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Form and Extent of the Grenville Front Tectonic Zone in the Proximity of Coniston, Ontario as Defined by Aeromagnetic and Paleomagnetic Studies of Sudbury Olivine Diabase Dikes.

Form and Extent of the Grenville Front Tectonic Zone in the Proximity of Coniston, Ontario as Defined by Aeromagnetic and Paleomagnetic Studies of Sudbury Olivine Diabase Dikes

by

Susanne Manning

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Abstract

Geophysical studies of the northwest trending Sudbury olivine diabase dikes, to the south of Coniston, Ontario establish a deformation zone, within the Southern province up to 10 km from the Grenville Front. Paleomagnetics reveal two directional groups within the dikes; those with a NRM direction of 300°/32° representing the primary magnetization of the dikes and those dikes with a Grenville overprint direction of 116°/56°. The deviation in direction of the two groups, in relation to previous studies (Palmer *et al.*, 1977) is interpreted to be due to fault block movement. Aeromagnetics reveal extensive ductile and brittle deformation in the dikes as they approach the front. The general orientation of deformation is to the northeast.

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Chapter 1

Introduction

The Grenville Front and the associated Grenville Front Tectonic Zone GFTZ has been subject to much debate as to it's origin and role during the short lived ≈ 1160 - 980 Ma Grenville Orogeny (Haggart *et al.*, 1993). The Front extends from the shores of Lake Huron in North Central Ontario to the shores of Labrador (Rivers *et al.*, 1993) and beneath younger rocks well into central United states. Typically it exhibiting NW dipping thrust faults, along with associated mylonite zones (Davidson 1986b). The Front is marked by an abrupt metamorphic transition from pre-Grenvillian greenschist or lower amphibolite grade to north of the front to upper amphibolite and granulite grade within the tectonic zone. The zone itself consists of Archean and Proterozoic granitoid rocks, locally cut by the Mesoproterozic Sudbury olivine diabase dikes. The Paleoproterozoic Huron Supergroup of the Southern province are absent within the tectonic zone (Davidson and Bethune, 1988, Rivers, 1993).

Geophysically the Front is characterised by prominant gravity and magnetic anomalies (Rivers *et al.*, 1989). Seismic reflection profiling (Green *et al.*, 1988) shows the front to be a crust scale feature, that is a deep shear zone along which rocks from the Grenville orogen were thrust to the northwest. Rivers *et al.*, (1993) and Haggart *et al.*, (1993) have presented a tectonic model for Ontario involving uplift of deep crustal rocks over the foreland in turn implying the exsistance of a crustal scale thrust wedge. The tectonic evolution of which involes crustal shortening, high pressure metamorphism and the formation of a fold and thrust belt at the top of the ramp. In Ontario the fold and thrust belt is poorly developed, indicating that the thrust wedge did not progress onto the foreland at the top of the ramp and therefore it is assumed that erosion kept pace with uplift.

One of the major problems associated with the Grenville orogeny is the definition of the extent of Grenvillian tectonic effects on the Southern Province. It has been conclusively shown that the Grenville Front is not a suture, since distinctive rocks units, such as the Sudbury dikes ≈ 1235 Ma (Bethune, 1988), can be traced across it for for up to ≈ 200 km (Rivers *et al.*, 1989). Based on their relationship to Nipissing diabase intrusions, the dikes clearly postdate teh Penokean deformation. For this reason, these dikes have been chosen for study as they best exhibite the extent of deformation resulting from Grenvillian tectonics. What is the extent of plastic and/or brittle deformation as seen in the dikes as the encroach the front? Why is there a limited metamophic aureole associated with the Front within the Superior Province? What is the tectonic process which is resposible for producing these effects? Ultimatley the answer lies in an understanding of the timing of deformation and metamorphism associated with the Grenville orogeny.

It is the goal of this thesis to use geophysical methods;

paleomagnetism and aeromagnetism, to better constrain and establish the extent of this deformation within the Southern Province and to propose a viable tectonic solution.

1.1 **Previous Works**

Various paleomagnetic studies have been conducted on the olivine diabase dikes to the north and west of Sudbury (Palmer *et al.*, 1977; Larochelle, 1967; Bethune, 1988). Contact test studies have conclusively shown that the remanence directions preserved in these diabase dikes are primary in origin.

The most extensive paleomagnetic study of the Sudbury olivine dikes was preformed by Palmer *et al.*, (1977). His findings resulted in two directional groups; those with a primary, single, isolated direction of remanence north of the front and well into the Southern province, and those sites possesing a Grenville overprint direction in proximity to the front and into the Grenville Province. A third group Palmer classified as *Spiralling Paleomagnetic sites*, based on the demagnetization paths that spiral in a clockwise fashion with an overall tendency to approach the Sudbury dike direction. These dikes record three components of magnetization with the Sudbury direction being the hardest (Palmer *et al.*, 1977). This suggests that the ESE remanence direction of the samples to the south are a result of remagnetization of the original Sudbury direction which has subsequently been replaced by the younger magnetization events related to the Grenville orogen.

Although Palmer *et al.*, (1977) firmly establishes the paleomagnetic signature within the dikes there was no atempt made to relate his findings to a tectonic model.

Initial Rb-Sr age dating done by Van Schmus, (1965) and estimates the age of the dikes at 1225 ± 25 Ma. Subsequent K-Ar ages estimates the dike age as 1250 Ma, Palmer *et al.*, (1977). Recent studies reflect a more accurate time of crystallization from U-Pb baddeleyite ages as 1238 ± 4Ma, (Krogh *et al.*, 1984).

1.2 **Geologic Setting**

The geology of the Grenville Front region, within the vicinity of Sudbury, Ontario is more fully described in other sources, (Bethune and Davidson, 1988 and Davidson and Ketchume, 1993) only an outline of which is given here. The Paleoproterozoic Huronian Supergroup are described as a thick succession of supercrustal rocks and exhibit folds with east trending axes, generally showing greenschist metamorphism which is attributed to the Penokean Orogeny, ca. 1.85 Ga, (Bethune and Davidson, 1986). Cross cutting these rocks is Nipissing Diabase, which occur as large gabbroic sills dated at 2.22 Ga (Corfu and Andrews, 1986). Cross cutting all of the above are the Sudbury diabase dikes. They are readily distinguishable from the Nipissing diabase on the basis of metamorphic grade. Nipissing diabase is in fact a metadiabase, as the primary pyroxene is now completely altered to actinolite amphibole. In most cases the olivine in the Sudbury diabases in unaltered. This mineralogical feature is readily discernable, where field drilling permits.

Nipissing diabase produces a green coloured drilling mud as opposed to the grey colour of the Sudbury diabase. Further visual differences can be made on the outcrop as the Nipissing diabase weathers to a rusty appearance.

Extensive faulting characterizes the entire region. Most prominent are the Murray fault and its extension the Wanapeitei Fault which locally occur in close proximity to and have the same orientation as the Grenville Front. The Wanapeitei Fault is described as a brittle, normal fault and which has been reactivated in post Grenvillian time (Davidson, 1992). Smaller less prominent faults strike in a north easterly direction. Recent geological mapping of the area to the South of Coniston by Davidson and Ketchum, (1993) have uncovered perviously unmapped Sudbury diabase dikes which clearly were intruded across the Grenville front into the GFTZ. The dikes are offset at faults and cut mylonitic fabrics on either side of the Front (Davisdon and Ketchume, 1993). As opposed to the dikes found in our sample area which showed little or no metamorphic signature, the dikes mapped by Davidson *et al.*, (1993) were composed in part by chloritized or amphibolized diabase.

The average width of the dikes, in this study area was approximately 1m, with the larger dikes averaging from 5 - 8m across and small diklets ranging in size from 0.05m to 1m. These dikes were found to trend in a northeasterly direction with the exceptions being offshoots from the main dike. On most outcrops the entire width of the dike was exposed, thus allowing for superb access to contact margins.

1.3 **Sampling**

Sampling of the Sudbury dikes was concentrated to the East of Sudbury, Ontario, around Ramsey Lake and to the west of Coniston, Figure 1 & 2. Of 16 Sample Sites, a total of 162 specimens for paleomagnetic analysis were obtained. An attempt was made, although in most cases this was limited by terrain and outcrop availability, to sample individual dikes at regular intervals moving progressively closer to the Grenville Front to establish the metamorphic and/or deformation front.

Most samples were drilled *in situ* by means of a portable drill and oriented (strike and dip) in the field using a Brunton Compass. Sun sightings were taken whenever weather permitted. Where field drilling was not possible, large hand specimens were taken and oriented, to be drilled later in the lab. Generally each site yielded 6 - 10 drilled cores, which were long enough to cut 2 - 3 paleomagnetic specimens.

Figure 1:

Map of regional geology. Box 1 indicates the study area and Box 2 indicates the aeromagnetic survey area.

