Basin and the Nipigon Plate.

Sedimentary rocks of the Southern Province were deposited unconformably on the eroded Archean Basement. In the study area these comprise the Port Arthur Homocline, the Lake Superior basin and the Nipigon Plate. Sediments within the western portion of the Southern Province can be subdivided into three conformable Formations, namely the Animkie Formation, Keweenan Rocks of the Sibley Formation and the basal Osler Formation. Sediments of the Animkie Group include the Kakabeka, Gunflint and Rove Members. They form a conformable sequence of shallow water deposits including mainly chert, jasper, iron formation, carbonate, argillite and tuffs. These are gently deformed in Ontario but were folded and mildly metamorphosed in Minnesota, during the Penokean orogeny Briefly,the lower Kakabeka Formation consists mainly of conglomerate, which is overlain by sediments of the Gunflint Member in which a large number of lithofacies occur, with rapid facies changes. Rove sediments consist of black, thinly bedded argillite. Interbedded limestones sandstone and shale over a basal conglomerate form the major part of the Sibley Formation. The basal Osler Formation is mainly conglomeratic.

2.2.1 The Port Arthur Homocline

The Port Arthur Homocline extends south westwards from Thunder Bay into the United States and is underlain mainly by Animkie strata with a persistant, gentle south-eastward regional dip. Faulting, warping and uplift appear to have occurred in early Proterozoic time.

The main outstanding linear features throughout this area are a series of diabase dikes which are oriented between 040° - 050°. Structural features are not numerous. The few major faults occur at 070° and 000°. Fault trends at 060° - 065° separate the sedimentary sequence from the Wawa Belt. Two minor lineaments were also noted at 090°.

2.2.2 The Lake Superior Basin

The Lake Superior Basin is a narrow, arcuate synclinorium, the long axis of which is paralleled by a series of faults. A major gravity anomaly lies over the structure which may represent a major rift in which considerable thicknesses of Helikian volcanics and sediments were deposited. The relatively undeformed rocks have been uplifted along major arcuate reverse faults during late Proterozoic time.

2.2.3 The Nipigon Plate

The Nipigon Plate is underlain by undeformed Helikian sedimentary strata and thick diabase sheets. It may represent an early external portion of the main Lake Superior Basin (Card, et al, 1972).

It forms the largest feature on the eastern margin of the map area. A series of major faults occur to the south of Lake Nipigon. These are oriented between 150° - 170°. The Sturgeon River follows the trend of one of these faults. Straight lineaments are found north and south of Lake Nipigon The majority of these are oriented between 010° - 020°. Other lineament trends occur between 060° - 090° and 170° - 180°.

2.3 Surficial Geology

Aspects of the surficial geology of northern Ontario have been discussed by a number of authors. Most of the study area was mapped by Zoltai in 1965 at the scale of 1:506,880. Much of the study area was also mapped during the late 1970's under the Northern Ontario Engineering Geology Terrain Studies by consultants on contract to the Ontario Geological Survey, Engineering Terrain Geology Section. These sources were used to assess the extent of Quaternary geology cover in the area.

Generally the area was last glaciated during late Wisconsin time. As the ice sheet receded from the Great Lakes regions, the ice margin was in direct contact with glacial Lake waters as to produce a complex glacio - lacustrine depositional sequence (Skinner, 1969). This took place from about 12,000 to 8,000 years, B.P. and included, in the study area, the deposition of Eagle - Finlayson (Wabigoon) moraine, the Hartmann moraine, the Lac Seul moraine and the Sioux Lookout moraine. These are major glacial depositional features which trend NW - SE across the study area. Interlobate moraines in the

vicinity of Lake Nipigon include the Dog Lake moraine and the Kaikask moraine. Ice recession to and from these moraines took place approximately between 12,000 years B.P. and 9,000 years B.P. Stratigraphic evidence suggests that for most of the time in question, the ice front ponded a large glacial lake. Glacio - lacustrine sedimentation occurs in the deeper basins of the study region, for instance within the Wabigoon basin and the Lac Seul basin.

