MICROSEISMICITY RELATED TO POTASH MINING

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by

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1985
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Saskatoon, Saskatchewan, Canada.
ABSTRACT:

A seismic monitoring array was operated over the Potash Corporation of Saskatchewan Mining, Cory Division potash mine just west of Saskatoon, Canada in the thirty-nine month period October, 1981 through December, 1984. The array was set up to investigate macro- and micro-earthquakes that occur regularly near the mine. 83 micro-earthquakes and one macro-earthquake were recorded during the monitoring period. In order to compute accurate locations for the events recorded a suitable earthquake location algorithm had to be found; standard linear location strategies could not be used, because severe refraction of the energy travelling from hypocenter to receiver rendered the problem non-linear. A method of iterative approximation was therefore developed, by which P-wave arrival times observed at the seismometer stations are compared to calculated arrival times. The method makes use of the Simplex Algorithm to home in on the point in space which gives a "best-fit" (between calculated and observed times) with a minimum of computation. Locations were determined for 72 of the 83 micro-earthquakes recorded. Events were mostly located near regions of active or recent mining, with a few events located near regions of local geological disturbances. Estimates of local event magnitude were made for the 72 located events. Study of the frequency of occurrence of the events, and of magnitude relationships, imply that Cory micro- and macro-earthquakes are fundamentally different. The relationship between micro and macro events is not yet clear.
ACKNOWLEDGEMENTS:

First and foremost, I wish to acknowledge the encouragement and continued support of Dr. Don Gendzwill. Dr. Gendzwill supervised the project, and was a source of new ideas throughout the study. I also thank Dr. Malcolm Reeves and Dr. Parviz Mottahed for their encouragement, and for critically reviewing a final edition of the thesis. Thanks are also extended to Mr. Jack Arnold, who provided friendship and technical support throughout the study, and to Mr. Brian Reilkoff of Academic Computing Services who helped with some of the programming difficulties.

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And finally, I wish to thank my wife Lindsay, and the many friends, fellow students, and faculty members at the University of Saskatchewan who provided moral support during the thesis study.
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1. INTRODUCTION:

In the ten month period November, 1979 through August, 1980 four noticeable macro-earthquakes occurred near the Potash Corporation of Saskatchewan (PCS) Mining, Cory Division potash mine, which is located just west of Saskatoon. Although two seismic events had been previously observed near potash mines at Esterhazy, (in south-eastern Saskatchewan), noticeable seismicity was a new phenomenon at the Cory mine, and caused some concern to PCS personnel. A preliminary study of seismicity patterns was carried out in the Cory area during the spring of 1981 (Gendzwill et al., 1982). This study showed a high level of microseismicity associated with mining activity at Cory. To gain further understanding of the geological processes that gave rise to these macro and micro seismic events a computer controlled seismic monitoring system was installed on the surface over the Cory mine in October, 1981. This system was installed and operated by members of the University of Saskatchewan, Department of Geological Sciences, under the direction of Dr. D. Gendzwill. Seismic monitoring was continued for forty months, until December, 1984. Results of this study, along with descriptions of some of the methods that were developed to interpret the results, are presented in this thesis.
1.1 General Background

The Prairie Evaporite, which underlies much of southern Saskatchewan, contains the western world's largest reserve of potash (Fuzesy, 1982). Potash is the name given to various soluble salts from which potassium, in the form of $K_2O$, can be extracted on a large scale. The predominant minerals occurring in the ore zones are halite ($NaCl$), sylvite ($KCl$), and carnallite ($KCl, MgCl_2, 6H_2O$), with some clays and shales. Concentrated $K_2O$ has its main use as a fertilizer, with small amounts used in other chemical industry applications.

Potash was first recognized in western Canada in late 1942 during the coring of an oil exploration well (Fuzesy, 1982). Reserves were further delineated through the 1940's and into the 1950's chiefly as a spinoff from the continuing oil exploration in the province. Once recognized, potash could be very easily mapped in boreholes by gamma-ray log, since one isotope of potassium ($K^{40}$) is radioactive. After a few unsuccessful attempts at sinking 1000 meter (approx.) shafts to the ore horizon during the 1950's, Saskatchewan became a steady supplier of potash after a shaft was completed in 1962 at the International Mining and Chemical Company (IMC) mine near Esterhazy in south-eastern Saskatchewan. After the success of the IMC mine, other companies were eager to develop mines in the province. In total ten mines were brought into production in the period 1962 through 1970. Mine locations in
the province, with respect to the Prairie Evaporite, are
given in Figure 1. Further general information concerning
the Saskatchewan potash mining industry can be found in
Saskatchewan Department of Mineral Resources, 1965 and 1973,
and in Fuzesy, 1982.

The main problem encountered during the shaft sinking opera-
tion was flooding of the opening in passing through water
bearing strata which overlie the ore-bearing horizon. Of
the seventeen shafts sunk in Saskatchewan to date, six have
encountered major water inflow problems: one shaft, begun
near Unity in 1952, was abandoned after nine years of
struggle, while the other five projects were rehabilitated
after much effort and expenditure (Prugger, 1980 and Fuzesy,
1982). Most recently, the Potash Corporation of Saskatchewan
Mining, Rocanville Division mine has been dealing with an
underground water inflow that began in November, 1984.

Because of the history of water inflow problems, and because
of the dangerous and costly consequences of a major water
inflow in a potash mine, all mining companies operating in
the province take extensive precautions to avoid any such
contingency. When earthquakes began to be noticed near
potash mines at Esterhazy and Cory in the late 1970's, an
initial concern was that these events might, in some way,
lead to a water inflow. But to date the effects of macro-
seismic events occurring near Saskatchewan potash mines have
FIGURE # 1: SASKATCHEWAN POTASH MINE LOCATIONS AND THE PRAIRIE EVAPORITE

○ Potash mine
□ Potash

1 - Cominco Vanscoy
2 - PCS Cory
3 - PCA Saskatoon
4 - PCS Allen
5 - CCP Colonsay
6 - PCS Lanigan
7 - IMC-K1 Esterhazy
8 - IMC-K2 Esterhazy
9 - PCS Rocanville
10 - Kalium Belle Plain

(after Holter, 1969 and Fuzesy, 1982).
been minimal. This is somewhat puzzling: in other mining areas earthquakes in the magnitude range seen at Saskatchewan potash mines have been very destructive.

One of the largest mining related earthquakes that has been observed to date was an event of body wave magnitude $m(b) = 5.4$ which occurred in June 1975 in a potash mine in Werra province, East Germany (Knoll et al., 1980 and Hurtig et al., 1982). The "body-wave magnitude" is a measure of the energy released by an earthquake, and is usually calculated from the amplitudes of seismic energy observed at a seismometer station. The Werra earthquake was caused by the sudden failure of a 3.35 square kilometer area at less than one kilometer depth over the mine. Mercalli scale intensity VIII effects were felt in the immediate vicinity of the epicenter; this corresponds to conditions when chimneys are knocked over, heavy furniture is overturned, panel walls are thrown out of frame structures, etc. Foundations and buildings were damaged in the nearby village of Sünna. And as far away as Leipzig, 180 kilometers from the epicenter, intensity III effects were felt, which corresponds to feeling vibrations like that of a heavy truck passing.

Earthquakes and rockbursts in the deep gold mines of South Africa have produced devastating results, killing mine workers and causing regions of mines to be shut down (Ortlepp, 1982 and Fernandez and Van der Heever, 1982). In the Klerksdorp
goldfield area more than 25 events with Richter magnitude greater than \( m(b) = 4.0 \) have been recorded. The tremors in this region often cause loss of life and extensive damage to underground mine workings. And in 1976 a multi-storeyed building in the town of Welkom collapsed as a result of an \( m(b) = 5.1 \) event. The largest event observed in the Klerksdorp region was a magnitude \( m(b) = 5.2 \) which occurred in April, 1977 and was recorded by seismometers worldwide.

In Canada a "bump", or severe ground disturbance, occurred in the working area of a Springhill, Nova Scotia coal mine in October, 1958 (Notley, 1984). The event claimed the lives of 75 mine workers and resulted in closure of the mine. The Springhill mine disaster is the most serious seismically induced mine accident seen in Canada to date. More recently an earthquake of magnitude \( m(b) = 3.9 \) occurred at one of the Falconbridge nickel mines near Sudbury, Ontario in mid-June 1984 (Northern Miner, 1984a). A rockburst at the 4000 foot level caused failure of portions of the backfilled sections of the mine, which trapped and killed four mine workers. The Falconbridge mine was closed as a result of the earthquake (Northern Miner, 1984b). Four weeks later a weaker event occurred at a nearby INCO mine, also forcing closure of a section of the mine. Loss of life was avoided in the INCO event, in part, because mining had been suspended for summer vacation at the time of the tremor.
The results of mine-related seismicity in other mining camps, along with the potentially disastrous consequences of any major water inflow, caused Saskatchewan mining personnel to be very interested in learning more about the earthquakes that were occurring near their mines. This interest provides the ongoing impetus for the study of macro and micro earthquakes that result from potash mining in Saskatchewan.

1.2 Geological Setting

Saskatchewan's potash reserve lies beneath much of the Great Plains of the province, in a belt 150 kilometers wide by 600 kilometers long, stretching from the Manitoba border in the east to the Alberta border in the west (see Figure 2). The deposits are of Middle Devonian age, and occur near the top of a thick evaporite sequence called the Prairie Evaporite. The Prairie Evaporite is found as shallow as 600 meters from the surface along the northern extent of the formation (Holter, 1969), and as deep as 3650 meters at the southern edge, towards the center of the Williston Basin (Anderson and Swinehart, 1979). Mining is carried out at 950 to 960 meters depth in the Esterhazy area, at 1000 to 1075 meters in the Saskatoon area, and at 1600 meters at the Belle Plain solution mine (Fuzesy, 1982); (see Figure 1 for mine locations).

The columnar geological section for the Cory area drillhole DUVAL 6 - 18 - 36 - 6W3 (Price and Ball, 1971) is given in
FIGURE #2: EXTENT OF THE PRAIRIE EVAPORITE IN WESTERN CANADA

Area of Potash Distribution
(from Fuzesy, 1982, p.7)
FIGURE # 3: COLUMNAR GEOLOGICAL SECTION / CORY # 1 SHAFT
(from Price and Ball, 1971)

<table>
<thead>
<tr>
<th>ERA</th>
<th>PERIOD</th>
<th>GROUP</th>
<th>FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENOZOIC</td>
<td></td>
<td></td>
<td>Judith River</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lea Park</td>
</tr>
<tr>
<td>MESOZOIC</td>
<td>Upper</td>
<td>Upper</td>
<td>Vermillion River</td>
</tr>
<tr>
<td></td>
<td>Cret.</td>
<td>Colorado</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unnamed beds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Joli Fou</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Viking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Penns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cantuar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Birdbear</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>Saskatchewan</td>
<td>Duperow</td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manitoba</td>
<td>Souris River</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dawson Bay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>potash</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Prairie Evaporite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winnipegosis</td>
</tr>
</tbody>
</table>

METERS - DEPTH
0.0  200.0  400.0  600.0  800.0  1000.0
Figure 3. This column is, in the main, typical for any potash mine in Saskatchewan. The Phanerozoic geology of the province's potash mining district can be summarized, from top to bottom, as:
- glacial till, drift;
- a thick sequence of Cretaceous shales, with minor amounts of sandstone;
- Cretaceous sandstones of the Mannville Group (often referred to as the Blairmore sandstone);
- a thick sequence of Devonian carbonates, (with minor amounts of shale, anhydrite, and salt), of the Souris River, Duperow, and Dawson Bay Formations;
- a thick sequence of Devonian salts of the Prairie Evaporite, including the potash ore horizon near the top of the sequence;
- Devonian, Silurian, and Ordovician carbonates with minor amounts of shale, including the Devonian Winnipegosis limestone / Ashern shale which directly underlies the Prairie Evaporite;
- Ordovician and Cambrian sandstones and shales.

No results of strength tests have been published for rocks in the Esterhazy mining area. However, extensive laboratory testing of rock units overlying the Cory mine have been carried out at the University of Saskatchewan, and are published in Pandit (1983) and in Gendzwill (1983a). These studies indicate that it is unlikely that the Cretaceous sands
and shales could build up enough strain energy to result in a noticeable earthquake. The brittle limestones of the Middle Devonian Dawson Bay and Souris River Formations are considered more likely locations for the micro-fault activity that would result in the types of events observed at Cory. It is therefore reasonable to constrain calculated earthquake locations to lie below the Mannville sandstones.

1.3 Historical Seismicity

Saskatchewan has a history of sporadic, low level, shallow seismicity in the region south of Regina, near the North Dakota - Montana - Saskatchewan border intersection. The activity in this region prompted Energy, Mines and Resources, Earth Physics branch (EMR) to install a permanent seismograph at Big Muddy, near the mid-point of the epicenters, in 1976. These events may be the result of movements along a system of north-east and north-west trending mid-continent faults, as discussed in Thomas (1974) and in Horner and Hasegawa (1978). In addition to the Big Muddy station, EMR operates permanent seismographs at Edmonton and Suffield Alberta, at Flin Flon Manitoba, and elsewhere in British Columbia and the Northwest Territories. The University of Saskatchewan (U. of S.) has operated a permanent seismograph at Saskatoon since late 1979.
In the fall of 1976 an earthquake of body-wave magnitude $m(b) = 3.0$ occurred near the International Minerals and Chemical Co. (IMC) mine located near Esterhazy in the south-east of the province (Gendzwill, 1982). The proximity of the Esterhazy earthquake to the mine, in an area where previous seismicity was unknown, led to speculation that the event may have been induced by the mining activity. Since this initial event, seven earthquakes in the magnitude range $m(b) = 2.5$ to $3.6$ are known to have occurred near the two IMC mines. These events were recorded instrumentally by the EMR and the U. of S. stations, and were noticed by residents of the farming communities of Yarbo (IMC-K1) and Gerald (IMC-K2). The IMC-K1 mine began production in 1962, fourteen years before the first earthquake was noticed in the area.

In November 1979 an earthquake of magnitude $m(b) = 2.4$ occurred near the Potash Corporation of Saskatchewan Mining Limited (PCS), Cory Division potash mine (Gendzwill et al., 1982). The Cory mine, located just west of Saskatoon, has been producing since 1967. As with the Esterhazy earthquakes, no seismicity had been previously observed in the Cory area. Since this initial event, seven noticeable earthquakes have been recorded in the vicinity of the mine ranging in magnitude $m(b) = 2.3 - 3.0$. The outskirts of the city of Saskatoon are beyond the region of perceptibility for any of the Cory earthquakes observed to date, but the seven events were noticed by many of the area's rural residents.
Besides the eight events at Esterhazy and the seven events at Cory, earthquake activity has been observed near only one other mine: one event of magnitude \( m(b) = 2.5 \) occurred at the Central Canada Potash Limited (CCP) mine near Colonsay in February, 1984.