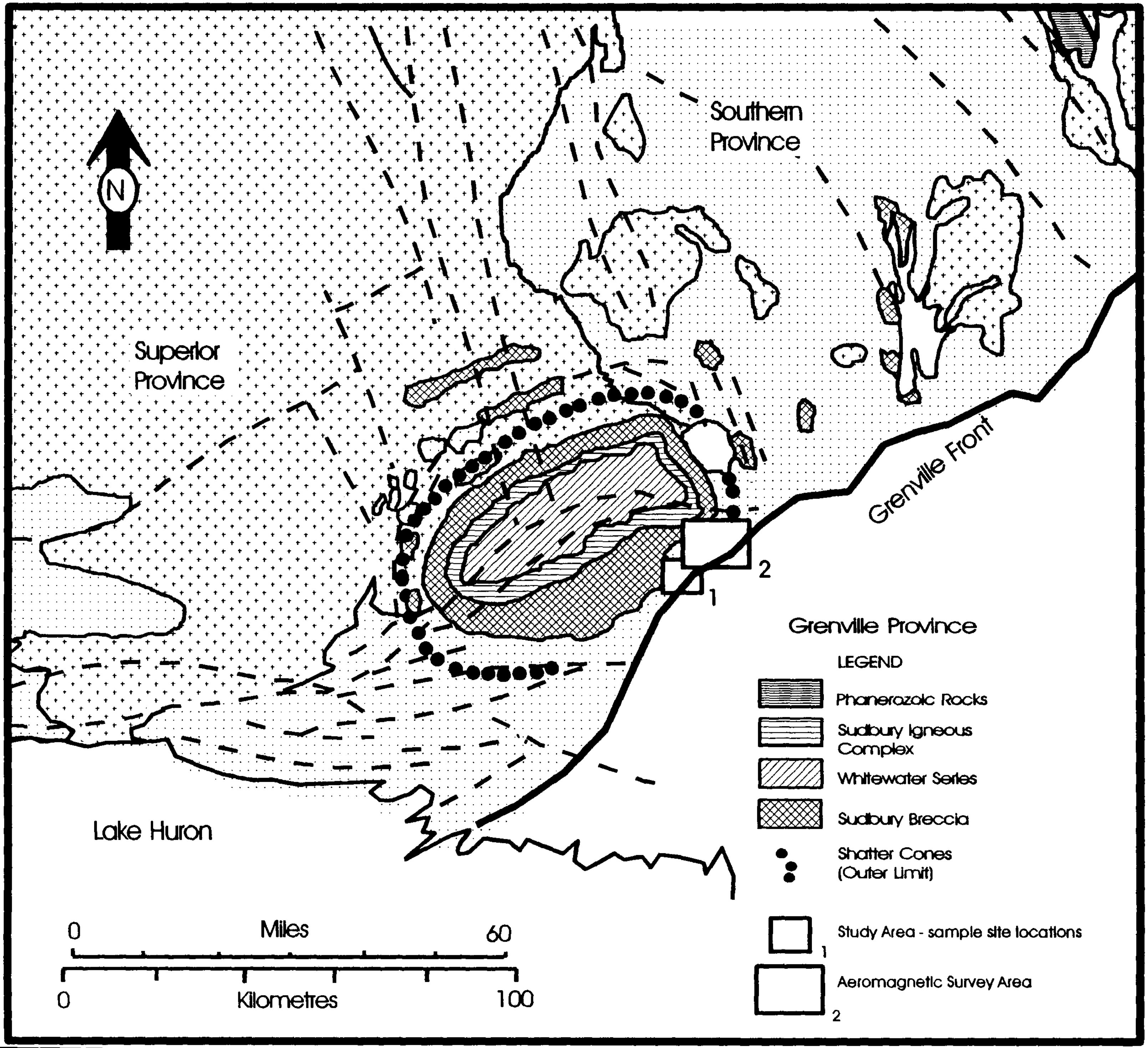

Southern Province
Superior Province
Grenville Front
N
1
2
Grenville Province
LEGEND
Phanerozoic Rocks
Sudbury Igneous Complex
Whitewater Series
Sudbury Breccia
Shatter Cones (Outer Limit)
Study Area - sample site locations
1
Aeromagnetic Survey Area
2
Lake Huron
0
Miles
60
0
Kilometres
100

Figure 2a:

Sample location map southeast of Sudbury, Ontario.

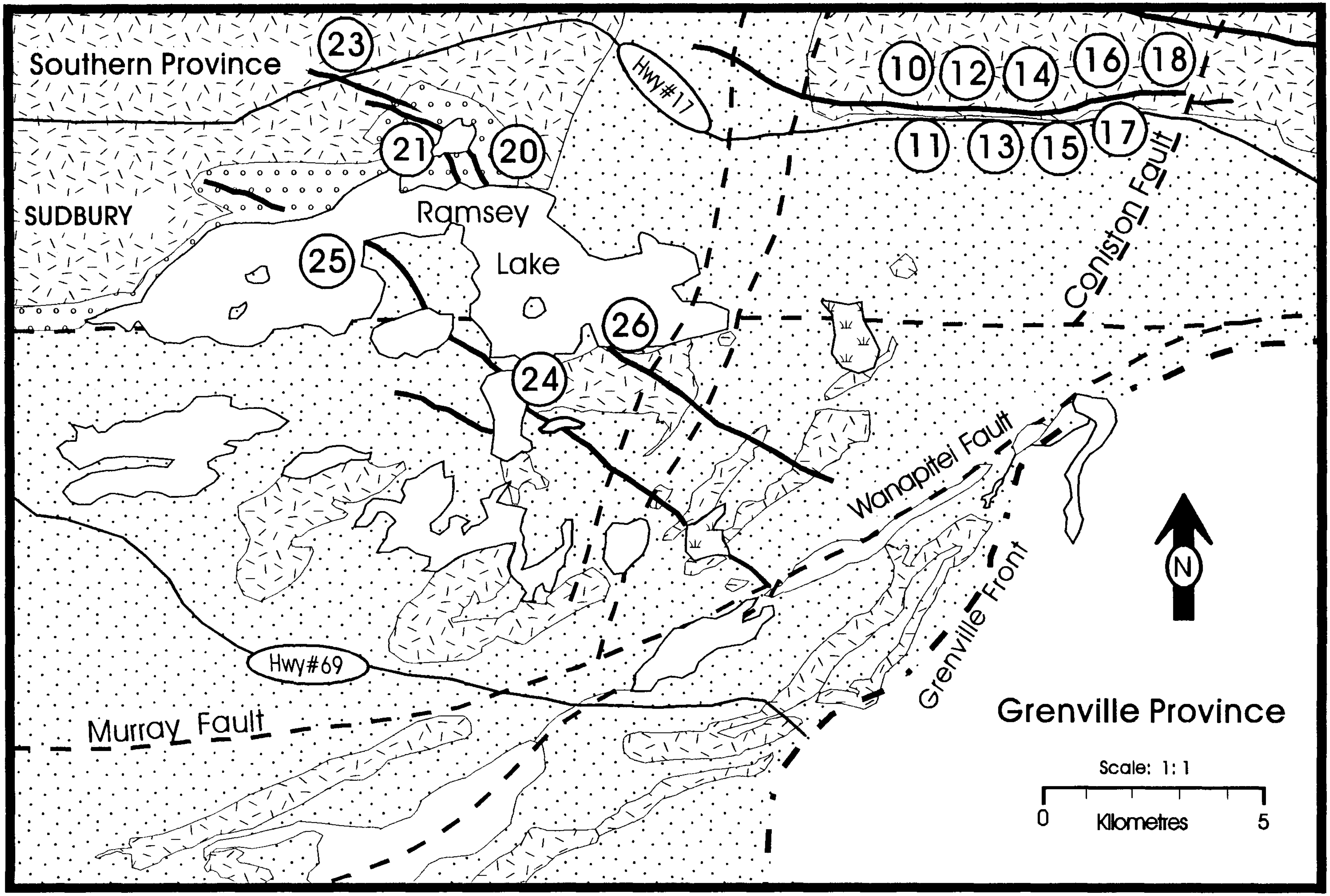

Southern Province
SUDBURY
23
21
20
Ramsey
Lake
25
24
26
Hwy#17
10
12
14
16
18
11
13
15
17
Coniston Fault
Wanapitei Fault
Grenville Front
Hwy#69
Murray Fault
Grenville Province
N
Scale: 1:1
0
Kilometres
5

Figure 2b:

Legend for sample location map.

LEGEND

· — —	Grenville Front
— — —	Fault
━━━	Olivine Diabase Dikes
▨	Nipissing Intrusive Rocks *Grabbro*
☐	Grenville Provice
⁙	Mississagi Formation *Arkose, subarkose, wacke*
⚬	Ramsey Lake Formation *Conglomerate, arkose, wacke*
ѱ	Marsh

Chapter 2

Paleomagnetism

2.1 Introduction

2.1.1 *Paleomagnetic Concept*

The concept on which paleomagnetism is established is in the preservation, or record of, the ambient magnetic field and its associated strength at the time of formation of the rock.

The magnetization persevered in a rock at present is termed the Natural Remanent Magnetization (NRM). The NRM of any given rock has two components: Primary and Secondary. The Primary magnetization is the original magnetization acquired by the rock at the time of formation. The Secondary magnetization being acquired anytime thereafter and overprinting the Primary magnetization. It is the vector sum of the Primary and Secondary magnetization that comprise the Natural Remanent Magnetization (NRM).

The magnetization acquired by an igneous rock at the time of intrusion usually has a high degree of stability. The magnetic minerals within the rock are cooled through their Curie temperatures in the ambient geomagnetic field resulting in the primary magnetization, termed a thermoremanent magnetization (TRM).

Secondary magnetization are acquired during the time period after the initial cooling of the rock. Rocks which have been subject to any further geological process such as, burial, intrusions or tectonic events generally undergo a rise in temperature. If this rise in temperature exceeds the blocking temperature of the magnetic grains, they will then acquire a partial thermoremanent magnetization (PTRM) when the rock subsequently cools.

The Primary NRM is of most interest to paleomagnetic interpretations, therefor it is necessary to remove any Secondary magnetization hopefully leaving the Primary magnetization intact. The process is called magnetic cleaning and is effective because the hardness of the PTRM is usually less than that of the original NRM.

Of interest in this study is to establish the extent of the thermal and/or tectonic boundary attributable to the Grenville orogeny, within the Southern Province, as seen in the Sudbury diabase dikes. Previous studies (Palmer *et al.*, 1977) have conclusively established that the Sudbury dikes possess a single, stable primary NRM and that thermal effects from the Grenville orogeny overprinted that signature with a single secondary PTRM. We propose to take these findings one step further and extract information, based on the observed NRM directions, and relate them to tectonic block rotations and uplift.

2.2 **Paleomagnetic Methods**

The most widely used magnetic cleaning method for thermal cleaning is stepwise thermal demagnetization. The principle of which is to incrementally raise the temperature of the rock until the relaxation time, the time required for a grain to reach equilibrium with its surroundings, of the particles carrying the PTRM has been reduced and therefor the PTRM of the particles will be successfully "unblocked" and their contribution to the remaining NRM is lost. After the initial NRM was measured at room temperature the specimens were heated in 50°C increments and cooled in zero field to avoid acquisition of a PTRM of sufficient strength that would contribute to the remaining NRM. This procedure is repeated at successively higher temperatures, through 600°C, above the Curie temperature of titanomagnetite ($\leq$ 575°C) until all secondary NRM components had been removed, thus leaving the primary component of high stability and with a blocking temperature near the curie point relatively unaltered.

At each successive temperature the intensity and direction of remanent magnetization was measured using a Molspin Spinner Magnetometer.

Values from each successive temperature step for every specimen was then processed, throwing out any meaningless results and doing tilt corrections, by using LSQ1 and Kirschvink analysis. In doing so a mean declination, inclination and intensity for each sample site was obtained, Table 1.

2.3 **Paleomagnetic Results**

2.3.1 *Curie Temperatures*

Mineral alteration and/or formation of new magnetic minerals, during thermal magnetic cleaning can pose a problem. Generally detection of any changes within the magnetic minerals can be seen during the measurement and shape of J_i - T curves. Ideally during heating and cooling any change will be indicated by one or more Curie points appearing within the curve, depending whether the new or altered mineral is formed above or below its Curie point. The shape of the curve is also important. In the ideal one mineral system there will be a slow decay with temperature with a rapid decrease as the Curie point is approached. A more linear decay suggests the presence of other phases with progressively lower Curie temperatures.