3.0 LINEAR TRENDS IN STRUCTURAL DOMAINS AND THEIR INTERPRETATION

The linear trends are portrayed on nine(9) Landsat maps, at 1:250,000 which accompany this report (indexed on Figure 2). Map 10 is a compilation map at a scale of 1:1,000,000, reduced from the 1:250,000 sheets in order to give an overall picture of the main lineament features and structural domain boundaries. The main Quaternary features are indicated on Map 13 so as to provide some guidance in the interpretation, particularly of areas showing relatively low lineament density. The main surficial features shown on this map are indicated in the legend.

General linear trends are described for each Subprovince, followed by a discussion of linear density (Map 11) and of linear intersection frequency (Map 12). Some indication is also made of zones of relatively low linear occurrence. In each case the linears were mapped and measured (at a scale of 1:250,000) as coherent structural elements. Whereas the amount of inference was limited, some inference did take place over gaps smaller than 0.5 cm, (representing about 1 km) both in the case of straight and circular features. Measurements took place directly on the lines drawn on the maps. However, because of the density of lineaments at certain locations, and because it was only feasible to undertake the exercise once, the following trends should be regarded as being derived from a representative sample of the lineament population, rather than an accurate accounting of each linear mapped. This is only true of the lineament trend and orientation analysis. In terms of the lineament frequency and frequency of intersection diagrams every mapped lineament is accounted for.

3.1 Linear Trends and Orientation

The average linear trends and their orientation are discussed for each major structural domain. Summary statistics used are as indicated by formulae in Appendix 1. The Superior Province is considered first, followed by the Southern Province.

3.1.1 Superior Province

The Superior Province is subdivided into four belts. within the study area. A discussion of linear trends and orientation is given below for each belts.

3.1.1.1 The English River Belt

The English River Belt is an elongated zone that occupies the northernmost portion of the study area.

Important unconsolidated materials of the Lac Seul sedimentation basin of Lake Agassiz, occur to the west; sediments in the Whitewater Lake area to the east also tend to mask the underlying structures. Elsewhere, the belt is generally covered by till where minor esker and kame complexes are mapped (Zoltai 1966). The last ice advance into the area appears to have flowed mainly from the northeast creating a series of arcuate end moraines in the Lac Seul area.

The resolution of the structural trends within the covered portion of the English River Belt is rendered problematical by the masked bedrock exposure. In general terms, four trends are recognized and are summarised in

TABLE 2: LINEAR TRENDS - English River Belt

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	69.	98	69.	13.	174	15.3	18.9	355.5
02	27.	57	27.	13.	178.	12.2	6.5	42.4
03	154.	45	154.	18.	311.	12.0	7.5	56.3
04	97.	11	97.	14.	198.	11.1	7.7	59.3

Table 2. The dominant trend is shown as having an east - northeast orientation (069°) azimuth, with a secondary north - northeasterly trend (027°), tertiary south - southeasterly trend (154°) and a minor quaternary east - west orientation (097°). A graphical representation of the frequency distribution of lineament orientation is shown in Figure 3 (in pocket). Minor orientation - frequency overlap exists between the trends of English River Belt. The average linear length is from 11 to 15.3 km, with the most dominant trend (01) being an average 15.3 kilometres in length. The lineament frequency - orientation observed on the imagery correspond to the general easterly trend of the structures of the English River Belt as mapped by Ontario Geological Survey and described in section 2.1.1. The 01 trend appears to correspond with the major trend(070 - 090) and 02 trend with a secondary fault system (025° - 040°). This study emphasized a third trend (03) which is orientated 160 and which did not appear as significantly on the geological map.

3.1.1.2 The Wabigoon Belt

The Wabigoon Belt is the second northern belt that crosses the study area. It is also covered by the most surficial sediment. Generally the bedrock surface is till covered except in a few small locations to the extreme west and east of the study area. Unconsolidated deposits cover two large areas, namely the lacustrine deposit of Eagle Lake, Wabigoon Lake and Dinorwic Lake and a large outwash and loess deposit north of Lac des Milles Lacs. A series of four arcuate end moraines indicate the temporary locations of active ice fronts during a last glacial recession, Map 13 (in pocket) illustrates the location of these surficial deposits.