A compilation of Saskatchewan seismic events is given in Table 1. Figure 4 is a map showing epicenter locations, along with seismometer station locations, and locations of the ten mines operating in the province. While seismicity has not been observed near six of Saskatchewan's ten potash mines, smaller events may still be occurring at these sites. The large scale seismic monitoring system covering Saskatchewan is unable to discern events weaker than magnitude 2.5 (Gendzwill et al., 1982).

Whenever a local earthquake has occurred "isoseismal" maps have been constructed over the epicentral area by Dr. D.J. Gendzwill of the University of Saskatchewan. An isoseismal map is a map showing contours of equal Mercalli-scale qualitative intensities felt by local residents. Maps are constructed by interviewing residents and assigning an intensity number to the effects of the earthquake felt by the resident. For example, if no effect was felt, that site would be assigned a "0", cracked plaster would be assigned intensity "V" (five), up to a maximum intensity "XII" (twelve) which would represent
TABLE 1: KNOWN EARTHQUAKES IN SOUTHERN SASKATCHEWAN

(Courtesy D. Gendzwill, University of Saskatchewan).

<table>
<thead>
<tr>
<th>Location</th>
<th>Date (U.T.)</th>
<th>Lat.</th>
<th>Long.</th>
<th>m(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Border</td>
<td>1909, May 16, 04:15</td>
<td>49.</td>
<td>104.</td>
<td>5.5</td>
</tr>
<tr>
<td>Val Marie</td>
<td>1968, Sep 11, 12:00:06</td>
<td>49.25</td>
<td>108.14</td>
<td>2.7</td>
</tr>
<tr>
<td>Radville</td>
<td>1968, Oct 11, 12:28:04</td>
<td>49.61</td>
<td>104.49</td>
<td>2.8</td>
</tr>
<tr>
<td>Bengough</td>
<td>1972, Jul 26, 03:58:19</td>
<td>49.35</td>
<td>104.93</td>
<td>3.7</td>
</tr>
<tr>
<td>Radville</td>
<td>1976, Mar 23, 22:31:47</td>
<td>49.56</td>
<td>104.37</td>
<td>3.2</td>
</tr>
<tr>
<td>Radville</td>
<td>1976, Mar 25, 00:12:16</td>
<td>49.39</td>
<td>104.27</td>
<td>3.5</td>
</tr>
<tr>
<td>Humbolt</td>
<td>1976, May 15, 06:21:12</td>
<td>52.45</td>
<td>105.44</td>
<td>2.3</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1976, Nov 7, 12:27:15</td>
<td>50.69</td>
<td>101.94</td>
<td>3.0</td>
</tr>
<tr>
<td>Cory / IMC</td>
<td>1978, Nov 4, 01:23:52</td>
<td>50.70</td>
<td>101.90</td>
<td>3.1</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1979, Nov 18, 23:02:13</td>
<td>52.10</td>
<td>106.92</td>
<td>2.4</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1980, Feb 29, 19:41:41</td>
<td>52.12</td>
<td>106.93</td>
<td>3.0</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1980, Mar 18, 00:31:51</td>
<td>52.08</td>
<td>106.90</td>
<td>2.8</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1980, Aug 6, 05:23:53</td>
<td>52.11</td>
<td>106.93</td>
<td>2.3</td>
</tr>
<tr>
<td>Kuroki</td>
<td>1981, Jan 10, 08:34:31</td>
<td>51.88</td>
<td>103.44</td>
<td>3.1</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1981, Jan 27, 06:13:11</td>
<td>50.70</td>
<td>101.90</td>
<td>2.9</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1981, Jan 27, 19:34:09</td>
<td>50.70</td>
<td>101.90</td>
<td>2.7</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1981, Apr 13, 03:28:21</td>
<td>50.66</td>
<td>101.85</td>
<td>3.2</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1981, May 11, 14:50:09</td>
<td>52.11</td>
<td>106.91</td>
<td>2.3</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1982, Jan 8, 16:46:16</td>
<td>52.11</td>
<td>106.93</td>
<td>2.4</td>
</tr>
<tr>
<td>Big Beaver / IMC</td>
<td>1982, Aug 17, 04:50:31</td>
<td>49.01</td>
<td>105.27</td>
<td>3.9</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1982, Sep 28, 07:17:49</td>
<td>50.72</td>
<td>101.95</td>
<td>3.4</td>
</tr>
<tr>
<td>Cory / PCS mine</td>
<td>1983, Jan 6, 02:35:04</td>
<td>52.12</td>
<td>106.93</td>
<td>2.6</td>
</tr>
<tr>
<td>Redberry Lk.</td>
<td>1984, Feb 5, 04:30:14</td>
<td>52.70</td>
<td>106.95</td>
<td>2.3</td>
</tr>
<tr>
<td>Colonsay / CCP mine</td>
<td>1984, Feb 20, 01:19:34</td>
<td>51.95</td>
<td>105.77</td>
<td>2.5</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1984, Sep 27, 08:48:13</td>
<td>50.65</td>
<td>101.89</td>
<td>3.6</td>
</tr>
<tr>
<td>Esterhazy / IMC</td>
<td>1984, Oct 25, 13:00:30</td>
<td>50.65</td>
<td>101.89</td>
<td>2.5</td>
</tr>
</tbody>
</table>
FIGURE # 4 : SASKATCHEWAN PERMANENT SEISMOGRAPH STATIONS, EARTHQUAKE EPICENTERS, AND MINE LOCATIONS 
(after Gendzwill, 1982)

- Seismometer Station
- Potash Mine
- Earthquake Epicenter
total destruction. A full description of the Mercalli intensity scale can be found in Bolt (1978, pp. 202-205).

The strongest effects that have been felt in a Saskatchewan mining area earthquake have been to crack plaster, assigned intensity V, and to knock a clock and a picture off their respective wallhooks, assigned intensity IV (D. Gendzwill, personal communication). Recall that the Werra potash mine earthquake caused intensity VIII effects in the vicinity of the epicenter (section 1.1). The complete set of the isoseismal maps constructed for the Esterhazy and Cory events, up to 1982, are presented in Gendzwill (1982). Three representative isoseismal maps are included here as Figures 5, 6, and 7. For all events recorded to date, the intensity contours drawn on the maps are invariably centered over active mining areas.

Earthquakes were initially recorded by short period instruments of the Canadian Seismograph Network and of the University of Saskatchewan, which were located far from the event epicenters, (see Figure 4). It was therefore decided to set up small scale seismic monitoring arrays in the vicinity of the mine (where earthquakes were considered likely to occur). In the spring of 1980 three Sprengnether "MEQ - 800" portable drum-type seismometers were set up over the Cory minesite by members of EMR and the U. of S. The results of this study are presented in Gendzwill et al. (1982). During the period
FIGURE # 5: ISOSEISMAL MAP: ESTERHAZY EVENT

Courtesy D. Gendzwill, University of Saskatchewan

GERALD EARTHQUAKE
APRIL 12, 1981 21:29 HRS M_b = 3.2

LEGEND:
ACTIVE MINING AREA
INJECTION WELL
SHAFT
UNDERGROUND WORKING BOUNDARY
DEHORN CREEK
SOUTH SHIP CREEK
FIGURE # 6: ISOSEISMAL MAP: CORY EVENT

Courtesy D. Gendzwill, University of Saskatchewan.

CORY
MERCALLI INTENSITY FOR JAN. 5, 1983 8:35 PM CST.
FIGURE # 7 : ISOSEISMAL MAP : COLONSAY EVENT

Courtesy D. Gendzwill, University of Saskatchewan

MODIFIED MERCALI INTENSITY FOR EARTHQUAKE 1984
FEB. 20 01:19:34 U.T., FEB. 19 7:19:34 PM CST.
mb = 2.5 h = 1 km
51.95°N, 105.77°W
* = INHABITED LOCATION
3 = INTENSITY FELT AT LOCATION

0 1 2 KILOMETERS

TP 34 R 28 R 27 R 26 W 2N
105°40' R 26
105°50'

TP 35 COLONSAY

POTASH MINE

VISCount
March 19 to April 14 seventy-five micro-earthquakes were recorded, establishing a clear spatial correlation between seismicity and potash mining activity. Of the six events which allowed location calculations, five were located directly over regions of active mining. But recording using the MEQ - 800 instruments was cumbersome, and allowed only low resolution location calculations. Although the data that were collected during this test survey were of limited usefulness, the number of micro-earthquakes recorded over such a short recording period showed that further study using more advanced equipment was justified.

1.4 The Present Earthquake Monitoring System

In the fall of 1981 a six-channel digital seismic monitoring system was installed on surface over the north-west section of the Cory mine (Figure 8). The geophones were placed at approximately 800 meter intervals along two east-west fence lines 800 meters apart, roughly forming an 800 meter by 1600 meter rectangular array configuration. In early 1984 the cable leading to geophone #6 was damaged, so the station had to be moved west a few hundred meters to position #6A. Then in June of 1984 station #4 was moved a few meters east and north to position #4A. In November, 1984 a triaxial geophone was purchased and set up at station #7. Exact geophone station locations are given in Table 2, both in coordinates relative
TABLE 2: GEOPHONE STATION LOCATION COORDINATES
FOR THE CORY SEISMIC MONITORING ARRAY

All Distances are in meters. The first value listed is
distance relative to geophone # 4, followed by distance
in Cory mine coordinate units. All stations are on
surface assigned depth Z = 0 (zero).

<table>
<thead>
<tr>
<th>Station</th>
<th>X - EAST</th>
<th>Y - NORTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>805.0</td>
</tr>
<tr>
<td>2</td>
<td>970.0</td>
<td>805.0</td>
</tr>
<tr>
<td>3</td>
<td>1657.0</td>
<td>805.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4A</td>
<td>13.0</td>
<td>8.0</td>
</tr>
<tr>
<td>5</td>
<td>915.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>1655.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6A</td>
<td>1252.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>460.0</td>
<td>805.0</td>
</tr>
</tbody>
</table>

The entire array lies in Township 36 and Range 7W3.
Station #4 is 470 meters west of the grid road centerline
separating sections 21 and 22, and 1610 meters south of
the grid road centerline separating sections 21 and 16.
to the south-west station (#4), and in Cory mine-plan coordinates as shown in Figure 8.

Cables lead from each seismometer to a central recording hut which houses the event recorders. The instruments operate in a pass-band of 0 to 50 Hertz, with an added front-end 60 Hertz notch filter to help remove spurious power line noise. The geophones used are the Mark Products "L-1" model, which has a natural resonance at 4.5 Hertz, and a flat response over the range 4 - 500 Hertz. Seismometer response has been tested in the frequency range 0 - 1000 Hertz using a vibrating table, and is shown in Figure 9.

The recording system is based on two "DCS - 302" three-channel seismic event recorders manufactured by the Terra-Technology Corporation of Redmond, Washington. One unit is assigned "master" status, triggering recording, while the second unit is a "slave", recording to tape when a signal is sent from the master box. The DCS - 302 is a computer based recorder capable of continuously monitoring seismic signals from three geophones, each at 200 samples per second and 12 bits per sample. The instrument stores several seconds of signal in a memory buffer, and when a seismic event is "recognized" the buffered signal and a fixed time of the incoming signal (chosen at 5 seconds) are transferred to cassette tape. This gives complete recording of the event from before the onset until signal levels die down to average background
FIGURE # 9 : MARK PRODUCTS "L-1" SEISMOMETER RESPONSE

Data Courtesy D. Gendzwill, Univ. of Saskatchewan.
levels. The instruments record about 35 five-second records before the tape has been filled; under usual circumstances this gives 3 to 4 days of recording.

Seismic event recognition, which is a built-in feature of the DCS - 302, is based on comparison of short term signal amplitudes to a long term running average of the signal level. The instrument continuously computes a short-term average signal amplitude (STA) over a few tenths of a second, and a long-term average amplitude (LTA) over a few seconds. Recording onto cassette begins when the STA exceeds the LTA by a specified amount. This method is intended to distinguish between a signal with a very sharp onset, such as an earthquake, and signals that build up more slowly to high amplitude levels. For the Cory array the STA is computed over 0.6 seconds, the LTA over 5.0 seconds, and recording is normally set to trigger when the ratio STA/LTA = 5.0.

Using these values the instrument does not turn on for typical ground noise, such as passing railway trains, and vehicles passing on the road nearby. Unfortunately any cultural noise with a sudden onset will be recorded. Electrical transients from the rural power-lines nearby have been especially troublesome.

Field tapes are read on an "SMR - 104" playback unit, also manufactured by Terra-Technology, and transferred via an RS-232 interface to an APPLE-II Plus micro-computer.
Recorded events are plotted on the computer and visually scrutinized to discriminate between true seismic events and "false triggers". True events are stored on floppy-disks for future processing and display. First break onset times are determined interactively by plotting events at suitable vertical and horizontal resolutions and then reading times using a screen cursor. Complete seismic records can also be transferred to the more powerful University of Saskatchewan VAX 11-780 computer. Since October, 1981 seismic signals from 83 micro-earthquakes and from 1 noticeable earthquake have been recorded. Recording over the Cory mine was stopped on December 20, 1984.
2. LOCATION OF SEISMIC EVENTS USING ARRIVAL TIMES OF COMPRESSIONAL WAVES

2.1 Preamble

The first problem facing the seismologist, after setting up a functional micro-earthquake monitoring array, is to calculate hypocenter locations from the seismic signals that have been recorded. The earthquake location problem is "by far the oldest inverse problem studied in seismology" (Aki and Richards, 1980). Many papers addressing location methodologies have been published, with important discussions by Richter (1958, pp. 314-323), Lee and Lahr (1975), Salamon and Wiebols (1974), and Dechman and Sun (1977).