Generally the observed J_i - T curves for this study indicted no substantial alteration or new mineralization during thermal cleaning as the curve decayed slowly with increasing temperature and the Curie temperature was marked by a sudden decrease in J_i. Any points beyond the observed Curie point were disregarded as they probably did show new mineral formation and/or alteration. Determination of an accurate Curie point is not always easy because of the existence of paramagnetism beyond the Curie point. This is seen in the observed J_i that does not fall to zero at the Curie point of the dominant magnetic mineral. Therefor the Curie point is determined by using the intercept on the temperature axis of the tangent to the J_i - T curve at its steepest point.

2.3.2 *Analysis of demagnetized data*

The most commonly used method of presentation of demagnetized data combines the intensity and directional changes on the same diagram, ie Zijderveld plot. The total magnetization vector is plotted as points on the horizontal and vertical planes where X,Y, and Z are the magnetization components. As demagnetization progresses each plane will trace out a path corresponding to the changes in declination and inclination and magnetic intensity. As previously mentioned the simplest case of magnetic cleaning is the removal of the single secondary magnetization J_s, whereby leaving the primary NRM J_p intact, so that the thermal spectra do not overlap, as opposed to the most complicated scenario involving total overlap of J_s and J_p. This information can be obtained from the Zijderveld plot and is reflected in components of the relevant vectors.

Most of the specimens that were thermally demagnetized showed a single component NRM direction likely to be the primary remanence directions acquired during the original cooling. Relatively few samples showed two or more components of NRM directions, the most distinctive coming from the baked contact study specimens, which are discussed further in the next section.

2.3.3 *Results*

The results of Table 1 were then subsequently plotted on

Table 1:

Mean declination and Inclination of all Sample Sites

Site #	Mean Dec	Mean Inc	n	r	k	@95
12	285.22	21.10	4	3.68	10	31
14b	341.04	-18.26	3	2.97	72	15
16	303.84	36.47	6	5.61	13	19
17a	282.60	24.50	2	1.99	18	6
18a	119.04	58.39	3	2.90	23	26
18b	300.36	34.70	7	6.68	19	14
19a	288.47	35.26	7	6.64	17	15
19b	286.47	-9.50	3	2.96	58	16
20a	300.21	33.90	7	6.70	20	14
24	296.07	37.87	13	12.60	38	7
25	277.77	3.50	5	4.84	26	15
26	119.47	46.36	9	8.63	22	11

n = # of samples
r = Vector resultant derived from unit of n cores
k = Precision estimate of the mean direction
@95 = Alpha 95, radius of the circle of confidence about the mean direction in degrees

Table 2:

Sudbury Olivine Diabase Possessing a Primary Sudbury Direction

Site #	Mean Dec	Mean Inc	n	r	k	@95
12	285.22	21.10	4	3.68	10	31
16	303.84	36.47	6	5.61	13	19
17a	282.60	24.50	2	1.99	18	6
18b	300.36	34.70	7	6.68	19	14
19a	288.47	35.26	7	6.64	17	15
20a	300.21	33.90	7	6.70	20	14
24	296.07	37.87	13	12.60	38	7
25	277.77	3.50	5	4.84	26	15

n = # of samples
r = Vector resultant derived from unit vectors of n cores
k = Precision estimate of the mean direction
@95 = Alpha 95, radius of the circle of confidence about the mean direction in degrees

Table 3:

Sudbury Olivine Diabase possessing a Grenville Overprint Direction

Site #	Mean Dec	Mean Inc	n	r	k	@95
18a	119.04	58.39	3	2.90	23	26
26	119.47	46.36	9	8.63	22	11

n = # of samples
r = Vector resultant derived from vectors of n cores
k = Precision estimate of the mean direction
@95 = Alpha 95, radius of the circle of confindence about the mean direction in degrees

Table 4:

Sudbury Olivine Diabase Possessing Negative Inclinations

Site #	Mean Dec	Mean Inc	n	r	k	@95
11b	285.77	-6.68	2	1.95	23	54
14b	341.04	-18.26	3	2.97	72	15
15a	341.11	-10.55	6	5.84	31	12
19b	286.47	-9.50	3	2.96	58	16
20b	313.32	-38.70	3	2.90	30	23

n = # of samples

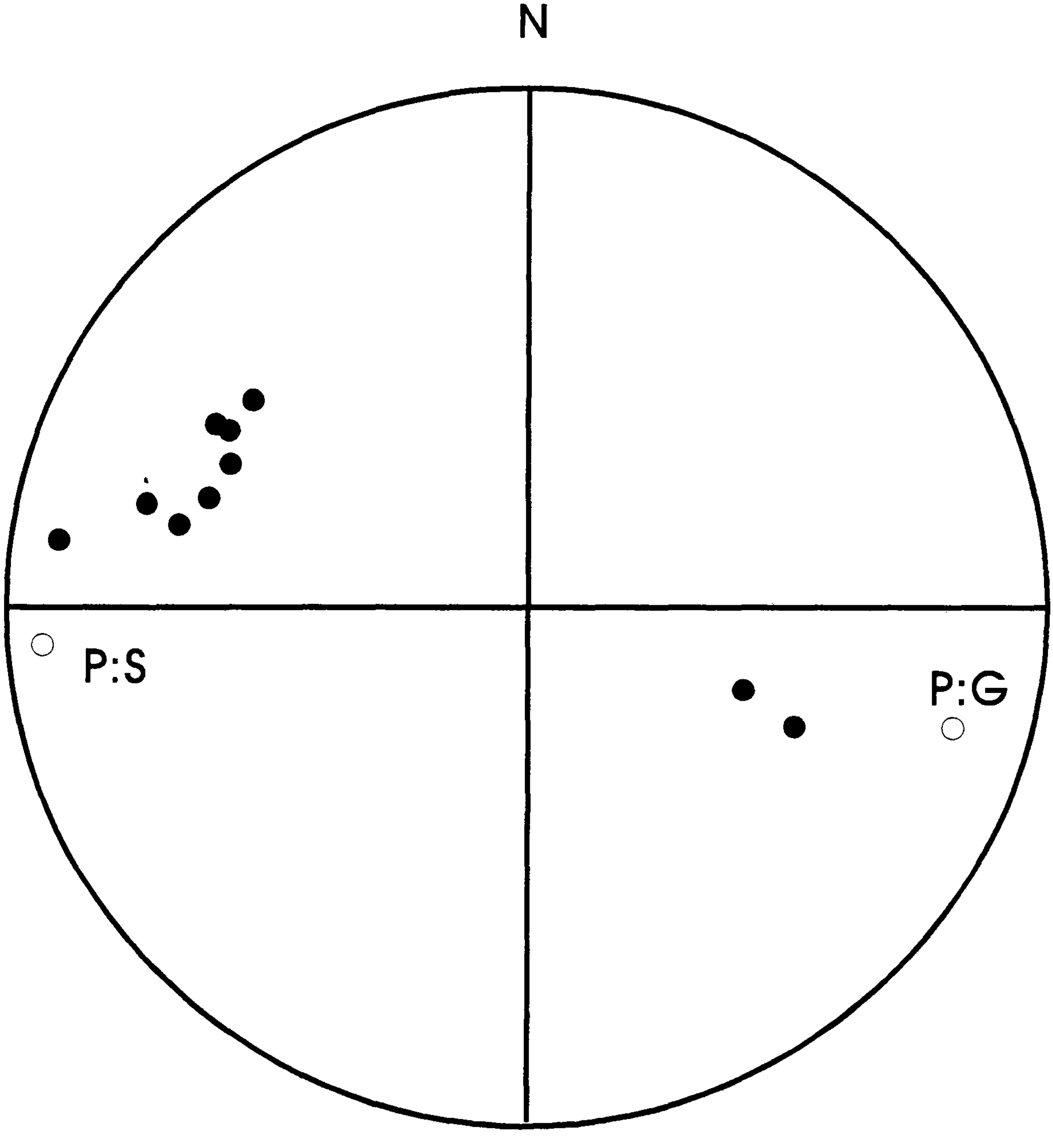
r = Vector resultant from unit vectors of n cores

k = Precision estimate of the mean direction

@95 = Alpha 95, radius of the circle of confidence about the mean direction in degrees

Figure 3:

Results of Table 1 plotted on an equal area projection steronet. Two distinct groupings are visible. Group 1 yields a mean inclination and declination of 300°/32° and group 2 yields a mean inclination and declination of 116°/56°. P:S is the mean for Palmer *et al.*, 1977 Sudbury dike direction and P:G is the mean for his Grenville overprint direction.


N
P:S
P:G

an equal area projection steronet Figure 3. The distribution of the sample sites can be subdivided into two distinct groups according to their declination and inclinations. The first group comprises the largest number of sample sites and yields a mean inclination and declination of 300°/32°, see Table 2. Table 3 shows two sample sites with significantly different directions, their mean being 116°/56°. A number of NRM directions from various sample sites have been excluded due to the high degree of error associated with their calculation, generally attributable to the lack of samples taken.

Comparison of these results to Palmer *et al.*, (1977) reveal similarities, Figure 3. Group 1 is comparable to Palmers observed Sudbury Dike direction, 265°/2°, which he attributes as being a primary remanence direction acquired during the original cooling of the dikes. This studies second group of directions is in general agreement with Palmer's observed Grenville overprint direction, 111°/27°. None of Palmer's *spiralling sites* were observed.

Table 4 represents some the spurious directions calculated from this study, all of which show northerly declinations with negative inclinations, the corresponding pole, 131°E, 22°S plots just off of the "Grenville Loop" (Dunlop *et al.*, 1980). The apparent polar wander paths for Precambrian paleomagnetism are complicated in nature. There are two groups of poles; those which record the APWP for Laurentia, and those which record a possible divergence of Grenvilla and Interior Laurentia during the late

Precambrian, thus providing justification for the continental collision that produced the tectonic events associated with Grenville orogeny (Dunlop *et al.*, 1980). Of concern is the need to establish accurate ages of the pole positions to confirm such theories.

2.4 **Baked Contact Studies**

2.4.1 *Introduction*

When an igneous rock intrudes into a formation already possessing a NRM, that NRM will generally be altered in the contact zone through the acquisition of a TRM in the immediately adjacent zone and a PTRM as far into the country rock as heating permits (> ≈ 100 °C). A positive result would prove stable magnetization of both the igneous intrusion and surrounding country rock if both had the same NRM. Further away from the intrusion it would be expected that in the country rock the superimposed PTRM would become progressively weaker.