TABLE 3: LINEAR TRENDS - Wabigoon Belt

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	64.	233	64.	17.	295.	12.3	14.7	215.3
02	188.	175	188.	24.	696.	8.6	5.6	31.3
03	86.	152	86.	98.	9557.	10.5	7.9	62.2
04	175.	71	175.	22.	481.	11.6	6.9	47.3

Four linear trends are recognized, and are summarised in Table 3. The dominant trend has a east-northeast orientation (064°), with a secondary north-south orientation (188°), a tertiary east-west orientation(086°), and a relatively minor quaternary south-southeast orientation (175°). The frequency distribution of lineament orientation is graphically represented on Figure 3 (in pocket). Important frequency - orientation overlap occurs between the trend of the Wabigoon Belt which can be partially described to the varying lengths of the linear groups; the average linear length is from 8.6 to 12.3 km, with most dominant trend(01) regrouping linears of 12.3 kilometres in average length. The lineament frequency orientation observed on this imagery corresponds mainly to the northeast trend of fault systems, oriented 030 - 040 and 070 - 090. Sets of curved and straight linears were also indicated on geologic maps with similar orientations. Also a series of lineaments on the imagery is oriented in the southeastern quadrant in a well distributed fashion with no linears occurring in a particular orientation.

3.1.1.3 The Quetico Belt

The Quetico belt is the third northern belt that crosses the study area. This narrow belt joins Rainy Lake to the area between Lake Nipigon and lake Superior. The resolution of lineaments of the Quetico Belt is masked in its centre by the extensive loess and outwash deposits of Lac des Milles Lacs and to the west by a small lacustrine deposit by Lake Manion and Lake Calm. A series of arcuate end-moraines also cross the Quetico Belt. Map 13 (in pocket) illustrates the location of these surficial deposits.

TABLE 4: LINEAR TRENDS - Quetico Belt

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	78.	92	78.	9.	84.	14.2	24.3	588.7
02	140.	28	140.	23.	538.	13.3	12.5	155.5
03	48.	97	48.	13.	176.	9.5	7.5	56.4
04	11.	62	11.	12.	133.	10.5	7.3	53.4

Four trends are recognised and are summarised in Table 4. The dominant trend demonstrated a east - northeasterly orientation (078°), with a secondary southeasterly orientation (140°), a tertiary north-east orientation (011°). The frequency distribution of all trends are graphically represented in Figure 3 (in pocket). The average linear length ranges from 14.2 to 915 km, the most important trend (01) is the trend with the greatest length (i.e. 14.2 km as an average). Some frequency - orientation overlap occurs between the trends of the Quetico Belt, but this is not significant and probably relates to differences in length. The lineaments observed on geologic maps correspond to lineament frequency orientation observed on the imagery, in particular the major fault systems trending 040, and 060. This exercise discovered two new orientation groups trending 020, and 070 - 080; these two trends are characterized with high frequency in Figure 3. A series of minor faults trend 150 - 170 which do not correspond to any peak concentration.

3.1.1.4 The Wawa Belt

The extent of the Wawa belt in the study area is confined to a small area which is overlain by till, a small outwash deposit and is crossed by two elongate end moraines. Map 13 (in pocket) illustrates the location of these surficial deposits.

Four trends were recognized, and they are summarised in Table 5. The dominant trend has an east-west orientation (084°), with a secondary southeast orientation (144°), a tertiary northeast orientation (052°) and a quaternary north-south (183°). A frequency distribution is graphically represented in Figure 3 (in pocket). The average length ranges from 10.0 to 16.4 kilometres. For the Wawa Belt, the most

TABLE 5: LINEAR TRENDS - Wawa Belt

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	84.	58	84.	16.	242.	15.3	13.8	191.0
02	144.	42	144.	15.	237.	12.3	9.0	80.8
03	52.	175	52.	24.	558.	10.0	10.9	119.4
04	183.	43	183.	12.	133.	16.4	19.0	360.9

dominant trend (01) groups linears of 15.3 kilometres in average length. This is the second highest length since there are two groups of linears with almost identical length and similar frequency occurring in two different orientation. Important frequency - orientation overlap occurs between the trends of the Wawa Belt, which suggests that the prime trend was defined as the one with its orientation approaching the general orientation of the Belt borders. The lineaments frequency orientation observed on the imagery corresponds to a fault system trending 080 as mapped in geologic map. In the lineament study, major lineaments were mapped between 030 and 080. These had not been previously recorded on the Ontario geological Survey maps.