Most discussions in the literature address the problem of determining hypocenter location for large earthquakes recorded at stations some distance, usually many hundreds of kilometers, from the epicentral area. Such teleseismic location algorithms often follow "Geiger's Method", after the first seismologist to implement the procedure in 1912. Geiger's algorithm, modified by Buland (1976), involves computation of the spatial derivatives of source-to-geophone travel times for some initial trial location, followed by a Gauss-Newton iterative procedure to home in on the location for which the derivatives become zero (or, at least, a minimum). A good discussion of the algorithm is given in Lee and Stewart (1981, pp. 132 - 139). This method forms the basis for the HYP071-
(REVISED) (Lee and Lahr, 1975) and HYPOELLIPSE (Lahr, 1979) earthquake location programs that are used extensively by seismologists in North America. Geiger's Method, however, has not been extensively used in hypocenter location calculations for epicentral seismic monitoring arrays. An "epicentral" seismometer array is defined here as an array set up within a few kilometers of the earthquake epicenter.

The general equation of particle motion for seismic energy travelling through a simple medium, observed far from the source, can be written as the sum of a pure irrotational component (i.e.- having zero curl) and a pure rotational component (i.e.- having zero divergence). This is another way of saying that seismic energy seen at a geophone station will be comprised of compressional ("P") waves and shear ("S") waves, each travelling at different velocities through the earth. Some hypocenter location algorithms use the arrival times of both P-waves and S-waves to refine computation accuracy.

In general the P-wave is recognized as the first arrival of seismic energy, and the S-wave is recognized as the next large amplitude event (see Figure 10). However, for an epicentral seismometer array the particle displacement vector \( \vec{U}(x,y,z,t) \) can, more accurately, be written as the superposition of the two far-field terms, plus one near-field term (Aki and Richards, 1980, pp. 70-77):
September 28, 1982 : UT 07:17:49

IMC Mine, Esterhazy, Saskatchewan, CANADA

Body-wave magnitude $m(b) = 3.4$

Courtesy D. Gendzwill, University of Saskatchewan.
\[ U(x,y,z,t) = U_p(X,y,z,t) + U_s(X,y,z,t) + U_n(X,y,z,t) \quad (1) \]

where \( U_p \) describes the far-field P-wave motion, \( U_s \) describes the far-field S-wave motion, and \( U_n \) describes the near-field motion. As distance from the hypocenter increases, \( U_p \) and \( U_s \) become dominant over \( U_n \), and alternately, near the hypocenter \( U_n \) becomes dominant over \( U_p \) and \( U_s \). \( U_n \) has contributions from both the gradient of the P-wave potential and from the curl of the S-wave potential. \( U_n \) is thus composed of both P-wave and S-wave motions, and as Aki and Richards (1980, p. 76) point out, it is therefore "not always fruitful to decompose an elastic displacement field into its P-wave and S-wave components" for near-field observations. This is especially true for displacement fields measured only in the vertical component. Aki and Richards go on to show that \( U_n \) will arrive at a geophone at the P-wave arrival time. It is therefore quite valid to set up the earthquake location problem to use arrival times of P-waves. But for epicentral arrays it may be better to avoid using S-wave arrival times, unless these can be clearly identified.

2.2 Formulation of the Hypocenter Location Problem for an Epicentral Seismic Monitoring Array

The earthquake location problem, for any seismometer array, is one of mathematically solving for a number of unknown parameters, given a set of known information which constrains the solution. The "known" information consists of P-wave...
arrival times measured at "N" seismometer stations situated at \((X_i, Y_i, Z_i)\) \(i=1,N\) in some coordinate system, and some model of the seismic velocity structure in the region of the geophone array. Using this data set the hypocenter location, \((X_{eq}, Y_{eq}, Z_{eq})\), and the time at which the seismic event occurred, \((T_{eq})\), must be calculated. If seismic velocities are not known one the problem can be set up to solve for an average velocity value for the region. However, this strategy is not recommended, since location solutions are not sufficiently constrained when velocity is left as an unknown.

For the Cory array a very good regional velocity model can be postulated using acoustic borehole logs from nearby drill-holes, along with knowledge of local subsurface geology. When the velocity model is known the origin time \(T_{eq}\) depends explicitly on only the hypocenter location \((X_{eq}, Y_{eq}, Z_{eq})\) and the geophone locations \((X_i, Y_i, Z_i)\). If \(X_{eq}, Y_{eq}, \) and \(Z_{eq}\) are found, \(T_{eq}\) can be immediately calculated by dividing the travel path distance from hypocenter to geophone by the travel path velocity. A hypocenter location \((X_{eq}, Y_{eq}, Z_{eq})\) can therefore be determined using arrival time information from only three geophone stations. This is the worst-case scenario, and in certain cases will result in nonunique location solutions. For example, if the seismometers are set up in a linear array configuration, there will always be at least two location solutions to the problem, one to each side of the array axis.
Although Teq is an auxiliary variable in the location calculation, it is included as an unknown in many location algorithms used by seismologists. For some mathematical formulations of the location problem Teq cannot be removed from the set of equations without causing the system of equations to go to zero. Therefore, most discussions of location algorithms deal with finding solutions to the problem in four unknowns (Xeq, Yeq, Zeq, Teq). This strategy increases the minimum number of geophones needed to find a solution from three to four.

2.3 Hypocenter Location By Least - Squares

The Least-Squares method for computing hypocenter location from P-wave arrival times has been used extensively in micro-seismic studies. Discussions of the method are given in Salamon and Wiebols (1974), Leighton and Duval (1976), McEvilly and Majer (1982), and Eccles and Ryder (1982). The Least-Squares method forms the basis of the seismic event location algorithm used in the ELECTROLAB seismic monitoring package that has already been, or is presently being, installed underground in six Canadian mines, including the Cory mine. Since this system is very popular at the moment, the Least-Squares event location method will be discussed in some detail here.
The problem consists of setting up a system of equations of:

\[ \text{distance} = \text{velocity} \times \text{time} \] (2)

for each hypocenter-to-geophone travel path, giving "N" equations for N geophones. In order to keep the hypocenter location an explicit unknown parameter in the equation (2) the seismic-wave propagation velocity must be assumed uniform for all geophones. For each "i"th geophone equation (2) becomes:

\[ \sqrt{ \left( X_i - X_{eq} \right)^2 + \left( Y_i - Y_{eq} \right)^2 + \left( Z_i - Z_{eq} \right)^2 } = V (t_i - T_{eq}) \] (3)

where "SQRT" = square root, or if both sides are squared:

\[ (X_i - X_{eq})^2 + (Y_i - Y_{eq})^2 + (Z_i - Z_{eq})^2 = V^2 (t_i - T_{eq})^2 \] (4)

where:  \( i = \text{geophone number} \) (\( i = 1,6 \) for the Cory array)

\( (X_i,Y_i,Z_i) = \text{geophone location} \) (known)

\( (X_{eq},Y_{eq},Z_{eq}) = \text{earthquake hypocenter} \) (unknown)

\( V = \text{P-wave velocity} \) (known)

\( t_i = \text{P-wave arrival at "i"th geophone} \) (known)

\( T_{eq} = \text{origin time of seismic event} \) (unknown)

One station, often the geophone nearest the hypocenter (ie.-the geophone with the earliest P-wave arrival time), is now chosen as a reference station. Arrival times at all stations are then given relative to the reference geophone arrival time, and are more properly called move-out times. Move-out time "tir" at station "i" is thus the absolute arrival time
at the reference geophone, "tr", subtracted from the P-wave arrival at "i"th geophone. Equation (4) can then be made linear by subtracting each station equation from the reference station equation. A discussion of various linearization strategies is given in Eccles and Ryder (1982).

If the reference station equation is subtracted from each other "i"th station equation, and after some algebraic manipulation, equation (4) can be rewritten in a form such that the unknown parameters (Xeq, Yeq, Zeq, Teq) are isolated:

\[(X_i - X_r) Xeq + (Y_i - Y_r) Yeq + (Z_i - Z_r) Zeq - V^2(t_i - tr) Teq = \]

\[\frac{(D_i^2 - D_r^2)}{2} - \frac{V^2(t_i^2 - tr^2)}{2}\] (5)

where: all variables are the same as for (4), except

\[D_i^2 = X_i^2 + Y_i^2 + Z_i^2\]

\[D_r^2 = X_r^2 + Y_r^2 + Z_r^2\]

McEvilly and Majer (1982) suggest that a better strategy for linearizing equation (4) is to subtract successive station equation pairs rather than to subtract a single reference station from all channels. For the first two stations this gives:

\[(X_1 - X_1) Xeq + (Y_1 - Y_1) Yeq + (Z_1 - Z_1) Zeq - (V^2)(t_1 - t_1) Teq = \]

\[\frac{(D_1^2 - D_1^2)}{2} - \frac{V^2(t_1^2 - t_1^2)}{2}\] (6)
They found the method to work best when the equations are ordered according to arrival time, earliest to latest, since certain errors tend to be cancelled.

For either set of equations (5) or (6) there are N-1 possible equations (for N geophones) to solve for the four unknowns. If information from 5 geophone stations is available the system of 4 equations is of the form:

\[
[A] [S] = [B]
\]  (7)

where \([A]\) is a 4X4 matrix, and \([B]\) and \([S]\) are 4X1 matrices:

\[
[A] = \begin{bmatrix}
(X_1 - X_1) & (Y_2 - Y_1) & (Z_2 - Z_1) & -(V^2)(t_2 - t_1) \\
(X_3 - X_2) & (Y_3 - Y_2) & (Z_3 - Z_2) & -(V^2)(t_3 - t_2) \\
(X_\nu - X_1) & (Y_\nu - Y_1) & (Z_\nu - Z_1) & -(V^2)(t_\nu - t_1) \\
(X_\nu - X_2) & (Y_\nu - Y_2) & (Z_\nu - Z_2) & -(V^2)(t_\nu - t_2)
\end{bmatrix}
\]

\[
[S] = \begin{bmatrix}
X_{eq} \\
Y_{eq} \\
Z_{eq} \\
T_{eq}
\end{bmatrix}
\]
If velocity $V$ in the preceding formulations is not known, an average velocity value can be found by keeping $V$ as an unknown in the system of equations. This results in a linear system with the unknowns $X_{eq}, Y_{eq}, Z_{eq}, (V^T T_{eq})$ and $(V^T)$. Information from at least six geophones is needed to compute a solution to the resulting matrix.
The most serious shortcoming of the Least-Squares algorithm is that velocity is treated as a constant value for all source-to-geophone travel paths. This is a poor assumption for the Cory area where vertical velocity changes cause significant refractions along any given ray-path: $V$ is not a single constant value for all ray paths in a layered earth, as illustrated in Figure 11. Unfortunately one must assume a constant velocity in order to reduce the problem to a linear system. "A fundamental shortcoming of all (Least-Squares) algorithms ... is that they concentrate on algebraic artifices to reduce the non-linear equations (3) to more tractable linear forms" (Eccles and Ryder, 1982). The mathematical model used to describe the earthquake system is in effect made simpler than it should be in order to achieve an adequate computational solution.

A program to solve the system of equations (6) has been tested using data collected by the six geophone Cory array. For five unknowns, ($X_{eq}$, $Y_{eq}$, $Z_{eq}$, $T_{eq}$, and $V$), using information from six geophones is essentially a worst-case situation: this gives exactly five equations in five unknowns. Further problems are introduced by having all the geophones in a single plane on the earth's surface. With no constraint on the velocity model (since $V$ is being treated as an unknown), location solutions tended to be artificially forced into the plane of the geophones. Testing of the same program using synthetic surface event data, for which $V$ is constant for all
To assume one single average velocity for all geophones is a gross oversimplification of what is actually happening in nature.

Each geophone 'sees' a different source-to-surface average velocity.

For example: \( V_{av(1)} \) = 3190 m/sec
\( V_{av(6)} \) = 4294 m/sec.

Figure #11: The Velocity Layering Problem
ray-paths, showed that the method works well. But for real
events recorded by the Cory array the method invariably gave
unreasonable earthquake locations. The linear mathematical
model is simply not describing what is happening in the non-
linear earth. For the Cory data set, and in fact for all data
sets recorded in areas of non-constant seismic velocities, a
more appropriate mathematical model must be developed before
location solutions can be calculated accurately.

2.4 Hypocenter Location By Iterative Approximation

The Iterative Approximation method for seismic source location
in a uniform velocity earth was first presented by Dechman
and Sun (1977). The algorithm was improved upon by Gendzwill
(1982), who incorporated a simple layered velocity model to
render solutions which are more reliable for the Cory situ-
ation. The fundamental advantage of Iterative Approximation
over Least-Squares methods is that one is not restricted to
reducing non-linear model equations to linear forms. Instead
earthquake location solutions are found by a trial-and-error
approach: an initial guess at the location solution \((X_{eq}, Y_{eq}, Z_{eq})\)
is made, then other points in space are tested about
the initial guess, and P-wave moveout times to each geophone
are calculated for each trial point. By testing many points,
the value of \((X_{eq}, Y_{eq}, Z_{eq})\) that gives the best fit between
measured and calculated move-out times is established. The
problem of earthquake location is thus addressed as one of
non-linear optimization.
The Iterative Approximation hypocenter location algorithm can be outlined as follows:

1. A velocity model which describes adequately how energy will travel from source to geophone is essential; for the Cory array such a model is developed in section 2.4.1.

2. An initial estimate of the earthquake location \((X_{eq}, Y_{eq}, Z_{eq})\) is made, and the resulting P-wave move-out times to each geophone is calculated.

3. In some manner points about the first location estimate are tested to find a location that gives calculated arrival times closer to those actually measured than the arrival times calculated for the first point.

4. Points are continually tested until the location point giving the best-fit with measured data has been found; the end point is the point for which theoretical arrival times are very close to the arrivals actually measured, and should, therefore, be the earthquake location.

The methodology as stated in steps 1 through 4 seems straightforward and simple. But as with most iterative methods, the problem is to minimize the amount of computation, and to ensure that the solution arrived at is unique. Step 3, the manner in which points about the first estimate are searched, is the key to the problem. A trial search procedure must be found that rapidly finds the best-fit solution.
2.4.1 The Cory Area Velocity Model

The acoustic borehole log for Cory drillhole DUVAL 6 - 18 - 36 - 6W3 is given in Figure 12; horizontal scale units have been converted to velocity (meters per second) from the slowness units (micro-seconds per foot) measured in the logging procedure. This velocity log is representative of the velocity structure seen throughout southern Saskatchewan. Using the sonic log, the seismic travel path from hypocenter to seismometer station can be mapped. The constraints for Cory are that events most likely occur within Devonian limestones overlying the mining level, and are recorded on the earth's surface a few kilometers from the epicenter.