2.4.2 *Results*

Where field drilling permitted, and contact zones were readily accesible, samples were taken to several dike widths away into surrounding country rock. The samples of country rock obtained were Nipissing diabase and proved to be inconclusive as they posses unstable or weak remanence directions.

Sample Site #20, located to the north of Ramsey Lake,

Table 5:

Results from Baked Contact studies from Sample Site #20 and #23. See explanation in text.

		Declination	Inclination	Intensity	@95
Sample Site #20 (dike width = 54cm)					
S132A		277	38	8.29E-04	8.3
S132B		293	39	8.33E-04	8.3
S133A		299	54	1.33E-03	8.6
S133B		306	65	2.14E-03	5.4
S134A		318	34	1.60E-02	1.7
S135A		312	6	6.90E-04	14.9
S135B		298	25	5.44E-04	11.2
S136A		283	76	4.76E-03	4.6
Nipissing Diabase (distance in cm from dike contact)					
S137A	1	332	-41	8.42E-03	1
S138A	2	302	-28	1.60E-04	2.6
S138B	2	302	-44	2.20E-04	5.6
S139A	4	256	3	5.50E-04	4.1
S139B	4	302	8	4.00E-04	3.2
S140A	7	303	-12	5.10E-05	7.3
S141A	8	303	66	1.20E-04	6.7
S142A	1	297	63	1.38E-04	7.7
Sample Site #23 (dike width = 15cm)					
Nipissing Diabase (distance in cm from dike contact)					
S148A	6	328	-46	2.50E-07	30
S150A	1	314	-23	4.70E-07	8.8
S151A	2	315	-40	4.80E-07	8

Figure 2, proved to be the only semi-reliable site. The dike at that location possessed a primary Sudbury dike direction. The country rock although possessing a relatively stable remanence declination had a fluctuating inclination, especially in the vicinity of the contact. This would suggest some sort of alteration, perhaps hydrothermal, which appears restricted to the vicinity of the contact zone. This is supported by mild hydrothermal alteration features as seen in thin sections from this local. Furthermore hand specimen samples of the country rocks show minor fracturing and veining. Further away from the contact zone we see a progressive change in inclination that agrees with the Sudbury Direction of the dike.

Country rock samples taken from Sample Site #23 to a distance of two dikes away, support the above conclusions, of minor hydrothermal alteration in the vicinity of the contact zone. The results of the Baked Contact Test are listed in Table 5.

Chapter 3

Aeromagnetics

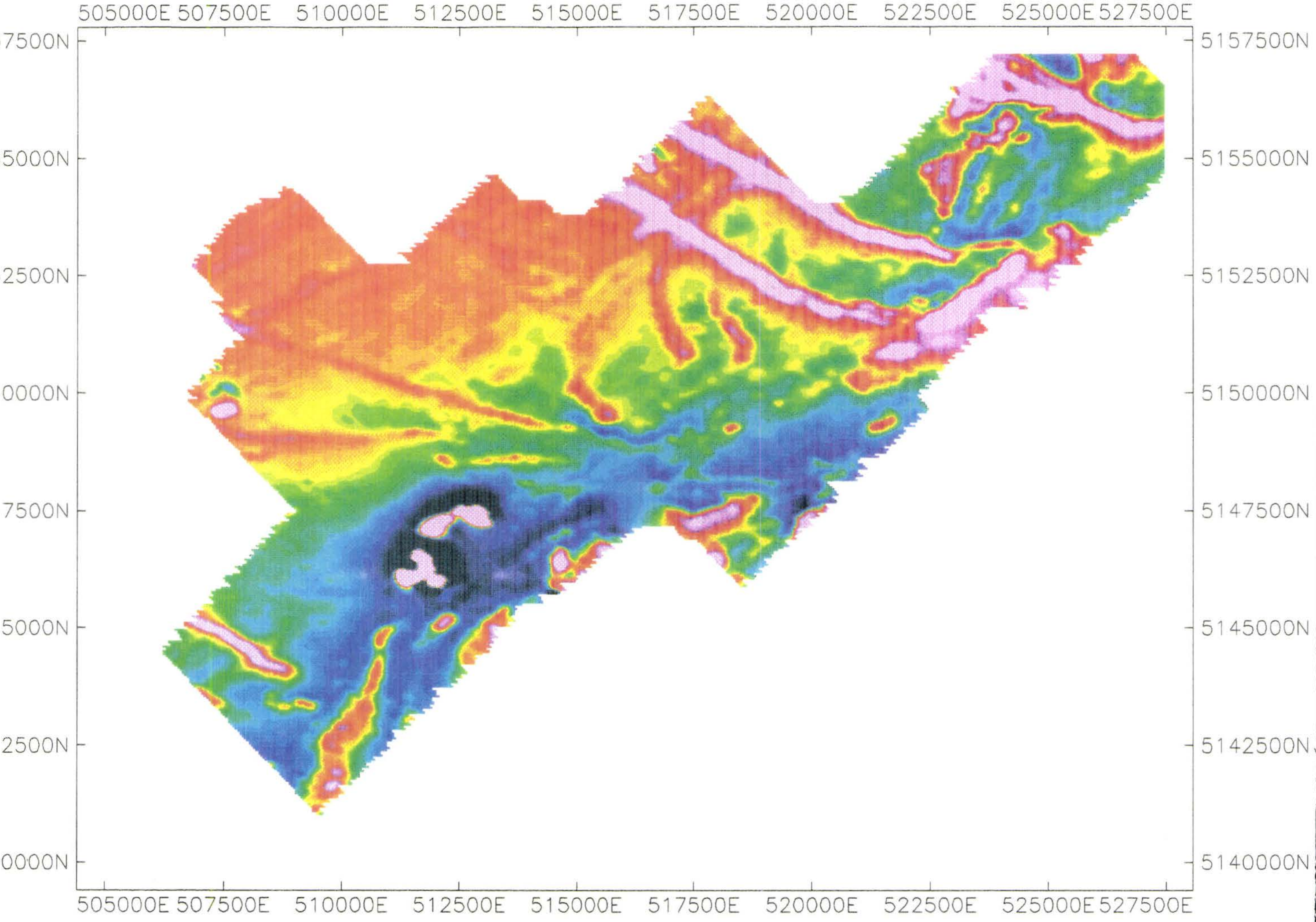
3.1 Introduction

Many aeromagnetic surveys have been done in the Sudbury region, one of which incorporated this studies sample area, Figure 1. Due to the highly magnetic nature of the Sudbury olivine diabase dikes this type of survey can prove to be exceptionally effective as the dikes can be traced for long distances, even if they do not outcrop. On the Ontario Geological Survey Map of Sudbury (map 2491), the dikes all appear as single structures, none of which outcrop near to the Front. An aeromagnetic survey allows for their analysis in much greater detail. Furthermore, an survey of this type, will allow for detection of any tectonic deformation that is reflected within the dikes as they approach the Front.

The raw information that was received, had already been gridded, therefore selection of grid cell size and any preprocessing (filtering) on the grid could not be accomplished. A scale of 1:160,000m was chosen for the final map, this was considered suitable as it produced a clear compact map that outline the major geological structures, Figure 4. A second map with a larger scale of 1:50,000 was also produced to facilitate identification and interpretation of geological structures. The colour zoning is in accordance with the parameters set by the

Figure 4:

Aeromagnetic map showing ductile deformation of the Sudbury olivine diabase dikes within the Southern Province.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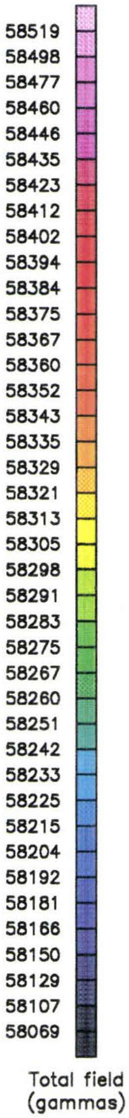
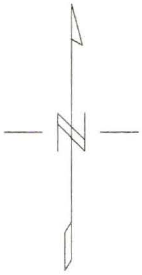
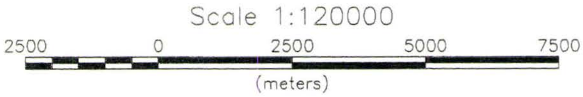






B.Sc Thesis

Aeromagnetics of Grenville Front
Southeast of Sudbury

Total Residual Magnetic Field (gammas)

Susanne Manning #8919012

Geological Surevy of Canada. The residual total magnetic field was measured in gammas and estimated to be 58000nT. The flight path was determined to be northeast-southwest and the map is oriented true to north.

It is important to note that aeromagnetic processing is an objective science. Of sole interest in the survey area are the olivine diabase dikes and associated Grenvillian deformation therein, hence this will bias the filtering of the final map to emphasize those features.