3.1.2 The Southern Province

The Southern Province is subdivided into three(2) Subprovinces within the study area. A discussion of linear trends and orientation is given below for each.

3.1.2.1 The Lake Superior Basin

The Lake Superior Basin is located to the southwestern corner of the study area. It includes Thunder Bay, and the area to the immediate west of the city. Some widely spaced lacustrine deposits lie close to the shore of Lake Superior Minor end moraines and a till veneer are also found in the Lake Superior basin. Most of the state of Minnesota is covered by extensive peat deposits within the study area.

The lineaments of the Lake Superior basin were grouped into four major trends as summarised in Table 6. The dominant trend demontrates a east-northeast orientation (060°), with a secondary south-southeast orientation (167°)

TABLE 6: LINEAR TRENDS - Lake Superior Basin

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	60.	11	60.	8.	68.	10.1	5.4	29.2
02	167.	6	167.	3.	7.	8.0	2.5	6.2
03	109.	1	109.	0.	0.	5.0	0	0
04	25.	10	25.	7.	49.	5.3	1.3	1.7

a tertiary east-southeast orientation (109°) and a quaternary north - northeast orientation (025°).

A frequency distribution is graphically represented in Figure 3 (in pocket). Summary statistics, compiled for this subprovince are derived from a much smaller linear sub sample size than the previous Belts. This reduces the representativity of the orientation and length for each trend. The average length is ranges between 5.0 to 10.1 km., with the most dominant trend (01) grouping linears of 10.0 kilometres in average length. No frequency orientation overlap occurs between linear groups in the Lake Superior Basin. The lineament frequency orientation observed on the imagery corresponds to a fault system oriented parallel to the long axis of the synclinorium. Although no new high frequency trends were discovered on the imagery, for this area a number of new individual lineaments were mapped. This subprovince is characterized by a very low number of lineaments observed on the imagery.

3.1.2.2 The Port Arthur Homocline

The Port Arthur Homocline lies in the southeastern extremity of the study area, and includes an area to the east of Thunder Bay along the shore of Lake Superior. The area is generally covered by a veneer of till with some lacustrine deposits on the northern shore of Black Bay and Nipigon Bay.

A relatively high frequency of lineaments were observed over this small subprovince. They were grouped into four major trends, which are summarised in Table 7. The dominant trend has an east-northeast orientation (058°), with a secondary trend southeast orientation (150°) a tertiary east-southeast orientation (102°), and a quaternary north-northeast orientation (028°). The average length ranges from

TABLE 7: LINEAR TRENDS - Port Arthur Homocline

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	58.	68	58.	19.	374.	8.9	4.7	22.0
02	150.	26	150.	23.	500.	6.5	2.9	7.9
03	102.	17	102.	10.	86.	6.6	3.4	11.0
04	28.	48	28.	15.	224.	5.3	4.0	15.3

8.9 to 5.3 km, with the most dominant trend (01) regrouping linears of 8.9 kilometres in average length. Some frequency - orientation overlap occurs between the trend of the Port Arthur Homocline. This is caused partly by the parameter length that differentiates lineaments into trends, which is not illustrated in the figure. It is also caused by the subjectivity of the observer in classifying lineaments outside the 01 trend systematically. The lineament frequency orientation observed on the imagery corresponds loosely to the diabase dykes oriented 040 - 050 and to the major faults oriented 070 - 060 and 000. The lineament trends suggest 2 new structural trends at 105° and 155°. Although thesurface area of this subprovince is small, the frequency of lineament occurrence is high per unit area.