Not all the velocity variations seen in the borehole log will be incorporated into the velocity model. Instead a simplified model will be used, subdividing the geology into a few distinct horizons. Some of the lithological units discussed in section 1.2 tend to show up very well as changes in the velocity log. Four main velocity zones are apparent (from top to bottom):

1. the Cretaceous sands/shales at an average velocity of 2025 meters per second,
2. the Mannville sandstone at an average velocity of 2695 meters per second,
3. the Souris River / Dawson Bay Cycles at an average velocity of 4905 meters per second,
FIGURE # 12 : PCS/CORY : 6-18-36-6W3

WELL LOG SONIC VELOCITY VS. DEPTH ------- LITHOLOGY
4. the Second Red Bed / Prairie Evaporite at a velocity of 4450 meters per second.

Velocities are fairly uniform throughout the two Cretaceous units and the Prairie Evaporite unit, but vary significantly within the Dawson Bay and Souris River Formations. These variations reflect the interlamination of shales (low velocity), carbonates (intermediate to high velocities), and anhydrites (high velocities) present in these formations.

The final simplified velocity model for the Cory area, including velocity data from the deeper borehole 8 - 13 - 36 - 7W3 is presented in Figure 13. Figure 13 also shows a high velocity sequence, the Winnipegosis limestone formation, directly underlying the Prairie Evaporite. This unit raises the possibility of earthquake energy being refracted along the Evaporite / Winnipegosis interface at the higher velocity, and thus eventually arriving at a surface geophone before the energy which is refracted directly upwards (Figure 14).

Calculations based on the velocity model given in Figure 14 indicate that geophones positioned 1800-2000 meters from the epicenter might receive energy refracted downward ahead of that refracted directly upward (for an earthquake at 1000 meters depth; see Figure 15). However, the energy from a doubly refracted wave will be less than the energy from a wave refracted directly upward. It is only for large magnitude events that the location algorithm must account for downward-refracted energy at far-away stations (i.e.- more
FIGURE # 13: CORY AREA SIMPLIFIED GEOLOGICAL SECTION AND SIMPLIFIED VELOCITY MODEL
FIGURE # 14: RAY-PATHS FOR ENERGY REFRACTED OFF THE WINNIPEGOSIS FORMATION

Surface Distance (meters)

Winnipegosis Formation

FIGURE # 15: TIME-DISTANCE PLOT FOR ENERGY REFRACTED OFF THE WINNIPEGOSIS FORMATION

Travel Time (seconds)

P-wave Refracted Up Winnegosis Fm.

Surface Distance (meters)
than 1800 meters from any single geophone). For events where Winnipegosis energy is suspected as the first arrival, the far-away stations will be omitted from the calculations.

2.4.2 Ray Tracing in a Layered Earth

Seismic energy propagates through the earth as complicated interfering wave patterns. It is possible to mathematically describe particle motion at any point in space and time, with respect to hypocenter location and onset time, in terms of wave theory. However, seismic energy propagation for a layered earth model is more easily described using the alternative ray theory. "Rays" are imaginary lines drawn perpendicular to wavefronts at any given time and position in space. The problem at hand is to find the ray-path from hypocenter to geophone which gives the minimum source-to-receiver travel time possible. This minimum-time ray-path describes the first arrival in the signal recorded at each geophone. Thus a parameter that is directly comparable to a measured parameter can be calculated.

For a horizontally layered velocity model energy travelling from hypocenter to surface geophone will be refracted at each interface following Snell's laws of refraction. The hypocenter location is given at point \((X_{eq}, Y_{eq}, Z_{eq})\), (constrained to lie somewhere within the Devonian limestones, just overlying the Prairie Evaporite and below the Blairmore
Formation), and geophone stations are on surface at \((X_i, Y_i, 0), \) 
\(i=1, 6.\) Seismic velocities and depths are known from the 
borehole velocity logs. The only unknown parameters are the 
refraction angles at the interfaces. The problem is set up 
diagrammatically in Figure 16. Using Snell's Law, the ray-
tracing problem can be re-written in terms of a single 
unknown refraction angle. For this three-layer case, in 
terms of angle \(\phi_3\) at the Devonian to Cretaceous interface, 
for geophone \(i\), the function describing the ray-path is:

\[
R_i = h_1 \times \tan \left[ \sin^{-1}\left( \frac{V_1 \times \sin \phi_3}{V_3} \right) \right] + \\
\frac{h_2}{\sin^{-1}\left( \frac{V_2 \times \sin \phi_1}{V_3} \right)} + \\
\frac{h_3}{\phi_3}
\]

where: 
\(R_i = \sqrt{(X_{eq} - X_i)^2 + (Y_{eq} - Y_i)^2}\)

\(h_1, h_2, h_3\) are thicknesses of layers 1, 2, 3 \((\text{Fig. 16})\)

\(V_1, V_2, V_3\) are velocities in layers 1, 2, 3 \((\text{Fig. 16})\)

\(\phi_1\) is the refraction angle in layer 3.

For upward refractions through "n" layers equation \((10)\) can 
be written in the more general form:

\[
R_{i,j} = \sum_{j=1}^{n} h_j \times \tan \left[ \sin^{-1}\left( \frac{V_j \times \sin \phi_{jn}}{V_n} \right) \right] \quad (11)
\]

where \(j=1\) refers to the uppermost layer, decrementing to \(j=n\)
for the bottom layer \((\text{in which the source is positioned})\), and

\(\phi_{jn}\) is the refraction angle in layer \(n\). The Cory region
layered geology can be adequately described using equation
FIGURE #16: THREE LAYER REFRACTION

\[ R_i = h_i \tan(\phi_i) \]
\[ R = R_1 + R_2 + R_3 \]
\[ S_i = \sqrt{h_i^2 + R_i^2} \]
\[ S = \sqrt{h^2 + R^2} \]
\[ \phi_i = \sin^{-1}(\frac{V_i}{V} \sin(\phi_i)) \]
\[ \phi = \sin^{-1}(\frac{V}{V_3} \sin(\phi)) \]
\[ R = h \tan(\sin(\frac{V}{V_3} \sin(\phi))) + h_1 \tan(\sin(\frac{V_1}{V_3} \sin(\phi_1))) + h_2 \tan(\phi_2) \]
\[ = R(\phi) \]

or, for 'n' rather than three layers:
\[ R = \sum_{i=1}^{n} h_i \tan(\sin(\frac{V_i}{V_n} \sin(\phi_n))) \]
(10), so equation (11) will not hence be referred to.

To find \( \Phi_i \) Ri is subtracted from both sides of equation (10) to give function \( f(\Phi_i) = \) zero:

\[
f(\Phi_i) = h_i \times \tan [\sin^{-1}(V_i \times \sin \Phi_i / V_3)] + h_i \times \tan [\sin^{-1}(V_2 \times \sin \Phi_i / V_3)] + (12)\]

\[
h_3 \times \tan [\Phi_i] - \text{Ri} = 0 \quad \text{(zero)}
\]

Function \( f(\Phi_i) \) has only one root at zero, and so \( \Phi_i \) can be found most conveniently by some iterative method. The derivative of \( f(\Phi_i) \) with respect to \( \Phi_i \) is given by:

\[
f'(\Phi_i) = \frac{h_i \times V_i \times \cos \Phi_i}{\cos^2[\sin^{-1}(V_i \times \sin \Phi_i / V_3)] \times [V_3^2 - V_i^2 \sin^2 \Phi_i]^{1/2}} + \frac{h_2 \times V_2 \times \cos \Phi_i}{\cos^2[\sin^{-1}(V_2 \times \sin \Phi_i / V_3)] \times [V_3^2 - V_2^2 \sin^2 \Phi_i]^{1/2}} + \frac{-h_3}{\cos^2 \Phi} \quad (13)
\]

Both \( f(\Phi_i) \) and its derivative \( f'(\Phi_i) \) are plotted in Figure 17, (using Cory thickness and velocity parameters), to illustrate the single root at zero. \( \Phi_i \) can be found by Newton-Raphson iteration:
FIGURE # 17: PLOT OF $f(\phi)$ AND $df(\phi)$

SOLID LINE FOR FUNCTION $f(\phi)$

$-x--x-$ LINE FOR DERIVATIVE $df(\phi)$

DEPTH FIXED AT: 1000.0

"R" = 1000.0

"R" = 2000.0
\[
\phi_3(n+1) = \phi_3(n) - \frac{f(\phi_3(n))}{f'(\phi_3(n))}
\]  

(14)

For hypocenters located within Upper Devonian limestones, up to 25 meters from the top of the formation, this function converges to 0.001 degrees accuracy in four to eight iterations. Starting angles (i.e. \(\phi_3(0)\) values) are not very critical for deeper events lying within the limits of the seismometer array. However, for shallow events and for events well outside the array, the \(\phi_3\) refraction angle will be very close to 90°, which is a singularity point in equation (13); see Figure 17. To ensure accurate convergence in the iteration (14) for these problem locations a starting angle that is close to the solution must be chosen. After some "trial-and-error", the following initial angles were chosen:

1. \(\phi_3 = 65°\) for hypocenters deeper than 600 meters from the surface and less than 1500 horizontal meters from the geophone. For these events rapid convergence to 0 for almost any choice of \(\phi\) is achieved.

2. \(\phi_3 = 85°\) for all other hypocenters.

Having found the proper value for \(\phi_3\), \(\phi\), and \(\phi_1\) can be found directly. The total travel time, with reference to Figure 16, is given by:

\[
T_{\text{net}} = T_1 + T_2 + T_3
= \frac{S_1}{V_1} + \frac{S_2}{V_2} + \frac{S_3}{V_3}
\]

(15)
where thicknesses $h_i$ and velocities $V_i$ are given by the velocity model, and the $\Phi_i$ values are found by the ray-tracing.

If the number of horizontal layers needed to describe the local geology becomes too large, the computation represented by the necessary equations for $f(\Phi_i)$, (12), and its derivative $f'(\Phi_i)$, (13), may be inhibitive. In such a case it may be preferable to use an iterative procedure that does not require derivative information instead of the Newton-Raphson methodology, (14). The Secant Method of finding zeros of equations gives convergence rates comparable to Newton-Raphson. The iterative strategy, equivalent to, and with the same parameters as, (14) is:

$$\phi_j(n+2) = \frac{\phi_j(n) \ast f(\phi_j(n+1)) - \phi_j(n+1) \ast f(\phi_j(n))}{f(\phi_j(n+1)) - f(\phi_j(n))}$$  (16)

The Secant Method requires two initial estimates of $\Phi_j$. This methodology tends to be less stable than the Newton-Raphson: as the solution in the iteration is approached, the two functions subtracted in the denominator become almost equal, resulting in division by a very small value. If this difference is less than the accuracy to which numbers are stored in the computer, there will be division by zero and a subsequent error in the computer program flow.

The Cory geology was modelled by a medium where seismic velocities change only at specified interfaces in one direction,
depth z. A medium where $V = V(z)$ is commonly referred to as a one-dimensional (1-D) medium. The ray-tracing for this case is simple, and could be developed using mathematics no more complicated than Snell's Law. However, mapping rays to give travel times between hypocenter and recording station should be feasible in areas of more complicated geology. Cerveny et al. (1977) present sets of differential equations that describe ray-tracing in both 2-D and 3-D media. Programs are available for ray-tracing in a 2-D earth, (Cerveny and Psencik, 1981). And as computer capabilities continue to improve in the future, programs to give ray-path solutions for the 3-D case will likely be developed. Seismologists operating microseismic monitoring arrays in hard-rock areas, such as the Sudbury nickel camp, should therefore not shy away from attempting ray-tracing methodologies in their hypocenter location calculations.

2.4.3 Iterative Approximation

P-wave arrival times measured at the stations comprising a seismic monitoring array are given as move-out times with respect to the earliest arrival time. By this method, the station nearest the hypocenter is always assigned a move-out time of exactly 0.000 seconds. Subtracting the calculated travel time to the nearest geophone from calculated times at all stations therefore results in a set of calculated move-out times directly comparable to the
measured values. The task at hand is to home in on the point in space that gives a set of calculated move-out times, at all six stations, that is statistically close to the set of move-out times that are actually observed.

However, the approach of subtracting the earliest arrival time from all travel times, both calculated and measured, gives a special significance to the arrival time at the nearest geophone. The move-out time at the geophone station nearest the hypocenter will always be 0.000. This effectively assumes no error in the arrival time at the nearest station, which is by no means justified. A better, and mathematically more sound, approach is to use the mean of the geophone times as a reference time instead of the single earliest arrival time. This gives two zero-mean sets of values "DT(i)" and "DTNET(i)" which can be statistically compared to one another with much more consistency than simply comparing the straight move-out times.

The next consideration is how to "statistically compare" DT(i) and DTNET(i) to enable us to find the point in space that minimizes the net difference between these two parameter sets. Begin by defining the residual vector RES(i), i=1,6, as the difference between measured and calculated travel times:

\[ RES(i) = DT(i) - DTNET(i) \quad , \quad i=1,6 \]  

(17)
Now define some function that assigns a positive real number as a measure of size to RES. The most useful and best known "measures" are the \( \ell^1 \) norms, defined by:

\[
RES = \left[ \frac{1}{N} \sum_{i=1}^{N} \text{RES}(i)^\rho \right]^{1/\rho}
\]  

for some real number \( \rho > 1 \) (Taylor, 1981, p.57).

The best known \( \ell^\rho \) norm is the \( \ell^2 \) norm, which is the least-squares minimization procedure:

\[
RES = \left[ \frac{1}{N} \sum_{i=1}^{N} \text{RES}(i)^2 \right]^{1/2}
\]  

Finding a best-fit using the \( \ell^2 \) statistic entails minimizing the sum of the squares of differences between calculated and observed times, DTNET(i) and DT(i). The \( \ell^1 \) norm looks for the arithmetic average value for the solution, or more specifically, we assume that the error in arrival times follows a Gaussian (normal) distribution for all stations, (Taylor, 1981). Errors in the input data, DT(i), are thus distributed equally over all geophones comprising the array. The \( \ell^2 \) norm thus gives equal weight to all arrival times.

This can lead to serious problems in the earthquake location calculation: if arrival times at five stations are measured correctly, but read incorrectly at the sixth station, the overall solution will be unnaturally biased towards an in-
correct location solution by the single incorrect input time. Taylor (1981) classifies three types of statistical error in event timing: (1) small, randomly distributed, measurement errors; (2) medium-sized errors due to picking the wrong phase; and (3) large errors due to picking the wrong event. The $l_1$ norm effectively assumes all input time error to be of type (1). If there is a type (2), and/or a type (3), error in the input data, using the $l_1$ norm will result in poor solutions.