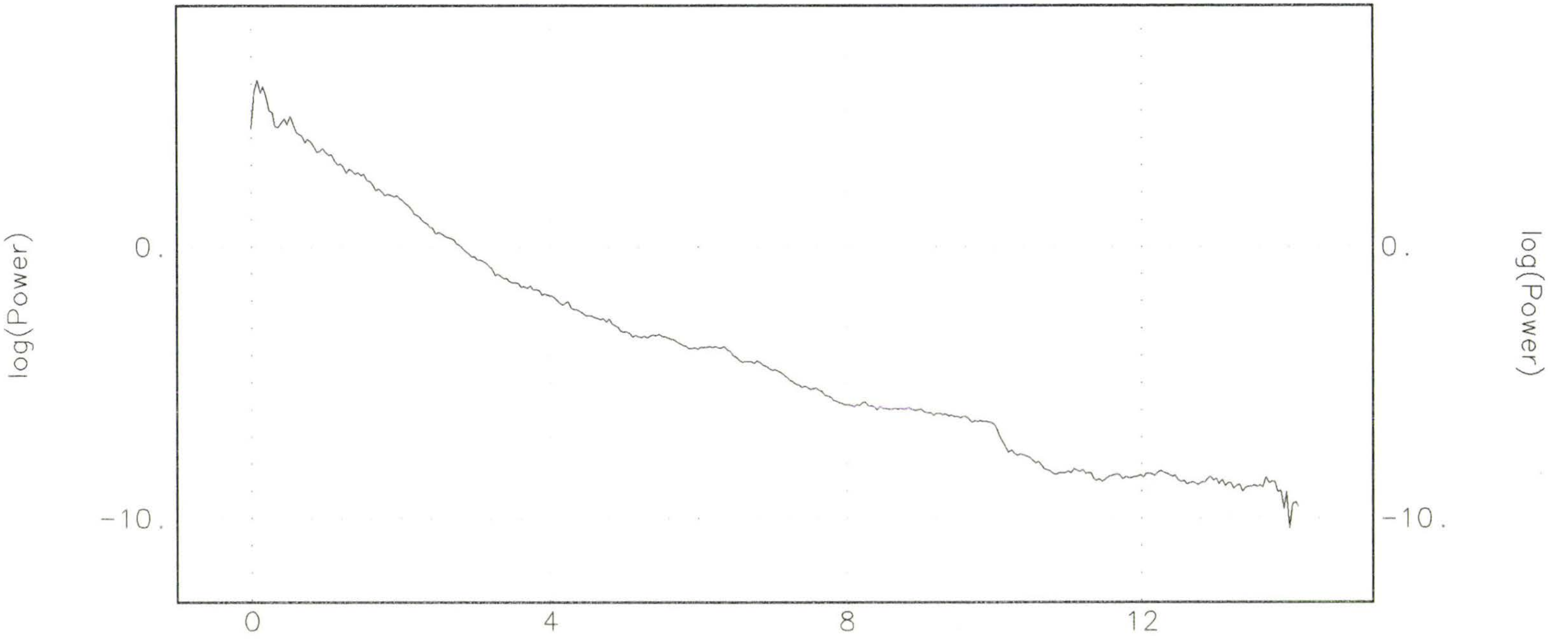
3.2 **Processing**

All processing was accomplished by using Sushi and Magmod3 in the Geosoft software package. In preparation for filtering a Radially Averaged Power Spectrum was made, Figure 5. From the spectrum the Nyquist Frequency was observed to be V_n=9.8 (1/km) and values above this point where rejected using a Band Pass Filter. Upon further examination of the Power Spectrum and the Depth Estimate revealed that a Low Pass Cosine Filter with a roll off of 2, would be appropriate within the wave number range of 3.2 - 9.8 (1/km). Sole examination of this range determined it to be mainly noise and therefore unimportant to the final product, in effect the above filter was a smoothing operation. A Band Pass filter that rejected all data above 0.6 (1/km), proved that the deep structures are the Sudbury olivine diabase dikes. The dikes are the

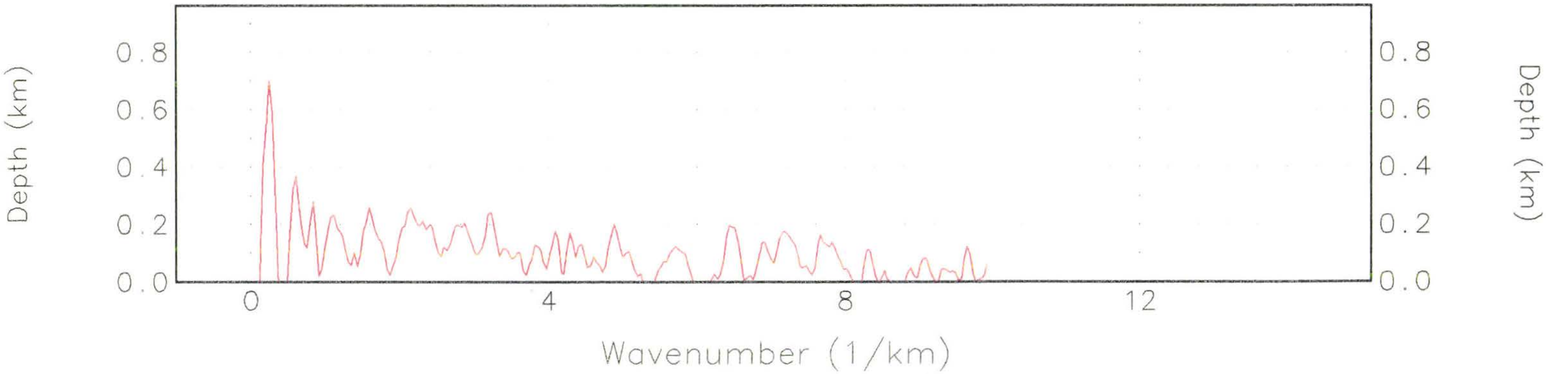
Figure 5:

Radially averaged power spectrum. Nyquist frequency is at V_n=9.8 (1/km).

RADIALLY AVERAGED POWER SPECTRUM



DEPTH ESTIMATE



overwhelming and magnetically strong features of the map, this will bias the magnetic field to some degree by suppressing any smaller or near surface features. A directional cosine filter at 285° in conjunction with a Butterworth filter (to remove any ringing as a result of the DCOS filter) was then applied to remove any aliasing as a result of the flight path. This then in turn presented the problem that the data may have been over filtered. Doing such selective filtering had actually introduced a ringing and too many important smaller scale features had been removed. It was subsequently proposed that any aliasing due to the flight path was inconsequential to the final processed map.

Producing a shaded image map, with a sun declination of 135° and inclination of 25°, from the final filter version enhanced any slighted geological features and structures that may have been overshadowed by the dikes, Figure 6.

3.3 **Interpretation**

The Olivine Diabase dikes are clearly defined as magnetic highs on the map. There appear to be two different sets of Sudbury dikes based on the strength of their magnetic signatures. Both types were sampled in this study area and expressed no mineralogical differences, on the microscopic scale, that might explain the varying magnetic signatures. This suggests a need for further geochemical analysis on the Fe-Ti oxide content of the

Figure 6:

Shaded relief image of aeromagnetic map, with sun declination at 135° and inclination at 25°.


505000E
507500E
510000E
512500E
515000E
517500E
520000E
522500E
525000E
527500E
5157500N
5155000N
5152500N
5150000N
5147500N
5145000N
5142500N
5140000N

sampled dikes.

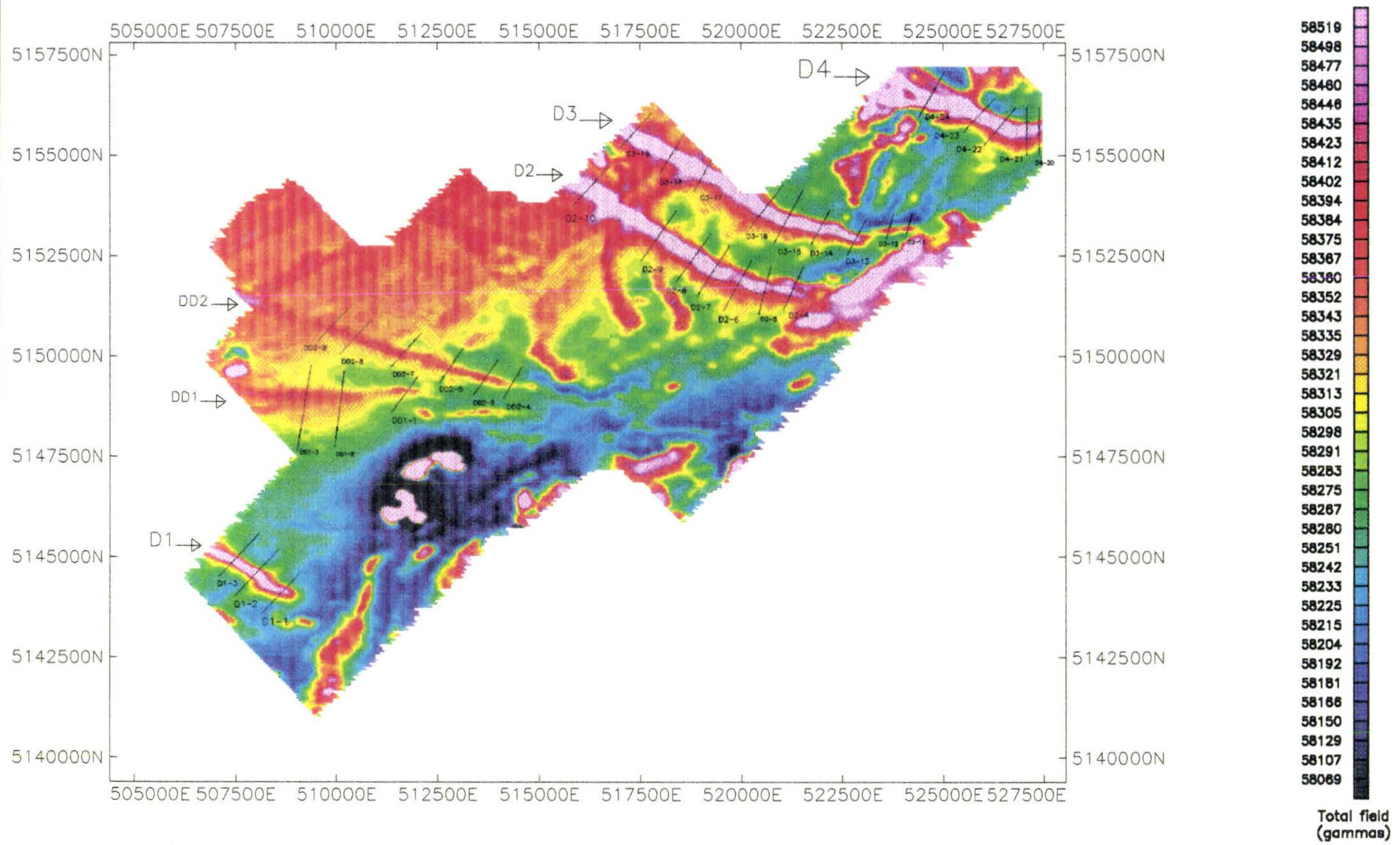
Although the Grenville Front does not appear as a major geological structure on the aeromagnetic map, Figure 4, it becomes much more visible on the shaded relief map, Figure 6, as a significant Northeast trending structure. Furthermore major faulting presumably associated with the Murray Fault and it's extension, the Wanapitei Fault, become visible as they offset the dikes. These faults all posses the same Northeast orientation as the Grenville Front.

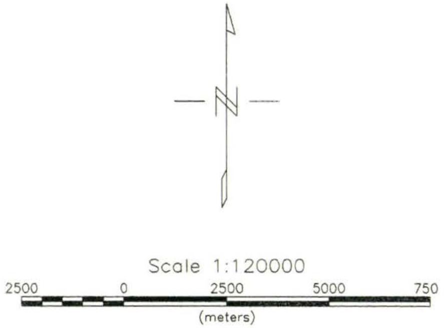
In the northeast corner of the map a deformation zone approximately 5 km in width can be identified, as seen by the ductile deformation within the dikes. The extent of which can be recognised by their reorientation in a northeasterly direction as they encroach on to the Grenville Front. Further examination of the shaded image map reveals that the less magnetic dikes also show a ductile deformation zone as the approach the Front with the same orientation in a northeasterly direction.