3.1.2.3 The Nipigon Plate

The Nipigon Plate is located peripheral to Lake Nipigon. This subprovince is covered by a myriad of surficial deposits such as an elongated end moraine, outwash deposits, and lacustrine deposits. These deposits are probably responsible for the low resolution of lineament observations as expressed in the sample frequency column of Table 8.

Lineaments were grouped into four major trends. The dominant trend demonstrated a north-south orientation (183°), with a secondary east-northeast orientation (055°), a tertiary southeast orientation (149°) and quaternary east-west orientation (088°). A frequency distribution is graphically represented in Figure 3 (in pocket). The average length is from 9.7 to 4.8 km. Only one sample of trend 03 and 04 was observed. The most dominant trend (01) regroups linears of 9.7 kilometres in average length. No frequency - orientation overlap occurs between the trend of the Nipigon Plate. The

lineament frequency orientation observed on the imagery corresponds mainly to major faults oriented 150 - 170, and to some linears oriented 010 - 020, 070 - 090, 170 - 180. No new trends were observed in the Nipigon Plate from the landsat imagery, although the number of "structurally" related features increased.

3.2 Lineament Density

Lineament density is defined as the frequency of linear occurrence in the study area per unit area. This can be measured using two different approaches. In previous studies, for instance Mussakowski (1974) and Peter Cooke (personnel communication), linear density is regarded as the total linear length per unit area. Alternatively the total frequency of linear occurence can be used. In this study, consideration was given to determine the most reasonable method of attaining a linear density map given that the resulting product is intended to provide an indication of areas of relatively low linear concentration. It proves extremely difficult to measure lineament lengths at the 1:1,000,000 scale using normal vision (Géo-analysis 1981). Even under magnification the procedure is extremely laborious. Essentially the difference between the two procedures lies in the range of data gathered which is reflected in a significantly steeper contour gradient when absolute length is used, as opposed to a shallow, more inferential gradient when total frequency is used. Both, however, show essentially the same features in that generally areas of higher absolute length are areas of greater lineament frequency. The methodology reflects the scale of work to be undertaken. For the purposes of the present study, lineament frequency was mapped at 1:1,000,000 scale. Should requirements occur for more detailed work, for instance at specific locations, frequency using absolute length measurements (at 1:250,000) is recommended.

TABLE 8: LINEAR TRENDS - Nipigon Plate

Trend	Direction	Sample Frequency	Orientation (deg)			Length (km)		
			Mean	Std. Dev.	Var.	Mean	Std. Dev.	Var.
01	183.	25	183.	9.	77.	9.7	6.3	39.7
02	55.	24	55.	17.	279.	8.4	5.4	29.5
03	149	1	149.	0	0	4.8	0	0
04	88	1	88.	0	0	6.5	0	0

In order to obtain significant results without measuring each linear directly, the actual number of lineaments (lineament frequency) method was used, by directly counting each lineament or portion thereof on the 1:1,000,000 compilation map (Map 10) as these occurred on a 10 km. grid (i.e. one centimetre square on the map). In this case every linear, including faults, fault parallel linears (01 - 04), folds and fault boundaries of structural domains were included. Boundaries of structural domains not co-incident with fault boundaries and glacial linears were excluded. The number of occurrences of each linear was noted in every 10 km square and later contoured at a 5 linear frequency. The contour map (Map 11) is intended to be used as an overlay to Map 10.

The contours of lineament density (Map 11) clearly show areas of relatively high and relatively low lineament density. Further consideration is here focussed on areas of relatively low lineament density as these <u>may</u> represent relatively fracture free zones or at least areas requiring further study.