"... there remains the problem of detecting and purifying from the input (arrival time) data gross errors or "outliers" - arising for example from noise or spikes, electronic crosstalk, or S/P confusions. Unless the number of good geophone arrivals is very large, one or more such gross errors lead to at best extremely poor solutions." (Eccles and Ryder, 1982). Some other $l_p$ norm must be found to help minimize the effect of bad data points. Claerbout and Muir (1973) discuss applications of the $l_1$ norm to seismic data processing. The $l_1$ norm, or absolute value, residual is given by:

$$\text{RES} = \left[ \frac{1}{N} \sum_{i=1}^{N} | \text{RES}(i) | \right]$$

(20)

where $| |$ denotes absolute value. Finding a best-fit using the $l_1$ statistic entails minimizing the sum of absolute values of differences between calculated and observed times,
DTNET(i) and DT(i). The $l_1$ norm looks for the median value to give the solution as opposed to the arithmetic mean (Claerbout and Muir, 1973). Now a few large errors among many good points in the data set will not make a major change in the minimization calculation solution. And so a solution using the $l_1$ norm is said to be robust. Taylor (1981) illustrates this "robustness" with a simple example. "Let $b(i) = i$ for $i=1,7$. Then the median and the average are both 4. If a large error of, say 28, is added to $b(7)$, so $b(7)$ becomes 35, the median would still be 4 but the average would become 8." The comparison of $l_1$ and $l_2$ norms is shown graphically in Figure 18. Straight lines have been fit to a set of points using both $l_1$ and $l_2$ norms, where the data set includes a few points that contain large errors. The $l_1$ norm gives the preferred curve-fit for this situation.

Therefore, the complete error determination algorithm is a three step procedure:

A. Compute the zero-mean measured times DT(i):

Measured move-out times are denoted as $T(i)$, $i=1,6$ for Cory;

1. compute the mean move-out time:

$$DTAV = \frac{1}{6} \sum_{i=1}^{6} T(i)$$  \hspace{1cm} (21)$$

2. subtract the mean value from all move-out times, giving DT(i):
FIGURE #18: COMPARISON OF L1 AND L2 NORMS

(after Taylor, 1981)

Straight line with 3 bad data points:

L1 curve

L2 curve
\[ DT(i) = T(i) - DTAV, \quad i=1,6 \quad (22) \]

resulting in a set of \( DT(i) \) about a mean value of zero.

B. Compute the zero-mean calculated times \( DTNET(i) \):

The calculated travel times are found by ray tracing from postulated hypocenter to respective geophone, giving \( TNET(i), \quad i=1,6 \):

1. compute the mean total travel time:

\[ TMEAN = \frac{1}{6} \sum_{i=1}^{6} TNET(i) \quad (23) \]

2. subtract \( TMEAN \) from the total travel times \( DTNET(i), \quad i=1,6 \):

\[ DTNET(i) = TNET(i) - TMEAN, \quad i=1,6 \quad (24) \]

giving a set of \( DTNET(i) \) about a mean value of zero.

C. Find the best-fit between \( DT(i) \) and \( DTNET(i) \) by finding the hypocenter which gives the minimum residual error:

1. by absolute value, or \( L_1 \) norm:

\[ ERR = \frac{1}{6} \sum_{i=1}^{6} |DT(i) - DTNET(i)| \quad (25) \]

2. by least squares, or \( L_2 \) norm:

\[ ERR = \left[ \frac{1}{6} \sum_{i=1}^{6} (DT(i) - DTNET(i))^2 \right]^{1/2} \quad (26) \]
For the data set collected at Cory, location solutions using both $l_1$ and $l_2$ norms have been tested. When P-wave onset times are clearly identifiable (Figure 19), the $l_2$ norm solution is preferred. This distributes the residual error between DT(i) and DTNET(i) evenly amongst all geophones. But for some events, onset times are very difficult to identify accurately, (Figure 20); in these cases the $l_1$ norm may help identify mis-picked times. A solution using the $l_1$ norm tends to put the residual error on the geophones with mis-picked arrival times. This allows easy identification of bad arrival time picks. For a well conditioned data set with zero mean location solutions were found to be the same, or very nearly the same, using either $l_1$ or $l_2$ norms. In practice, hypocenter location calculations are first run using the $l_1$ norm; the results are scrutinized for bad data points (and if bad picks are found, go back to the seismic trace and try to identify a more appropriate arrival, or simply omit that geophone from the final calculation); followed by a final solution calculation using the $l_2$ norm which normally distributes small random errors over all geophone times.

2.4.4 The Errorspace

For a given set of observed arrival times, DT(i), i=1,6, the $l_1$ or $l_2$ error "ERR" corresponding to point $(X, Y, Z)$ can be found by equations (25) or (26). Calculating parameter ERR systematically over a three-dimensional re-
FIGURE # 19 : SEISMIC SIGNAL SHOWING CLEAR ONSET TIMES

FIGURE # 20 : SEISMIC SIGNAL SHOWING UNCLEAR ONSET TIMES
region in the subsurface gives a set of values which can be contoured. This set of ERR values in space is defined as the "errorspace". To avoid contouring the large values it is convenient to use the logarithm of ERR rather than the raw values. The contoured errorspace for an event located within the limits of the Cory array is shown in Figure 21, in plan view, and in north-south and east-west sections. The contours close about the minimum point (Xeq, Yeq, Zeq), the best-fit hypocenter location. Notice that in three dimensions, the contoured errorspace is closed, and that there is only one such closure over the map area.

The oval shape of the minimum-error contour is determined largely by the geophone station positioning with respect to the hypocenter. The error contour is slightly longer in the north-south direction than in the east-west direction, since geophones are positioned along only two north-south coordinate lines, as opposed to three (or more) east-west coordinate lines. The contour shape is longest in the vertical dimension since all geophones are located on the same plane, far from the event. Location error will be worst for hypocenter depths. The dimensions and shape of the errorspace will be used to develop quantitative distance error-bars for hypocenter location calculations in chapter 3.
FIGURE # 21 : CORY MINE ERRORSPACE

LOG-RESIDUALS (m/sec)

DISTANCES IN METERS

TIMES IN SECONDS

THO(1) = 0.125  THO(2) = 0.000
THO(3) = 0.015  THO(4) = 0.150
THO(5) = 0.025  THO(6) = 0.035
SPACING = 100.0 m / sec
V1 = 2695.0 m / sec
V2 = 4905.0 m / sec
V3 = 4500.0 m / sec

L2 MAP FOR EVENT : 1982 / JUNE 28
The hypocenter location in space can thus be found by mapping the errorspace in the vicinity of the geophone array. But in order to draw the plan and section views given in Figure 21 accurately, complete ray-tracing solutions, for all six geophones, were calculated for 963 points in space. Detailed contouring becomes difficult for fewer data points. A computationally more efficient algorithm for finding the center (i.e., minimum ERR-value point) of the error contour must be found.

Since there is only one minimum for the layered-earth velocity model, (assuming no gross error in the set of arrival times), there is no need to worry about convergence to an incorrect, artificial minimum. But in a more complicated earth there may in fact be a number of distinct, reasonable, minima. It will then be necessary to draw the entire three dimensional errorspace to find all possible hypocenter locations.

2.4.5 Finding the "Minimum" of the Errorspace

The earthquake-hypocenter location problem has now been formulated as a problem in non-linear optimization. A mathematical model describing the situation has been developed, real measured data have been collected, and now the mathematical model must be fit to the data set. A "good" fit will give the answer to our problem, the location (Xeq, Yeq, Zeq)
in space of the event that gave rise to the signal observed at the six geophones. Non-linear curve-fitting algorithms invariably involve iteration, or recursion. The unknown parameters in the mathematical model, point \((X, Y, Z)\) in space, must be adjusted in an iterative way to converge to the best-fit answer. The task is to ensure that the answer to which the iteration procedure converges is in fact the correct solution to the problem, and subsequently to achieve convergence with a minimum amount of computation.

2.4.5.1 The Cube-stepping Algorithm

The method of "cube-stepping" through the errorspace is the first solution-finding algorithm tested using Cory data. The procedure was initially set up by Gendzwill in 1981, shortly after the Cory array became operational. The algorithm has since been incorporated as the main location method in the ELECTROLAB automatic seismic monitoring system recently installed underground at the Cory mine. The scheme is similar to the optimization algorithm presented in Dechman and Sun (1977). The method gives very reliable location solutions, ascertained by extensive testing using both real and synthetic data, but requires some computational effort.

In the cube-stepping procedure an initial trial hypocenter location is chosen, and surrounded by 26 points on the
corners, edges, and face-centers of a cube centered on the original point. The error function \( \text{ERR} \) is calculated for all 27 points that comprise the cube. The point with the smallest value for \( \text{ERR} \) is chosen as the center for the next trial cube. If the smallest error point is at the center of the cube, the cube-size is halved for the next trial. This procedure is continued until the cube has been reduced to 8 meters a side. The starting cube is usually chosen with an edge of 512 meters a side. The end point is then the best fit hypocenter location \((X_{eq}, Y_{eq}, Z_{eq})\) at, or near, the center of the error contour. A diagrammatic description of the cube-step algorithm is given in Figure 22.

The cube-stepping procedure "works" in that the correct solution to the problem will be found, virtually every time, for any reasonable starting location. But the amount of computation needed to find a solution is substantial. For a complete solution, parameter \( \text{ERR} \) must be calculated at least \((7 \times 27) = 189\) times. More typically, assuming a few cube-center moves for each cube-side shrinking, \( \text{ERR} \) will have to be calculated about 400 times per complete location calculation. The cube-stepping methodology is what Caceci and Cacheris (1984) would call a "brute-force stepping procedure". No use is made of the information contained in the set of previously determined \( \text{ERR} \) values; this is a straightforward systematic search method.
FIGURE # 22 : DESCRIPTION OF THE CUBE-STEP ALGORITHM

Initial Cube

Cube after Translation

Cube Translated and Reduced
2.4.5.2 The Simplex Algorithm

One of the fastest available minimization procedures is the Simplex algorithm. The complete Simplex algorithm was first presented by Nelder and Mead (1965), who based their method on an "ingenious idea for tracking optimum operating conditions" given by Spendley et al. (1962). Other scientists, notably George Dantzig of Stanford University, appear to have tried the method as early as the late 1940's (Science, 2 November 1979, p. 545). But it was not until the digital computer became common through the 1960's that the Simplex method came to be used routinely. Today, "the method, which is quite fast to begin with, has been honed down to its essentials by generations of computer scientists and is sold commercially in the form of a highly efficient assembly language program", (Science, 21 September 1984, p. 1379).

Any recent textbook on numerical optimization methods will devote a sub-chapter or a section to describing the Simplex algorithm (for example, see Williams, 1969; Wolfe, 1978; Nash, 1979; or Fletcher, 1980).

A geometrical simplex is a figure having one more vertex than the number of dimensions for which it is defined. For the earthquake location problem the errorspace defined by ERR is a function of three unknowns (X, Y, Z), making this a three-dimensional (3-D) problem. The corresponding simplex
will therefore be a four-point tetrahedron. If one unknown, say depth \( Z \), is fixed in the location problem, ERR becomes a function of two dimensions \((X, Y)\), and the simplex will be a three-point triangle. For \( M \) dimensional space the corresponding simplex will have \((M+1)\) vertices.

The basic idea of the Simplex algorithm for finding minima in \( M \)-dimensional space is to create an \((M+1)\)-dimensional simplex, and then to replace high-error points on the simplex with other points, moving and distorting the simplex to home in on the solution. The Simplex Algorithm, for the three dimensional Cory earthquake location problem, can be outlined as follows:

1. Recall that the known input consists of: geophone location coordinates, \((X_i, Y_i, Z_i)\); first break P-wave arrival times, \( DT(i) \), at each station; and a detailed velocity model.

2. Form a starting tetrahedron in the errorspace by specifying four \((X, Y, Z)\) coordinates. Evaluate parameter ERR, as defined by equations (25) or (26), at each of these four positions.

3. Find which of the four vertices has the highest value for ERR and which has the lowest value.

4. Replace the high-ERR point with another location position, choosing this new location coordinate according to one of the following mechanisms: "reflection", "expansion", "contraction", or "shrinkage". These procedures are
described diagrammatically, (and for the two-dimensional / three-point simplex case), in Figure 23. Reflecting the vertex creates a new position reflected about the centroid of N-1 points of the simplex, omitting the point being reflected. Expanding the vertex creates a new position by reflecting about the centroid by twice the distance of the simple reflection. Contracting the vertex creates a new point at half the reflection distance toward the centroid. Shrinking, this time for all vertices except the best (lowest-ERR) point, creates new points at half the distance towards the best value. The specific testing sequence of reflection, expansion, contraction and shrinkage is given in the flow-chart in Figure 24.

5. Computation is stopped when all points comprising the simplex are within four radial meters of each other. The final solution (Xeq,Yeq,Zeq) is the point having the smallest value for ERR.

The simplex shape "adapts itself to the local landscape, ... contracting in the neighborhood of a minimum" (Nelder and Mead, 1965). An excellent discussion of the Simplex algorithm is given in Caceci and Cacheris (1984).

The Simplex procedure moves towards the minimum of the errorspace by what are essentially heuristic criteria, with a component of the maximum movement always in the direction of the maximum gradient. There is no explicit mathematical
FIGURE # 23 : SIMPLEX REFLECTION, EXPANSION, CONTRACTION, AND SHRINKAGE

( after Caceci and Cacheris, 1984 )

B-W-O : original Simplex (2-D)
B : 'best' vertex
W : 'worst' vertex
1. R : reflected vertex
2. E : expanded vertex
3. C : contracted vertex
4. S : shrunken vertices
FIGURE # 24 : FLOWCHART SUMMARIZING THE SIMPLEX ALGORITHM

(from Caceci and Cacheris, 1984)
formulation to prove that the method will end up at the minimum value for ERR. It is informative to follow the simplex as it moves towards the solution. While this can be done for three unknowns conceptually, with the aid of pictures of the errorspace (Figure 21), it is much easier to describe on paper what is happening for the two-dimensional (2-D) case. By fixing depth Z to 1000 meters, the errorspace of Figure 21 becomes a plane surface contour plot. This 2-D errorspace, showing the simplex moving along the ERR response surface, is given as an illustrative example in Figure 25.

In general the Simplex strategy has important advantages over other optimization methods, as outlined by Caceci and Cacheris (1984):
- the method will not diverge;
- no knowledge of derivatives is needed, allowing the handling of non-continuous functions;
- no matrix operation is involved;
- response parameter ERR need only be computed a few times for each iteration.