Detailed review of the dikes as they become effected by the Front reveal more extensive tectonic activity than simple ductile deformation. In conjunction with the shaded relief map, considerable faulting in a north-northeast direction is discernable, with minor displacements in an northeast direction. Moreover, the dike furthest to the northeast, which does not outcrop on the OGS map, appears to have a very complicated structure, attributable to both ductile and brittle deformation.

Figure 7:

Location of profiles taken for magnetic modelling.





B.Sc Thesis

Aeromagnetics of Grenville Front
Southeast of Sudbury.

Total Residual Magnetic Field (gammas)
Trend Removed
Profile Locations

Susanne Manning #8919012

The complicated nature of these dikes, within the zone of deformation, is substantiated by magnetic profiling, outlined in the next section.

3.4 **Modelling**

3.4.1 *Introduction*

When doing Magnetic Modelling two assumptions must be made:

(1) That the magnetic field is measured in a constant direction, whether horizontal, vertical; and

(2) The body being modeled is uniformly magnetized.

33 small profiles were extracted from all major dikes on the aeromagnetic map, from which 20 viable models were produced. The locations of the profiles are outlined in Figure 7. Profiles were extracted from each dike at sequential localities, in order to better constrain the dip, depth and width changes in the dikes with decreasing distance from the Grenville Front. Any change especially in the dip would substantiate the existence of the deformation zone within the Southern Province.

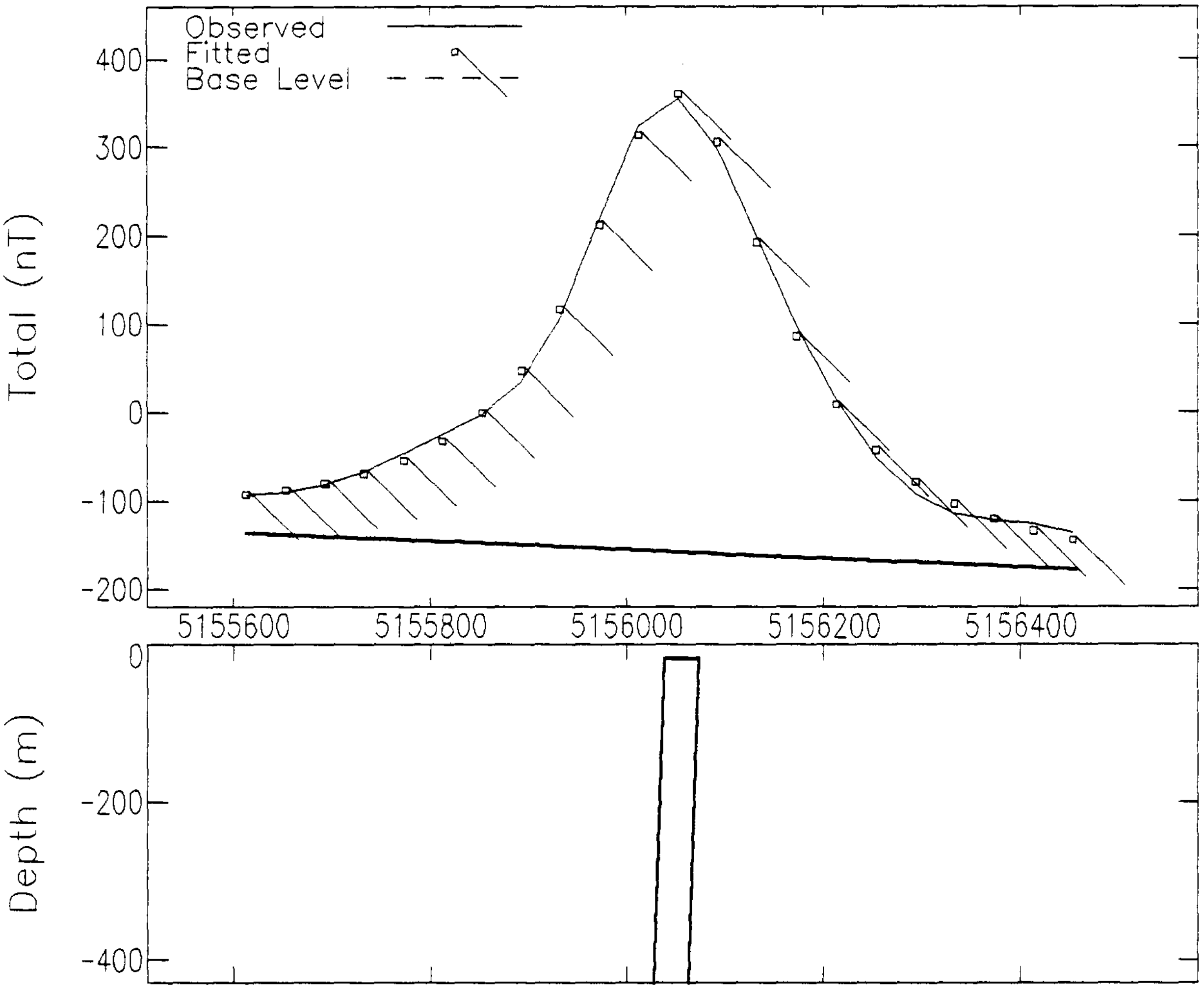
For the modelling procedure the following parameters were adopted; strength of the Earth's magnetic field, 58000nT, the field inclination and declination are 75° and 8° respectively, sensor height was 100m. The direction of each profile was orthogonal to the direction of the dikes. One of the problems in modelling is estimation of the magnetics properties of the dike. A

Figure 8:

Model of profile D4-23, with a Sudbury remanence direction.

Model D4-23 Sudbury Direction

9L 01



MODEL PARAMETERS:

Model Type		Tabular
Depth	F	17.9 m
Half Width	F	22.1 m
Dip	F	92 deg
Susceptibility	F	0.0123 emu
Remnance Ratio	X	.5
Remnance Incl	X	1 deg
Remnance Decl	X	265 deg
Main Position	F	5156057 m
Cross Position	X	525806.6 m
Base Level	F	-158.3327 nT
Base Slope	F	-.0394547 nT/m
Base Curvature	X	0 nT/m2

(F-fitted, X-fixed, L-limit)

GEOMAGNETIC FIELD:

Field Strength	58000 nT
Inclination	75 deg
Declination	8 deg

COORDINATES:

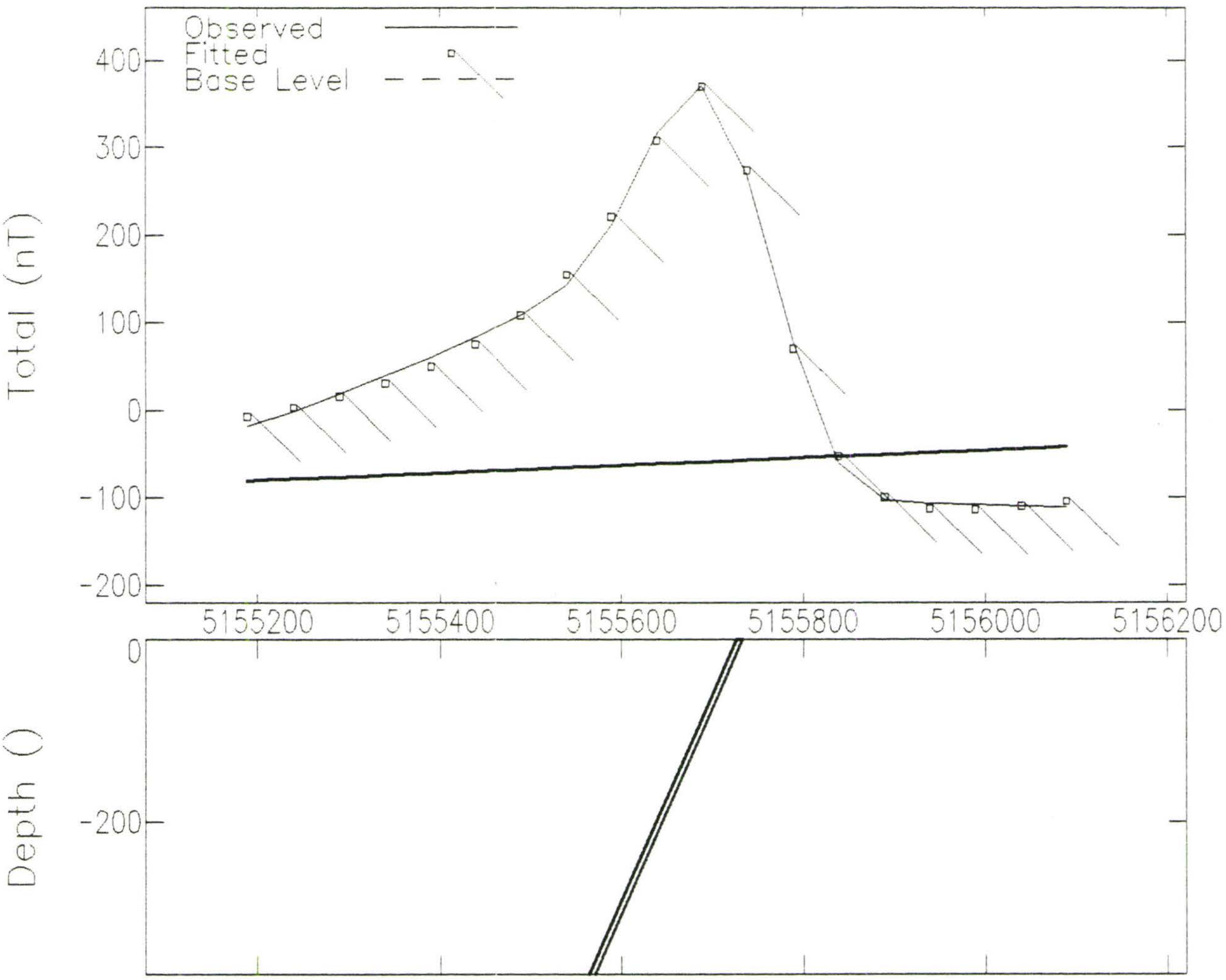
Sensor Height	100 m
Strike Perp	45 deg
Line Direction	82 deg
Main Direction	45 deg
Main Offset	
Cross Direction	135 deg
Cross Offset	

Figure 9:

Model of profile D4-21, with a Grenville Overprint remanence direction.