Three large zones of relatively low lineament density were defined on the study area, and all three correspond to extensive surficial deposits that mask the bedrock structure. A first zone is located ~~to~~ in the south-eastern portion, and a second zone ~~to~~ in the southwestern portion of the study area. They correspond mainly to lacustrine deposits along Lake of the Woods and Rainy Lake to the west, and along Thunder Bay and Black Bay of Lake Superior to the east. The third zone is a large "U-shaped" low frequency zone occurring in the northern portion of the study area. This zone corresponds to extensive surficial

material deposits, namely (1) lacustrine deposits of Lac Seul, of Eagle Lake, of Wabigoon Lake and of Lake Nipigon, (2) a long arcuate series of glacial end moraines, (3) an outwash deposit, and (4)an eolian deposit in the Lac des Milles Lacs area (Map 11).

To determine bedrock low lineament density areas, the three large areas as defined above were integrated with the surficial maps of Zoltai (1962). The engineering geology maps of Mollard(1979, 1980) and Roed (1980) were compared to enhence the degree of detail. A series of twenty-three zones were thus defined, and filtered to remove thelarge bodies of standing water. *Map 13 shows the distribution of of these areas.

These 23 zones may represent relatively fracture free areas, or at least area requiring further study. However, since the thickness of the till cover is unknown, important till deposits may mask the bedrock structure, even in these areas.

3.3 Lineament Intersection Density

Lineament intersection density is defined as the frequency of linear intersections in the study area per unit area. In order to determine significant densities, the number of intersections are counted at the 1:1,000,000 scale, using Map 10 as a base. For this portion of the study, all structural lineaments in contact with one another are considered to be intersecting, and lineaments

contacting a structural fault boundary are also considered to be intersecting. Boundaries of structural domains non co-incident with fault boundaries and glacial lineaments are excluded. In each case, the number of occurrences of each bona fide intersection was noted in every 10 km square and later contoured at a frequency of five intersections. The contour map (Map 12) is intended to be used as an overlay to Map 10.

The contours of lineament intersection frequency show areas of relatively high and relatively low intersection density. This reflects, to a large extent, the highs and lows of lineament density. The three main areas of low lineament density are found on the intersection frequency map. Moreover, the 23 zones, as defined in the previous section on lineament densities, are confirmed by the intersection frequency map. However, because there are large surfaces of the study area with low intersection frequency, it was concluded that this last parameter neither adds to nor improves the precision of resolution of zones of low structural occurrance requiring further study.

4.0 CONCLUSIONS

Lineaments within an area of 156,000 km^2 of predominantly Precambrian terrain were mapped in northwestern Ontario using 1:250,000 Landsat imagery. Dominant to quaternary (01 to 04) lineament trends were discerned for seven geological subprovinces. Mean lineament trends for the English River Belt lie at 069° (east of north); for the Wabigoon Belt at 064°; for the Quetico Belt at 078°. The mean orientation of linears in the Wawa belt lies at 084°. Mean dominant trends within the Lake Superior Basin lie at 060°; within the Port Arthur Homocline at 058°, and within the Nipigon Plate at 183°.

A 1:1,000,000 reduction of the linear mapping shows the study area and structural domains as a coherant entity (Map 10). Two overlays were prepared showing lineament density (Map 11) and overall lineament intersection frequency (Map 12). From these, three areas of low density or intersection frequency were identified. In many cases these areas correspond to areas of thick glacial sediment which appears to mask the bedrock beneath, to the extent that not all the structural lineaments are visually apparent. There are however, significant areas which appear to warrant further study. These are idenfied on Map 13, as zones 1 to 23 in terms of low lineament density.

A major finding of this study is the significant increase of lineaments mapped from the Landsat data. This provides a more complete data base for geology maps in that the greater perspective of the landsat imagery coupled with a good resolution and uniform coverage of winter imagery is demonstrably an improvement over interpretation of lineament identification by traditional air photography.

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Appendix 1

Appendix 1

Formulae for Mean, Standard Deviation and Variance.

Mean $= \dfrac{\sum_{i=1}^{n} x_i}{n}$, for n = 1, 2, 3, ..., n.

Standard Deviation $S_x = \sqrt{\dfrac{\sum_{i=1}^{n} x^2 - \dfrac{(\sum_{i=1}^{n} x)^2}{n}}{n - 1}}$

Variance $S_x^2 = \dfrac{\sum_{i=1}^{n} (x - \bar{x})^2}{n - 1}$