This last point is possibly the most important: the Simplex algorithm converges to a solution very quickly. Testing of the procedure for typical Cory events resulted in convergence to (Xeq,Yeq,Zeq) for about 30 to 40 calculations of parameter ERR. Recall that the Cube-step algorithm required at least 179, and usually about 400, ERR calculations. The method does have problems converging in some situations, specifi-
FIGURE #25: CORY L2 ERRORSpace, EVENT 1982 / JUNE 28

TMO(1) = 0.135  TMO(2) = 0.000  TMO(3) = 0.015  TMO(4) = 0.150  TMO(5) = 0.025  TMO(6) = 0.035

LOG-RESIDUALS (msec) = 100.0
SPACING = 1000.0
DEPTH = 2025.0
V1 = 2025.0
V2 = 2695.0
V3 = 4905.0

X = EAST
Y = NORTH
cally for the case where the error ellipsoid is long and narrow, or cigar shaped. The simplex moves back and forth from side to side of the cigar, along the steepest ERR gradient, rather than moving straight down the length of the errorspace. The errorspace is cigar shaped for events occurring outside the limits of the array either to the east or west. But even so, the Simplex algorithm finds the correct solution faster than the Cube-step procedure.

2.6 Summary of Conclusions

A viable method for determining earthquake hypocenter locations from measured arrival times of compressional waves has been developed through chapter 2. For the six-channel seismic monitoring array set up over the Cory potash mine the conventional Least-squares hypocenter location method will not give reliable location solutions. Refractions at various velocity interfaces in the subsurface must be taken into account for accurate location calculations. To this end, the problem is posed as one of comparing calculated source-to-receiver times to the times that were actually measured. This method of Iterative Approximation is non-linear, and so some iteration procedure must be employed to arrive at a solution.

Ray-tracing methods are used to find the minimum-time travel path from hypocenter point to geophone station. Mean values
are removed from the two data sets to avoid dependence on the accuracy of the arrival time at the nearest geophone station. Comparisons between calculated and observed data sets can be done using either $l_1$ or $l_2$ norms to form the error statistic ERR. The location in space that gives a minimum value for ERR is the best-fit hypocenter location. Parameter ERR can be contoured to give an idea of the shape of the errorspace; the result is a single contour shape in space closed about the hypocenter location. But this is a computationally tedious procedure if all that is needed are the final location coordinates. A location solution can be arrived at rapidly by using the Simplex algorithm to home in on the minimum of the errorspace. Solutions are generally found in 30 to 40 iterations.
3. EFFECTS OF VARYING INPUT PARAMETERS ON THE LOCATION SOLUTION

3.1 Preamble

A fast method for computing hypocenter location using P-wave arrival times has been formulated (Chapter 2.); the method must now be tested. To this end, arrival time data have been generated for nine representative hypocenter locations near the Cory monitoring array. These synthetic move-out time data were then used as input to the location program. The time inputs were perturbed in various ways to determine the extent to which gross, and even slight, errors in the input data would affect the location solution. Locations of the synthetic hypocenters, with respect to the geophone array, are given in Figure 26, and the corresponding calculated move-out times are given in Table 3.

Testing of the hypocenter location algorithm has shown that location solutions will be good for events occurring within the horizontal dimensions of the seismometer array. For events occurring outside the array solution errors will be greater. The depth of the synthetic hypocenters has been fixed at 1000 meters, near the base of the Dawson Bay limestones. Events F, G, and H near the center of the array are all located at the same horizontal coordinate, but at 1000, 750, and 600 meter depths. And event I is at the location of an underground dynamite roof blast carried out on June 28, 1982.
### Table 3: List of Move-Out Times Used as Input to the Hypocenter Location Program During Testing of the Algorithm

(Event location given in meters relative to geophone # 4).

<table>
<thead>
<tr>
<th>EVENT NAME &amp; LOCATION</th>
<th>MOVE-OUT TIME (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. 0 / 800 / 1000</td>
<td>0.000000 0.108009 0.237213 0.078928 0.152679 0.272718</td>
</tr>
<tr>
<td>B. -500 / 500 / 1000</td>
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<td>D. -500 / -500 / 1000</td>
<td>0.123750 0.233845 0.344478 0.000000 0.142878 0.282787</td>
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<td>E. 800 / -800 / 1000</td>
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<tr>
<td>F. 800 / 400 / 1000</td>
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<td>------------------------</td>
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FIGURE 26: SYNTHETIC HYPOCENTERS / CORY MINE PLAN

SCALE 1:2000

GEOPHONE LOCATION

HYPOCENTER
3.2 Rounding Error

The first source of error to be discussed is the error inherent in the digital sampling of the continuous seismic signal. There is a difference between usual rounding and the discrete rounding that results from digital sampling. If P-wave energy arrives just after sample "n" has been read, it will be stored digitally as if it had arrived at sample "n+1". For the DCS-302 instrument used in the Cory array, with a sampling rate of 5 milliseconds, this means an arrival time almost 5 milliseconds later than the true arrival time. Usual rounding would have ascribed the arrival more properly to sample "n". The worst sampling error at any single station will therefore be just less than 5 milliseconds. Thus for the situation of a 5 millisecond error at all six stations, the RMS error "ERR" (equation (25) or (26)) will also be 5 milliseconds.

This allows development of quantitative distance error bars for the hypocenter location solution. For an errorspace contour map, (section 2.4.3), it can be argued that the "correct" hypocenter location should always lie within the 5 millisecond average error contour, (assuming no gross errors in the input data set). Detail of the errorspace shown in Figure 21 is given in Figure 27; (note that simple residuals are contoured in Figure 27 while log-residuals are contoured in Figure 21). The 5 millisecond error
FIGURE #27: CORY MINE ERRORSPACE

L2 MAP FOR EVENT: 1982 JUNE / 28

Y - NORTH

Z - DEPTH

DISTANCES IN METERS
TIMES IN SECONDS
RESIDUALS (mees)

V1 = 2025.0 m/sec
V2 = 2045.0 m/sec
V3 = 4905.0 m/sec

TIMES: T1 = 0.000
T2 = 0.015
T3 = 0.035
SPRING = 50.0 m

V1 = 0.000 sec
V2 = 0.015 sec
V3 = 0.035 sec

TIMES: T0(11) = 0.135
T0(13) = 0.015 T0(15) = 0.025

TIMES: T0(1) = 0.135
T0(3) = 0.015 T0(5) = 0.025

RESIDUALS (mees)

V1 = 2025.0 m/sec
V2 = 2045.0 m/sec
V3 = 4905.0 m/sec

TIMES: T0(11) = 0.135
T0(13) = 0.015 T0(15) = 0.025
contour in Figure 27 is approximately 200 meters diameter in either horizontal dimension, and 800 meters in the vertical dimension. This is the region in which we can say with great confidence that the earthquake occurred. Rather than map the error figure by drawing the complete error-space for each event analysed, an average errorbar of ± 100 meters horizontal and ± 400 meters vertical could therefore be assumed for the real event locations that will be presented in Chapter 4. These are very large errorbars.

The synthetic arrival time data given in Table 3 were rounded in four ways:
1. rounded to ± 0.001 seconds;
2. rounded to ± 0.005 seconds (one sample interval);
3. digitized to + 0.005 seconds (one sample interval);
4. digitized to + 0.010 seconds (two sample intervals).

The rounded times were then used as input to the hypocenter location program. The results are summarized in Table 4. For each of the 8 synthetic event locations A - H, and for situations 1. - 4. above, the RMS error and the distance error (both $\ell$, and $\ell_1$) have been listed. Recall that the location method stops calculations when all points of the computation simplex are within four orthogonal meters of one another. The distance error can therefore be
$$\text{SQRT}(4^2 + 4^2 + 4^2) = 7 \text{ meters}$$ simply as a result of limiting calculations.
### Table 4: Compilation of the Effects of Rounding Error

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<tr>
<th></th>
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<th>+ 0.010</th>
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<td>ERR (m)</td>
<td>RMS (msec)</td>
<td>ERR (m)</td>
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The notable points presented in Table 4. include:
- The largest distance errors are for locations to the east or west of the array, even for rounding to ± 0.001 seconds, (see events B and D).
- The smallest errors are for events in the center of the array, (F, G, H), with error slightly greater for the shallower event (F).
- The average error distances for the above situations 1, 2, 3, 4, are respectively:
  1. 7 - 15 meters,
  2. 25 - 40 meters,
  3. 30 - 55 meters,
  4. 90 - 125 meters.
- Computed RMS errors are generally less than half the worst-case error for all situations. For digitization to + 0.005 seconds the RMS time error is 0.002 seconds. Rather than use the 0.005 second error space contour as the error ellipsoid it would therefore be more realistic to use the 0.002 second contour.
- A small RMS error does not necessarily indicate a small distance error; (i.e.- a mathematically good time fit does not guarantee that the location coordinates will be physically correct).
- There is no systematic difference between solutions using the $l_1$, or the $l_2$ norm.
Situation 3, (digitization to + 0.005 seconds), is the most important test since this approximates most closely the DCS-302 sampling process. The maximum likely error distances determined earlier for the worst-case situation were ± 100 meters horizontal and ± 400 meters vertical. The error distances given for situation 3 are a better approximation of the worst probable error distances. The distance error is small (20 meters) for the three events within the array, (F, G, and H), and increases for events outside the array to a maximum of 200 meters for event B to the east. Using the 2.0 millisecond errorspace contour gives an errorbar contour of ± 50 meters horizontal and ± 150 meters vertical (see Figure 27).

The sampling interval of 0.005 seconds is therefore a significant factor in limiting the computation location accuracy. The effect is not pronounced within the horizontal dimensions of the seismometer array, but can lead to very large solution errors for events outside the array. For some events it may therefore be best to draw the complete errormap to get an idea of the range of possible solutions for that specific event.

3.3 Incorrect Times

A step beyond general rounding error is the location error introduced by having gross time-pick errors at some geophones.
For event I arrival times rounded to ± 0.001 seconds have been perturbed by adding and subtracting ± 0.005, ± 0.010, ± 0.020, and ± 0.030 seconds to successive single geophone times. Event I was chosen since it is representative of a typical event within the limits of the array, and since the move-out times are the same when rounded to either ± 0.001 or ± 0.005 seconds.

Adding time error to single geophones is a way to compare the location accuracy using the $l_1$ and the $l_2$ norms. Calculations using the $l_1$ norm are considered preferable for data sets having a few isolated bad data points (section 2.4.3). The time difference between calculated and observed travel times should be greatest at the station with the incorrect "observed" arrival time when using the $l_1$ norm, while time differences should tend to be the same at all stations when the $l_2$ norm is used. Plots of the time difference between observed and calculated travel times for the 8 input time error situations are given in Figure 28. Each of the six plots is for time error added to one channel; (ie.- the "CH. 1" plot is for time errors of ± 0.005, ± 0.010, ± 0.020, ± 0.030 added to the correct arrival time at channel 1). The individual points plotted on each graph are the resulting time differences at each geophone for the given situation, a black square for the $l_1$ solution, a colored triangle for the $l_2$ solution. The two plus / minus maximum time difference points have been labelled with their geophone number.
FIGURE #28: EFFECT OF TIME ERROR ADDED TO ONE CHANNEL BLACK POINT FOR L1 DATA / COLOR POINT FOR L2 DATA
In each of the six plots the $l_1$ time errors tend to be at the two maximum values with the remaining points near zero. On the other hand, the $l_1$ time errors tend to be evenly distributed about zero. This reaffirms the argument that the $l_1$ norm tends to assign less weight to bad data points, while the $l_2$ norm treats all points equally. Secondly, for each of the six plots, one of the two $l_1$ plus/minus maximum error points is always for the geophone to which the time error was added. The $l_1$ solution assigns the greatest error to the point that is in fact incorrect. The other maximum is always for the geophone north or south of the "perturbed" station. This results because successive north-south station pairs are at similar distances from the location of event I: similar arrival times are observed at stations 1 and 4, 2 and 5, 3 and 6 for event I. In most cases the $l_2$ solution also puts the greatest error on the "incorrect" geophone.

The radial distance between the input coordinate and the best-fit solution coordinate, calculated using perturbed input time data, can also be compared. The degree of distance error allows a more detailed comparison of location solutions using both $l_1$ and $l_2$ norms. The results are presented in Figure 29, one plot for each channel. The plots are of the radial distance in meters between the input coordinate and the best-fit calculated solution coordinate, versus the time-error (in seconds) added or subtracted to
FIGURE 29: EFFECT OF TIME ERROR ADDED TO ONE CHANNEL

BLACK LINE IS L1 CURVE / COLOR LINE IS L2 CURVE

TIME ERROR (SEC)

TIME ERROR (SEC)

TIME ERROR (SEC)

TIME ERROR (SEC)

TIME ERROR (SEC)

TIME ERROR (SEC)

DIST. ERROR (m) DIST. ERROR (m)
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the given input time. Each plot consists of two sets of $l_1$ and $l_2$ pairs of curves; one set is the distance error for all three (X, Y, Z) coordinates, and the second set, having less error, is the distance error for only the horizontal (X, Y) coordinates.

The information presented in Figure 29 is summarized in Table 5. The values listed are average distance errors that result from sequentially adding/subtracting $\pm 0.005$, $\pm 0.010$, $\pm 0.020$, and $\pm 0.030$ time error to the correct move-out times of channels 1, 2, 3, 4, 5, and 6. Using averages allows more quantitative discussion of the effects of bad input data. Four different values are given: three-coordinate $l_1$ and $l_2$ distance error, and horizontal $l_1$ and $l_2$ distance error. Average and median distance errors are listed for each of the four time-error input situations. The two additional columns are, respectively, ratios of three-coordinate $l_1$ to $l_1$ norm distance errors, and ratios of horizontal $l_1$ to $l_2$ norm distance errors; when this ratio is less than 1 the $l_1$ solution gives the better fit, when it is greater than 1 the $l_2$ solution is better, and when the ratio equals 1 both $l_1$ and $l_2$ solutions give equally good fits. The points of interest presented in Table 5 include:

1. The average radial distance error for three-coordinate solutions is about 7 meters per millisecond of time error (up to 30 milliseconds).
2. The average radial distance error for horizontal-coordinate solutions is 3 meters per millisecond of time error (up to 30 milliseconds).

3. For three-coordinate errors $l_1$ and $l_2$ solutions are statistically very similar. This may be the result of having input data from only six stations, too few to be able to reliably differentiate between the methods.