D4–21 with Grenville Overprint Direction

7L 01



MODEL PARAMETERS:

Model Type		Tabular
Depth	L	0.102
Half Width	F	2.89
Dip	F	114 deg
Susceptibility	F	0.0679 emu
Remnance Ratio	X	.5
Remnance Incl	X	27 deg
Remnance Decl	X	112 deg
Main Position	F	5155731
Cross Position	X	527125.1
Base Level	F	-58.13459 nT
Base Slope	F	.0424276 nT/
Base Curvature	X	0 nT/2

(F–fitted, X–fixed, L–limit)

GEOMAGNETIC FIELD:

Field Strength	58000 nT
Inclination	75 deg
Declination	8 deg

COORDINATES:

Sensor Height	100
Strike Perp	0 deg
Line Direction	10 deg
Main Direction	10 deg
Main Offset	
Cross Direction	100 deg
Cross Offset	

eosoft MAGMOD–3 Modeling Result 94/03/24 susceptibility value for olivine diabase was selected from Telford *et al.*, (1990), and limited for all models at 0.002emu. A regional slope was calculated by extracting a couple of large profiles over the entire map and then calculating the slope. The regional slope was then fixed for all models at 0.012nT/m. For all models a model type of tabular was chosen, as it assumes infinite depth and mathematically best approximates a dike-like object. The remanence ratio was fixed at 0.5 for all dikes with the remanence Inclination and Declination varying depending on the location of the profile. Values for remanence Inclination and Declination were obtained from Palmer et al., 1977; 1°/265° for a primary Sudbury olivine diabase direction and 27°/112° for a Grenville overprint direction.

3.4.2 *Results*

In modelling it is very important to know whether the magnetization is induced or remanent. In this case these dikes are strongly remanent and therefore an accurate inclination and declination would appear to play a significant role in dip calculations as it would appear that this is the most significant parameter.

Four models that were produced in the 5km deformation zone, as defined by aeromagnetics, a Grenville remanence direction was used, according to Palmer *et al.*, (1977). This generally produced a good fit, with the depth of the dike usually within 0.5m of the surface, Figures 8 & 9. Only some of the models are presented here. The half width of the dike was usually fixed to be no greater than 10m. In all cases the dip was steep, ranging through 90° to 100°. Profiles that were extracted from areas within this zone occasionally exhibited two or more anomalies, ie; two dikes side by side, these profiles were not used in the modelling process as a clean anomaly could not be extracted.

Most of the models calculated used a Sudbury remanence direction after Palmer *et al.*, (1977) in an area extending well into the Southern Province. It was found that the dip remained relatively steep ranging from 80° - 90°. Any distinctive swings in the dip within this area were attributed to profiles located ontop of fault structures.

In modelling the above profiles many parameters were fixed based on previous knowledge and some assumptions. These assumptions will bias the outcome to a large degree. For a model to be reasonably accurate, details as to whether or not it outcrops, width and dip should be measured at the outcrop to insure the least biased solution.

Chapter 4

Mineralogy

4.1 Petrography

4.1.1 *Introduction*

A total of 18 thin sections were cut from selected core specimens and hand specimens from sample sites and are grouped into the following categories based on calculated paleomagnetic directions: 1. Sudbury olivine diabase, found in the Southern Province with Primary Sudbury NRM directions; 2. Sudbury olivine diabase in the Grenville Front region possessing overprinted Grenville NRM directions.

4.1.2 *Sudbury Olivine Diabase with Sudbury Directions*

The thin sections of these dikes display an ophitic to subophitic texture. Based on the petrography, the order of crystallization, of the three primary minerals is: plagioclase + clinopyroxene, preceded by olivine. The plagioclase is well preserved as defined by the euhedral grain boundaries. The clinopyroxene is augitic in composition. Biotite, which is commonly associated with the augite, is usually present in varying amounts. The matrix is fine grained to glassy and comprised mainly of calcite, biotite and chlorite.

Most slides do not show any evidence of metamorphism or hydrothermal alteration. This is supported by the olivines which have remained relatively fresh and have not undergone any serpentinization. There does however, appear to be some evidence of localized sericitization and to a lesser extent, extremely restricted kaolinization of the plagioclase, as seen in the development of small amounts of chlorite. There is no uralitic alteration of clinopyroxene. The Fe-Ti oxides consist of abundant separate ilmenite and subhedral titaniferous magnetite grains. Sulfides are much less common and include sporadic development of chalcopyrite and pyrite. As is evident from the present mineralogy the overall maximum grade of metamorphism of the dikes appears to be sub-greenschist.

4.1.3 *Sudbury Olivine Diabase with Grenville Directions*

Thin sections from dikes that possess Grenville directions express the same mineralogical compositions as the aforementioned group. There is absolutely no metamorphic signature visible in any of these slides, which is supported by the pristine nature of the plagioclase. Thin sections cut across contact zones clearly indicate the order of crystallization: Plagioclase + Clinopyroxene, preceeded by olivine. The matrix in these zones is glassy at the margins and becomes progressively coarser grained towards the core of the dike. The alignment of feldspar grains along the chilled margins indicate flow direction. The slightly coarser grained matrix at the core, is comprised mainly of calcite with lesser amounts of chlorite and biotite. The Fe-Ti oxides consist of ilmenite and titaniferous magnetite. The sulfides are less common and include chalcopyrite and pyrite.

From the petrology, two distinct groups of feldspars are observed, based on habit, alteration and zonation. Those feldspars found in sample sites possessing Sudbury directions are generally subhedral, exhibit minor hydrothermal alteration, and are distinctly zoned. Those feldspars found in the sample site possessing Grenville directions are, euhedral, pristine in nature, and are not zoned. This zoning is best shown in the detailed plagioclase microprobe analysis outlined in the following section.

4.2 **Microprobe Analysis of Feldspars**

4.2.1 *Introduction*

An attempt was made to try to establish the extent of the Grenville Front alteration zone by analyzing the change in anorthosite to albite content within the plagioclase. The samples came from a successive suite of sites taken along one dike, moving progressively towards the Grenville Front.

5.2.1 *Sampling*

Polished sections from sample sites 10,12,14,15 and 16, Figure 2a, were sent to Western for plagioclase microprobe analysis using the JEOL JXA 8600. Typically 7 -10 spot analysis of plagioclase were made in each thin section. These sample sites all possessed Sudbury directions as calculated by paleomagnetic studies detailed in the following section.

4.2.2 *Results*

The average composition of the plagioclase in these samples is An_{60}. The orthoclase content was generally less than 1 mol %. The expectation to obtain a gradual increase in albite content was not realized as shown in Table 6. These results would indicate that the extent of sampling towards the Front was not sufficient to establish this zone. The proposed increase would help determine the extent or boundaries of the hydrothermal - metamorphic alteration front.

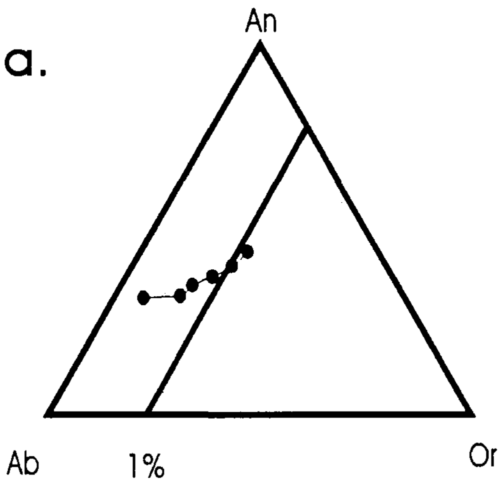
The zoning of the plagioclase can be best explained by the bimodal distribution of grains. The difference between the zoned and unzoned plagioclase relate to their crystallization history. Those grains which crystallized at depth exhibit no zoning and are almost pure anorthosite. Those plagioclase grains which crystallized during intrusion, *in situ*, are strongly zoned. Figure 10 clearly shows the compositional changes, progressing from relatively high anothosite cores to albitic margins. This suggests a gradational crystallization path which followed the liquidus, and therefor is strongly dependant upon liquid within the melt. Whereas those crystals which nucleated and grew at depth had an

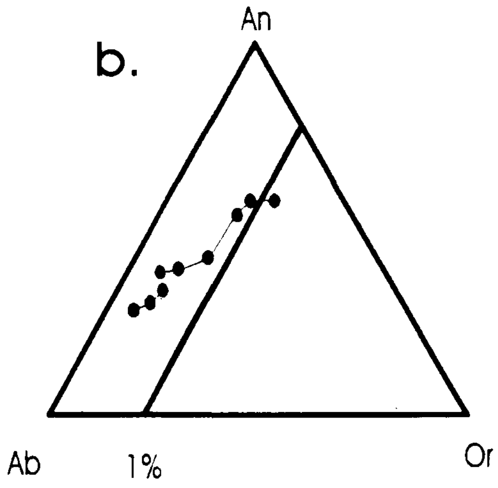
Table 6:
Average Plagioclase Compositon

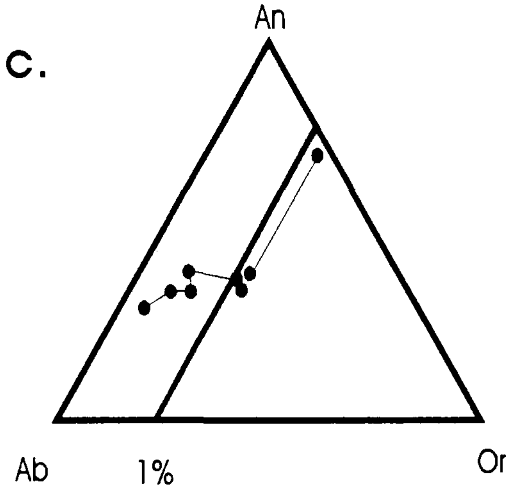
	Sample 101a		Sample 108a		Sample 112a		Sample 116d		Sample 118a	
SIO2	53.28		54.57		54.71		53.26		53.29	
AO3	29.29		28.5		28.56		29.35		29.26	
NAO	4.36		4.95		4.82		4.25		4.36	
K2O	0.12		0.14		0.15		0.12		0.11	
CAO	12.65		11.9		11.83		12.86		12.7	
SUM	99.69		100.06		100.05		99.83		99.72	
SI	9.676	*	9.857	*	9.872	*	9.662	*	9.677	*
AL	6.268	15.944	6.065	15.922	6.072	15.943	6.274	15.936	6.262	15.938
AL	0	*	0	*	0	*	0	*	0	*
NA	1.535	*	1.734	*	1.685	*	1.496	*	1.534	*
K	0.029	*	0.031	*	0.034	*	0.027	*	0.026	*
CA	2.461	4.024	2.304	4.069	2.286	4.005	2.5	4.023	2.471	4.031
O	32	*	32	*	32	*	32	*	32	*
AB	38.41		42.94		42.43		37.43		38.3	
AN	61.59		57.06		57.57		62.57		61.7	