4. For horizontal coordinate errors $l_1$ solutions consistently give slightly better answers than $l_2$ solutions.

To sum up, $l_1$ solutions are always as good as, or better than $l_2$ solutions. Location solutions can confidently be computed using only the $l_1$ norm. Time pick errors of up to four digital samples, or $\pm 0.020$ seconds, at a single station will give location solutions within the 0.002 second error ellipsoid discussed in section 3.2, (at least for events within the limits of the geophone array). However, if time picks are very bad, significant error can be induced in the calculations. If it is difficult to pick the P-wave onset time accurately one is better off leaving that channel out of the solution calculation entirely than risk the bad location that will likely result.

3.4 Missing Data

For some events P-wave arrivals may be impossible to pick at certain stations, or the seismic signal may not have been
recorded at some stations because of instrument malfunction. To test the effects of missing data on the location error, location solutions were run for event I using arrival times, (rounded to $\pm 0.001$ seconds), at 5, 4, and 3 geophones. The three-component error results are summarized in Table 6a, and the horizontal component error results in Table 6b. Values are radial distances between the input location and the location calculated using the incomplete set of input times. In each of the Tables the top box gives error results for omitting 1 and 2 stations. The next four boxes list errors for omitting three stations: first channel 1 and two others, then channel 2 and two others, channel 3 and two others, and finally channel 4 and two others. Median and mean radial distance values for each of the three situations are given at the bottom of the page. All solutions were computed using the $\ell_2$ norm.

The important points presented in Tables 6a and 6b include:

1. For calculations using five of six stations (omit 1) the three-component distance error is 5 meters and the horizontal distance error is 2 meters.

2. For calculations using four of six stations (omit 2) the three-component distance error is 13 meters and the horizontal distance error is 5 meters. However, there is a chance that in some instances the solution will have a very high error, as for the omission of channels 1 & 4, 2 & 5, and 3 & 6.
3. For calculations using three of six stations (omit 3) the three-component distance error is 210 meters and the horizontal distance error is 90 meters. Recall that solving for three unknowns using only three input times is the worst-case situation (section 2.2).

Location solutions using four or five geophone times are thus as reliable as the solutions computed using six arrival times, (at least for events occurring within the limits of the seismometer array). The exception is for the situations where station pairs 1 and 4, 2 and 5, or 3 and 6 are omitted. When any of these three pairs are left out of the calculation the remaining four geophones form a very symmetrical (square or rectangular) array about epicenters near the center of the array. Earthquakes occurring over a large region near the center of array will then give very similar arrival times at all geophone stations.

Three channel solutions may be very far from the actual location. The three channel distance error is in the range of the location error that results from ± 0.030 second time pick error at one geophone. Although location solutions are possible for arrival times measured at only three stations the results should be considered reliable only within ± 200 to 250 meters for all components.
TABLE 6a: THREE-COORDINATE DISTANCE ERROR FOR MISSING DATA AT ONE, TWO, AND THREE CHANNELS

Radial distance error is in meters

<table>
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<tr>
<th>Omit Channel:</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>22</td>
<td>227</td>
<td>4</td>
<td>13</td>
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<td>262</td>
<td>204</td>
<td>257</td>
<td>273</td>
</tr>
<tr>
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<td>320</td>
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<td>Omit 4</td>
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<td>209</td>
<td>204</td>
<td>262</td>
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<tr>
<td>Omit 6</td>
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<td>35</td>
<td>35</td>
<td>35</td>
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<td>35</td>
</tr>
</tbody>
</table>

Omit 1 CHANNEL:
Mean = 5 m.
Median = 5 m.

Omit 2 CHANNELS:
Mean = 51 m.
Median = 13 m.

Omit 3 CHANNELS:
Mean = 209 m.
Median = 212 m.
TABLE 6b: HORIZONTAL - COORDINATE DISTANCE ERROR FOR MISSING DATA AT ONE, TWO, AND THREE CHANNELS

Radial distance error is in meters

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<th>4</th>
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<td></td>
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<td></td>
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<td>31</td>
</tr>
</tbody>
</table>

OMIT 1 CHANNEL
Mean = 2 m.
Median = 2 m.

OMIT 2 CHANNELS
Mean = 20 m.
Median = 5 m.

OMIT 3 CHANNELS
Mean = 92 m.
Median = 81 m.
3.5 Variations in Layered-earth Velocities

The final perturbation to the earthquake location input data is to the P-wave propagation velocities \( V_1 = 2025, V_2 = 2695, \) and \( V_3 = 4905 \) meters/second determined in section 2.4.1. First individual, then all three, velocities are systematically changed by \( \pm 100, \pm 200 \) and \( \pm 300 \) meters/second. The resulting radial distance errors for event I are shown in Figure 30. Both three component and horizontal distance-error is plotted against the added velocity error for each of the four situations. Note that the vertical distance-error axis, which went to 300 in Figure 29, extends only to 100 in Figure 30. Results plotted were computed using the norm.

The important points seen in figure 30 are:

1. Horizontal location is virtually unaffected by velocity variation. This is a result of using a horizontally layered earth as model for the Cory region geology.
2. Variations in the slower near-surface velocities \( V_1 \) and \( V_2 \) have little effect on the location solution.
3. Only variations in the Devonian Limestone velocity \( V_3 \) will have significant effect on the vertical component of the location solution.
The effects of using slightly incorrect layered-earth velocities is minimal. All location solutions presented in Chapter 4 will therefore be calculated using a single set of velocity values in order to remain consistent for all events recorded.
FIGURE # 30: EFFECT OF VELOCITY ERROR ON EQ LOCATION

UPPER LINE IS 3 - D ERROR
LOWER LINE IS HORIZONTAL ERROR

VARY V1

VARY V2

VARY V3

VARY V1, V2, & V3

VELOCITY ERROR (m/sec)

4.1 Preamble:

Microseismic monitoring at the Cory potash mine began in October, 1981, and ended in late December, 1984. In this forty month period 83 micro-earthquakes and one macro-earthquake were recorded. A second macro-earthquake occurred during the monitoring period, but was not recorded by the six channel array. Both macro-earthquakes were felt by local residents, and were recorded by the University of Saskatchewan's permanent short-period seismometer station.

Problems with the monitoring system, especially during the first 18 months of recording, resulted in both downtime and occasional times ineffective operation. A major problem was lightning storm activity occurring near the seismic array. The lightning would induce high voltage surges through the cables causing severe damage to the pre-amplifier of the instruments. Since August, 1983, all instruments have been equipped with front-end lightning protection circuitry which keeps input voltages below dangerous levels. This circuitry was designed (by Dr. D. Dodds) and built at the University of Saskatchewan. Recording time was also lost because of problems with the DCS-302 amplifier circuit boards. The boards were redesigned by the manufacturer, after consultation with University of Saskatchewan personnel, and
new amplifier boards were installed in all instruments by early 1984.

Ineffective recording refers to times of high background noise levels, and times when cassettes were filled by noise events. The various high noise levels include 60 Hertz power-line grounding leakage, (both in the form of spike transients and continuous high background levels). This noise problem was virtually eliminated by adding a filter to the front end of each recording unit. One source of transient noise was traced to electric arcing across defective power line insulators. These were repaired by Saskatchewanan Power Corporation personnel as soon as the problem was identified.

Some events were recorded with 60 Hz noise on one or two channels, as shown in Figure 31a. In such cases the noise, (which in Figure 31a completely swamps the signal on channel six), could be digitally filtered. A recursive filter was developed following the method presented in Shanks, 1967. The filtered traces of Figure 31a are given in Figure 31b. Recursive filtering requires relatively little computation, and should be viable when using a microcomputer.

For each trace made up of “N” digital samples it took $8 \times N$ multiplications and $8 \times N$ additions to get from the traces in Figure 31a to the traces in Figure 31b. (A convolution filter would have required $N \times N$ additions and $N \times N$ multiplications).
FIGURE # 31a: MICRO-EARTHQUAKE 83-285 8 3 32
FIGURE # 31b: MICRO-EARTHQUAKE 83-285 8 3 32
Seismic noise was generated whenever a train passed on the rail-line 400 meters north of channels 1, 2, and 3, and by farming activity especially in the spring and fall. There is unfortunately not much that can be done to eliminate the effects of such cultural activity. One macro-earthquake, (January 6, 1983 of magnitude m(b) = 2.4) was not recorded because high noise levels from a train passing by at the time of the earthquake prevented the instruments from triggering. Due to these problems the time of effective monitoring during the first 18 months of operation is estimated at 50% to 70%. The percent "ontime" from May, 1983 through December, 1984 is shown in Figure 32, along with the number of events recorded each month. The recording efficiencies presented in Figure 32 represent the percentage of time for which the instruments themselves were fully operational. The actual efficiency is somewhat reduced by times of high background noise levels when seismic events could not be "seen" by the system's recording trigger mechanism.

A histogram of the number of microseismic events per month over the entire recording period, along with the 30 day running total, is given in Figure 33. The two noticeable macro-earthquakes which occurred on January 8, 1982 and on January 6, 1983 are marked as solid dots in the diagram. There are three times of increased microseismic activity apparent on the histograms:
FIGURE # 32 : CORY MICRO-SEISMIC RECORDING

RECORDING EFFICIENCY
( NUMBER OF 'x' S GIVES EVENTS PER MONTH )
FIGURE #33: CORY MICRO-SEISMIC RECORDING

HISTOGRAM OF MICRO-SEISMIC EVENTS

30 DAY RUNNING TOTAL
1. in December 1981, just before the January 8, 1982 macro-earthquake;
2. in October through December 1983, not associated with any macro-earthquake;
3. and in November and December 1984, not associated with any macro-earthquake (to date).

The December 1981 microseisms appear to be foreshocks to the large earthquake that followed. In contrast, there was a marked absence of micro-earthquake activity in the 6 months preceding the January 6, 1983 macro-earthquake. Unfortunately instrument problems kept the recording efficiency at about 50% during the fall of 1982, so that some microseisms may have been missed during this time period.

An explanation for this variable correlation between micro and macro seismic activity may possibly be found in looking at the mining rate at Cory over the seismic monitoring period. Throughout 1981 the Cory mine was producing potash at near full capacity. But since mid-1982 the world market for potash has been depressed, with low prices and excess supply plaguing producers. This resulted in temporary but extended periods of mining shut-downs and slowed production at Cory, so that the mine worked only at 50% to 70% of the usual ore extraction rate throughout 1983 and 1984. When mining stops (or slows down), earth-quakes and micro-earthquakes stop, or diminish, in both frequency of occurrence and in magnitude.
4.2 Locations:

Event locations were determined for 72 of the 83 micro-earthquakes recorded at Cory. Locations could not be established if P-wave times could not be picked accurately on three or more channels. A summary of all micro-earthquakes recorded, giving event time, location coordinates (if determined), and magnitude estimate (to be discussed in section 4.3) is given in Appendix A. Event locations are presented in plan view and in north-south / east-west section views in Figures 34a through 34g, one figure for every six months of recording, (except Figure 34a which covers only October, November, and December, 1981).

Each map view shows the mine plan outline and surface geophone locations, and both vertical sections show the velocity model used in event calculations. The geological interfaces drawn in the profiles are, from top to bottom, Cretaceous sandstones and shales - the Mannville (or Blairmore) sandstone - Middle Devonian limestones - the Prairie Evaporite - Winnipegosis (and other) limestones. The two lower interfaces are not included in the velocity model, and so appear as dashed lines. Recall that mining activity is proceeding at 1000 meters depth, just below the upper dashed-line interface. Geophones appear as black dots, micro-earthquakes as colored circles, and macro-earthquakes as large black circles.
FIGURE # 34b: CORY MINE MICRO-EARTHQUAKES
FOR SIX MONTH PERIOD: 1982 JAN – JUN

Y - NORTH

Z - DEPTH

GEOPHONE LOCATION
MICRO-EARTHQUAKE DISTANCES IN METERS
CORY MINE COORDINATES

GEOPHONE LOCATION
MICRO-EARTHQUAKE DISTANCES IN METERS
CORY MINE COORDINATES
FIGURE # 34c: CORY MINE MICRO-EARTH QUAKES

FOR SIX MONTH PERIOD: 1982 JUL - DEC

- GEOPHONE LOCATION
- MICRO-EARTHQUAKE DISTANCES IN METERS
CORY MINE COORDINATES
FIGURE 34d: CORY MINE MICRO-EARTHQUAKES
FOR SIX MONTH PERIOD: 1983 JAN - JUN

Y - NORTH

Z - DEPTH

X - EAST

GEOPHONE LOCATION
MICRO-EARTHQUAKE DISTANCES IN METERS
CORY MINE COORDINATES
FIGURE # 34e: CORY MINE MICRO-EARTHQUAKES

FOR SIX MONTH PERIOD: 1983 JUL – DEC

- GEOPHONE LOCATION
- MICRO-EARTHQUAKE

DISTANCES IN METERS
CORY MINE COORDINATES
FIGURE 34f: CORY MINE MICRO- EARTHQUAKES FOR SIX MONTH PERIOD: 1984 JAN - JUN
FIGURE # 34g: CORY MINE MICRO-EARTH QUAKES

FOR SIX MONTH PERIOD: 1984 JUL – DEC

- GEOPHONE LOCATION
- MICRO-EARTHQUAKE

DISTANCES IN METERS

CORY MINE COORDINATES
The important points shown in Figures 34a through 34g are listed, figure by figure, in point form:

1. Figure 34a, 1981 OCT - DEC (October - December):
   - Most events occurred near the entry to panel 2-33, the region of active mining.
   - A few events were scattered about the rest of 2000 block.
   - One event occurred south of future panel 2-33, possibly in mining block 6000 south of the map.
   - Two events were shallow, occurring near the top of the Devonian carbonate sequence, while the rest occurred at depth, probably just above the Prairie Evaporite.
All 1981 events were located using only three geophones so that depth accuracy was very poor during this initial recording period.

2. Figure 34b, 1982 JAN - JUN (January - June):
   - One macro-earthquake occurred on January 8 at time UT 16:46:16. This was a magnitude 2.4 event which was located just west of panel 2-32. This room was mined out in the late 1981. No micro-earthquakes had occurred in this region during the previous 2 months of recording, and none occurred there again until March, 1983.
   - Events continued to occur along panel 2-33 as the room was being mined.
   - Two events occurred just south-east of the recording array, near panels 2-23 and 2-21.
One event occurred north-east of the array near panel 2-19, and one event occurred to the south-east near panel 6-10. These are both near regions where the usually uniform potash beds of the Prairie Evaporite have been locally disturbed.