Figure 10:

Plagioclase zoning from core to margin: a. sample 101, b. sample 108a, c. sample 112a, d. sample 116d, e. sample 118a.


a.
An
Ab
1%
Or


b.
An
Ab
1%
Or


c.
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Ab
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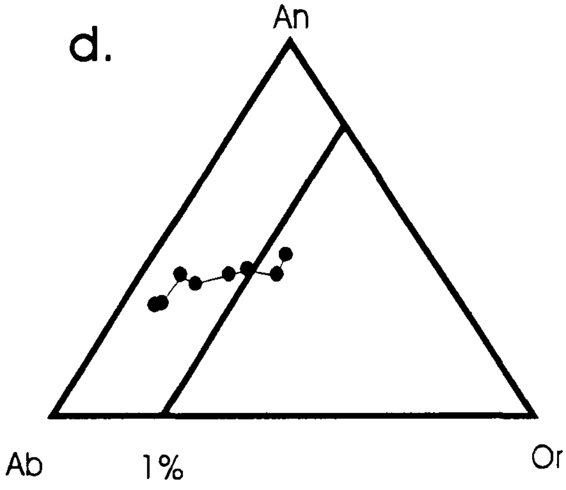
Or


d.
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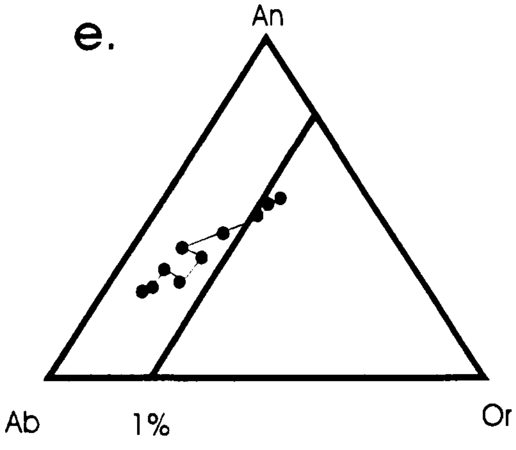
e.
An
Ab
1%
Or

initial anorthosite composition below the liquidus.

Temperature determination is impossible at this stage, without any analysis of amphiboles, this possess an other problem that the dikes, within this study are not sufficiently metamorphosed to have produced any amphiboles. It is therefore suggested that temperature determination be done on the country rock in the contact zones and a temperature extrapolated.

Chapter 5

Discussion and Conclusions

Evidence from both paleomagnetic and aeromagnetic studies show there to be a deformation zone within the Southern Province, extending for 5 - 10 km just to the north of the Grenville Front. This zone is characterized by both ductile and brittle deformation as seen in the Sudbury dikes. Of interest is the apparent lack of metamorphism in the dikes on the microscopic scale within this zone.

Paleomagnetic results from this study conclusively show two groups of remanence directions;

(1) Sudbury Olivine Diabase with Sudbury directions possessing a mean of 300°/32°;

(2) Sudbury Olivine Diabase with Grenville directions, possessing a mean of 116°/56°; both of which represent single component NRM directions.

In Palmers *et al.*, (1977) sample area, although considerably larger than this study, a boundary between the two directional groups can clearly be established, with the *spiralling sites* marking the transition from one to the other. It was hoped that this boundary could have been established, but the limitation of sample area size and therefore lack of samples from dikes proved to be very significant.

The direction of magnetization obtained does vary somewhat from that found by previous studies (Palmer *et al.*, 1977, and Larochelle, 1967). It is proposed that the discrepancy between the values can be attributed to tectonic processes in the form of rotated and/or displaced blocks. The rotation required for those dikes possessing a Sudbury direction is 42°/32° and those possessing a Grenville direction 28°/26°. This would seem to indicate a localized area of fault block movement with some associated rotation. Only sample site #25 was in agreement with Palmers *et al.*, (1977) calculated Sudbury directions, and this is notably one of the furthest from the Grenville Front.

Examination of various maps (Palmer *et al.*, 1977, Davidson and Bethune, 1988, Davidson and Ketchum, 1993) show evidence to supported the above conclusion of fault block movements, as seen in the discontinuous and rotated nature of the dikes. It would therefore appear to be logical for further paleomagnetic analysis involving sampling of a series of dikes through their entire length, moving progressively away from the front well into the Southern Province to a distance of 10km or more.

Further paleomagnetic sampling of this nature would also allow for confirmation of the third group of directions found in this study. Those directions which show steep declinations and negative inclinations, with the corresponding pole of 131°E, 22°S. There is an obvious need for age dating to validate these findings.

Aeromagnetic studies from within the sample site area and further to the northeast support the above conclusion. There is a definite zone of deformation, both ductile and brittle, as the dikes encroach upon the Grenville Front. The complicated nature of the faulting within the area further supports the fault block model. The ductile deformation seen in the dikes, in the form of folding, would appear restricted to a northeasterly orientation. Magnetic profiles along the dikes within this zone of deformation support the complicated history of movements as the dikes undergo a change in steepness of the dip within the deformation zone, but other than that they do not tell us much else.

In thin section no significant metamorphism was visible in either grouping. This concurs with previous studies (Palmer *et al.*, 1977) which maintain that the Sudbury dikes do not exhibit any aspect of metamorphism until well into the Grenville Province. Presumably if sampling had been more extensive closer to the Front, metamorphism in the greenschist grade of higher would be seen. Liquid within the melt appears to be the governing factor of localized plagioclase zoning. Whole rock geochemistry would be an asset in determining the bulk composition of the dikes.

The findings of the study support the tectonic model presented by Rivers *et al.*, (1993) of a crustal scale ramp and development of a foreland fold and thrust belt. It is proposed that within the Southern Province there are a fault blocks, which are rotated or otherwise deformed that can be associated with the Grenville Orogeny. Ultimately further sampling of the Sudbury olivine diabase dikes need to be conducted to substantiate the above claims.

REFERENCES

Bethune, K.M., and Davidson, A., 1988, Diabase dykes and the Grenville Front southwest of Sudbury, Ontario, *in* Current research: Geological Survey of Canada Paper 88-1C. p.151-159.

Bethune, K.M., 1989, Deformation, metamorphism, diabase dikes, and the Grenville Front southwest of Sudbury, Ontario, *in* Current research: Geological Survey of Canada Paper 89-1C. p.19-28.

Berger, G.W., and York, D., 1980, Reinterpretation of the North American apparent polar wander curve for the interval 800-1500 Ma. Canadian Journal of Earth Sciences, v.17, p.1229-1235.

Berger, G.W., and York, D., 1981, ^{40}AR/^{39}Ar dating of the Thanet gabbro, Ontario: looking through the Grenvillian metamorphic veil and implications for paleomagnetism. Canadian Journal of Earth Sciences, v.18, p.266-273.

Buchan, K.L., Berger, G.W., McWilliams, M.O., York, D., and Dunlop, D.J., 1977, Thermal overprinting of natural remanet magnetization and K/Ar ages in metamorphic rocks. Journal of Geomagnetism amd Geoelectricity, v.29, p.401-410.

Corfu, F., and Andrews, A.J., 1986, A U-Pb age for mineralized Nipissing diabase, Gowganda, Ontario. Canadian Journal of Earth Sciences, v.23. p.107-109.

Dunlop, D.J., and Buchan, K.L., 1977, Thermal remagnetization and the paleointensity record of metamorphic rocks. Physics of Earth and Planetary Interiors, v.13, p.325-331.

Dunlop, D.J., York, D., Berger, G.W., Buchan, K.L., and Stirling, J.M., 1980, The Grenville Province: a paleomagnetic case-study of Precambrian continental drift. *In* The continental crust of the Earth and its mineral deposites. Geological Association of Canada, Special Paper 20, p.487-502.

Davidson, A., 1986b, Grenville Front relationships near Kilarney, Ontario, *in* Moores, J.M. et al., eds., The Grenville province: Geological Association of Canda Special Paper 31. p.107-117.

Davidson, A., and Bethune, K.M., 1988, Geology of the north shore of Georgian Bay, Grenville Province of Ontario, *in* Current research: Geological Survey of Canada Paper 88-1C, p.135-144.

Davidson, A., and Ketchum, J.W.F., 1993, Grenville Front studies in the Sudbury region, Ontario, *in* Current research: Geological Survey of Canada Paper 93-1C, p.271-273.

Green, A.G., Milheriet, B., Davidson, A., Spencer, C., Hutchinson, D.R., Cannon, W.F., Lee, M.W., Agena, W.F., Behrendt, J.C., and Hinze, W.J., 1988, Crustal structures of the Grenville Front and adjacent terranes. Geology, v.16, p.788-792.

Haggart, M.J., Lamieson, R.A., Reynolds, P.H., Krogh, T.E. Beaumont, C., and Culshaw, N.C., 1993, Last gasp of the Grenville orogeny: Thermochronology of the grenville Front Tectonic Zone near Killarney, Ontario. Journal of Geology, v. 101, p.575-589.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D., and Nakamura, E., 1984, Precise U-Pb isotopic ages of diabase dykes and mafic to ultramafic currocks using trace amounts of baddeleyite and zircon: *in* Diabase Dyke Swarms, eds. H.C. Halls and W.C. Fahrig, Geological Association of Canada, Special Paper 34, p.147-152.

Palmer, H.C., Merz, B.A., and Hyatsu, A., 1977, The Sudbury dikes of the Grenville Front region: paleomagnetism, petrochemistry and K-Ar age studies. Canadian Journal of Earth Sciences, v.14, p.1867-1887.

Rivers, T., Martignole, J., Gower, C.F., and Davidson, A., 1989, New tectonic divisions of the Grenville Province, southeast Canadian Shield. Tectonics, v.8. p.63-84.

Rivers, T., van Gool, J.A.M., and Connelly, J.N., 1993, Contrasting tectonic styles in the northern Grenville province: Implications for dynamics of orogenic fronts. Geology, v. 21, p. 1127-1130.