All events located near or within the limits of the seismometer array occurred at depths above the Prairie Evaporite, within the Middle Devonian limestones; three near the top of the limestones (possibly in the Duperow Formation), three at intermediate depth (possibly in the Souris River Formation), and two just above the Prairie Evaporite (possibly in the Dawson Bay Formation). The only events (apparently) located below the Prairie Evaporite lie well outside the limits of the recording array. The depths of the two "deep" events must therefore be considered unreliable.

3. Figure 34c, 1982 JUL - DEC (July - December):

Only three micro-earthquakes were recorded during this recording period, far fewer than were recorded previously. The monitoring system was plagued by various difficulties in this period, which may account for some events being missed. However, there does seem to have been a general decrease in seismicity as mining slowed down during 1982.

All three events occurred near panel 2-33, in an area of previous seismicity.
- One event occurred near the top of the overlying limestone sequence. The other two events appear to have occurred below the Prairie Evaporite, but these events were recorded on only the south line of three channels, and so their depth must be considered unreliable.

4. Figure 34d, 1983 JAN - JUN (January - June):

- One macro-earthquake occurred on January 6 at time UT 02:35:04. This was a magnitude 2.6 event which was not recorded by the Cory seismometer array, and so could not be accurately located. The isoseismal map for this event is centered about the west edge of the mine, near geophones 1 and 4.

- Two events occurred near panel 2-33, a recently mined panel.

- Two events occurred in panel 2-32, very close to the location of the January 8, 1982 macro-earthquake.

- Two events occurred north-east of the array between panels 2-22 and 2-19, and one event occurred to the south-east near panel 6-10. These are both areas of geological disturbance.

- One event occurred south-west of the array, possibly in the southern regions of the mine (6000 block).

- One event occurred near the top of the overlying limestones, one occurred at intermediate depth, two occurred just above the Prairie Evaporite, and four appear to have occurred below the mine level. All of the four deep events lie outside the limits of the recording array, and so their depths must be considered unreliable.
5. Figure 34e, 1983 JUL - DEC (July - December):

- There was a period of increased microseismic activity during October, November, and especially December. No macro-earthquake was associated with this increased level of seismicity.

- Most events occurred near panels 2-32, 2-34, 2-33, and 2-35, the regions of active mining. There is a noticeable concentration of events near the west edge of the mine.

- There were six events in the region between panels 2-32 and 2-34, near the location of the January 8, 1982 macro-earthquake.

- One event occurred in panel 2-29.

- One event occurred west of the array along panel entry 2000, which was being cut during this recording interval.

- Nine events occurred at scattered depths within the Devonian limestones which overlie the Prairie Evaporite. One event appears to have occurred within the Prairie Evaporite. Five events, four of which lie outside the limits of the seismic array, appear to have occurred below the Evaporite. These five events were all located using five or six geophones.

6. Figure 34f, 1984 JAN - JUN (January - June):

- There was a very noticeable decrease in the amount of seismic activity during this recording period after the heightened level of activity throughout late 1983.
- Single events occurred near each of panels 2-33, 2-34, and 2-35, regions of recent or active mining.
- One event occurred in panel 2-29.
- One event occurred to the south-east near panel 6-10, an area of geological disturbance.
- One event occurred south-west of the array, possibly in 6000 mining block.
- Two of the events recorded occurred within the limestones overlying the Prairie Evaporite. The other four events appear to have occurred below the Evaporite, but are located outside or near the edge of the limits of the recording array. All deep events were recorded on five or six channels. One event near room 2-29 was located well south the array and just above the Prairie Evaporite.

7. Figure 34g, 1984 JUL - DEC (July - December):
- Most events (eleven) were concentrated near room 2-35 which was actively being mined during this period.
- Three events occurred near rooms 2-32 and 2-34, of which two were close to the location of the January 8, 1982 macro-earthquake.
- One event occurred along panel entry 2000 near panels 2-26 and 2-27.
- One event occurred to the west of the array, probably near the west end of panel entry 2000.
- One event occurred south-east of the recording array near panel 6-12, close to an area of geological disturbance.
Location depths during this recording period were generally deep, with twelve of the eighteen events apparently located below the Prairie Evaporite. Just two of the twelve deep events were recorded on only three channels. However, fourteen of the eighteen events recorded lie outside the limits of the geophone array.

The location results have been listed in some detail in this section, and will now be briefly summarized. Figure 35 is a map view of all events for which locations were found. It can be used to help draw more general conclusions about the seismic events that have been occurring at the Cory mine over the past forty months.

More than half of the events recorded were located outside the boundaries of the recording array. This is unfortunate since location error is significantly worse for such events, especially in the depth dimension; (as discussed in Chapter 3).

Most events occur in regions that were actively mined during the recording period, near panels 2-30, 2-32, 2-34, 2-33, 2-35, and near the west extent of panel entry 2000. Comparatively few events occurred in older mining panels.

Four events occurred to the north-east of the recording array near, or between panels 2-22 and 2-19. This is a localized region over which the generally uniform potash
FIGURE #35 : CORY MICRO EARTHQUAKES / 1981 THRU 1984

- GIVES GEOPHONE LOCATION
- GIVES EVENT LOCATION

Y - NORTH (METERS)

X - EAST (METERS)
beds have been disturbed. And four events occurred to the south-east of the recording array near panels 6-10 and 6-12. This, also, is a region of locally disturbed geology.

At least three events occurred far south and west of the seismometer array. These events probably originate in the southern regions of the mine, in mining block 6000.

The January 8, 1982 macro-earthquake occurred along the west edge of panel 2-32, (before panel 2-34 was mined). There has been a great deal of microseismic activity in this region since the macro-earthquake occurred, continuing into late 1984. But no events were recorded near the macro-earthquake location during the three months of monitoring prior to the large event.

Many events appear to have occurred below the mining horizon. Reasons can be found to discount, or at least distrust, the depth of location for most of the "deep" events; either the event was recorded on only three geophones, or it occurred some distance from the recording array. But some of the events apparently located below the Prairie Evaporite may in fact be legitimate, the events recorded on five or six channels and located within the geophone array. Of the 72 events for which locations were determined roughly half were located above the mining level and half below:
- 18 events (25%) were located near the top of the Devonian limestones, (depth < 700 m);
- 20 events (28%) were located at intermediate depth or near the bottom of the limestone sequence, (700 - 1050 m);
- 13 events (18%) were apparently located within or just below the Prairie Evaporite, (1050 - 1300 m);
- and 21 events (29%) were apparently located at depth, well below the Prairie Evaporite, (depth > 1300 m).

Gendzwill (1982 and 1983b) has suggested that the most likely mechanism for the macro-earthquakes at Cory is horizontal shear failure along planes of weakness in the carbonate rocks over the mine. The shear failure is a result of subsidence and flexure of overlying strata as mine rooms close. The 38 micro-earthquakes recorded above the mining level seem to support this hypothesis. But a shear flexure mechanism cannot explain events that occur below the mine. While subsidence is the most logical explanation for events occurring above the mine, there is no simple rock-mechanics reason for having microseismic events below the mine.

4.3 Magnitudes

The magnitude of an earthquake is a measure of the energy released by the event. There are two simple approaches to determining magnitude from an observed seismic signal. The first approach, proposed by C. F. Richter (1935), involves finding the relationship between the amplitude of
the signal measured, and the distance between the earthquake hypocenter and the seismometer station. A second approach, originally proposed by Bisztricsany (1958), is to use the duration time, or coda length, of the observed seismic signal. An excellent discussion of this method is given in Lee et al. (1981). Attempts were made at using both methods for determining magnitudes for the Cory events. However, for most events recorded at Cory it was very difficult to measure signal coda lengths accurately. A magnitude scale based on measured amplitudes was therefore considered to be more appropriate.

A number of relationships between signal amplitudes and hypocentral distance have been developed since the early work by Richter. These scales can be based on amplitudes of either surface waves ("M(s)") or body waves ("m(b)"); for a good discussion of these various methods see Willmore (1979) or Lee and Stewart (1981). The determination of earthquake magnitude " M ", (for either surface or body waves) is given in generalized form by Bath (1973, pp. 114 - 122):

\[
M = \log( A / T ) + c_1 \cdot \log( R ) + c_2
\]  \hspace{1cm} (27)

where :

- **A** = ground amplitude
- **T** = wave period
- **c_1** = a constant
- **R** = hypocentral (or ray-path) distance
- **c_2** = correction factor (also a constant).
For the geophones used in the Cory array output amplitudes measure ground velocity, (the derivative of ground displacement). Amplitudes will be left as a voltages rather than a true velocities, since geophone voltage outputs are linear with velocity (see Figure 9). Then, if it is assumed that the wave period is more or less constant for all events at all geophones, and by combining some of the constants, equation (27) can be approximated by:

\[ K = \log(A) + B \cdot \log(R) \]  

(28)

where:
- \( K \) = relative (local) magnitude
- \( A \) = ground amplitude
- \( B \) = a constant
- \( R \) = hypocentral (or ray-path) distance

Equation (28) is in the form of the equation for a straight line:

\[ k = Y - b \cdot X \]  

(29)

where:
- \( k \) = the "Y" intercept / \( K \)
- \( b \) = the slope of the line / \( B \)
- \( Y \) = the dependent variable / \( \log(A) \)
- \( X \) = the independent variable / \( \log(R) \)

Then for any one of the events recorded at Cory, a plot of \( \log(A_i) \) versus \( \log(R_i) \), \( i=1,N \) (where \( N \) is the number of geophones) should be a straight line. Furthermore, if many events are plotted in this manner the slope of all individual lines should be the same, at least in a statistical sense.
The Y-axis intercept will give the relative local magnitude for the event, and will differ from a Richter or body wave magnitude by an additive (or subtractive) constant "correction factor". Unfortunately this correction factor could not be determined for the Cory seismic monitoring array since signals were clipped for the only event recorded by both the surface array and calibrated seismometer stations, (for the January 8, 1982 macro-earthquake). Calculation of the relative magnitude "K" is still useful, however, since it allows comparison of relative magnitudes for the various Cory events.

The first step in the process involves determining the value to be used for the slope "B". B can be found from the entire data set of amplitude / distance values (for the 72 located events) using a curve fitting strategy:
- First the straight line equation (29) is fit to each of the 72 sets of points for different values of B.
- For each B value there will be a resulting error between the straight line and the measured amplitude data set.
- The B that gives the lowest error value for the complete data set will be the best-fit value for the slope.

A Simplex stepping procedure was used to determine B, giving a value of:

$$B = -1.090045 \pm 0.000001$$

(30)

The stepping procedure was tested using synthetic input.
data with excellent results before being used to find B.

Using the value for B given in (30) the best-fit Y-axis intercept, "K", can be determined for each event located. Plots of amplitude (in micro-volts) versus ray-path distance are, (as with micro-earthquake locations in section 4.2), given in Figures 36a through 36g, one figure for every six months of recording, (and with Figure 36a covering the first three months of recording during 1981). Values of K for each event are included in the legend, with the average K value for the six (or three) month time period given at the bottom of the column. For comparison, the January 8, 1982 macro-earthquake clipped signals at all stations, with peak (clipped) amplitudes of greater than 100,000 micro-volts. This corresponds to a K magnitude value of greater than 9.0 for the body-wave magnitude $m(b) = 2.6$ event. The Cory micro-earthquakes range in K value from 5.37 through 7.41, or approximately in the $-1$ to $+1$ magnitude range.

Although Figures 36a through 36g are cluttered, it should be immediately apparent in looking at the set of figures that in almost no case do the data plot along a straight line. The points are very scattered, with far geophones often having significantly larger signal amplitudes than near geophones. This scatter is not random, in that sometimes all stations to one direction of the epicenter show unusually strong amplitudes, while those to the opposite
FIGURE # 36a: 1981 OCT - DEC
MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 323 5 16 36 6.43
- 323 12 48 2 6.17
- 340 9 33 44 6.14
- 342 21 13 58 6.38
- 346 0 42 15 6.62
- 346 10 36 35 7.33
- 350 7 0 56 6.15
- 356 10 15 23 5.92
- 356 15 38 11 6.14
- 364 1 25 22 6.34
- 365 6 21 35 5.94
FIGURE # 36b: 1982 JAN – JUN
MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

\[
\begin{align*}
\square & = 23 \ 19 \ 13 \ 30 \ 6.71 \\
\diamond & = 59 \ 22 \ 23 \ 30 \ 6.81 \\
\triangle & = 76 \ 16 \ 27 \ 49 \ 6.64 \\
\ast & = 94 \ 20 \ 52 \ 0 \ 7.39 \\
\times & = 96 \ 19 \ 37 \ 55 \ 6.58 \\
\circ & = 117 \ 20 \ 44 \ 25 \ 6.36 \\
\n & = 124 \ 5 \ 6 \ 20 \ 6.46 \\
\n & = 140 \ 21 \ 46 \ 25 \ 6.02 \\
\n & = 141 \ 9 \ 24 \ 38 \ 5.99 \\
\n & = 150 \ 16 \ 48 \ 57 \ 6.86 \\
\end{align*}
\]
FIGURE # 36c: 1982 JUL - DEC
MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 205 2 51 12  6.61
- 277 17 49 23  7.41
- 353 9 3 20  6.54

LOG AMPLITUDE

LOG DISTANCE (METERS)
FIGURE # 36d: 1983 JAN – JUN

MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 56 9 56 6 6.22
- 68 10 12 57 6.67
- 86 8 59 35 5.88
- 87 14 25 0 5.59
- 149 5 45 23 7.14
- 156 77 41 56 6.29
- 164 8 15 46 6.32
- 164 10 39 35 6.34
FIGURE # 36e: 1983 JUL - DEC

MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 285 7 48 32 6.28
- 285 8 3 20 6.19
- 286 8 35 54 6.21
+ 294 7 48 47 7.20
x 301 5 4 29 6.21
* 314 12 42 47 5.87
v 326 20 57 10 6.42
- 333 1 42 22 6.00
- 337 10 53 32 5.81
* 337 11 17 6 6.04
- 338 13 4 39 5.37
- 349 19 0 46 7.08
- 351 23 41 50 6.32
- 352 4 45 23 6.46
- 353 9 36 54 6.10
* 361 23 32 26 6.07
FIGURE # 36f: 1984 JAN – JUN

MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 42 1 21 53 6.10
- 74 1 27 15 6.76
- 85 7 25 25 5.79
- 149 23 54 33 6.86
- 158 20 37 12 6.23
- 177 12 44 23 6.77
FIGURE # 36g: 1984 JUL - DEC
MICRO-EARTHQUAKE AMPLITUDE VS. RAY-PATH DISTANCE

LEGEND

- 183 16 55 44 6.00
- 193 7 0 26 6.93
- 193 17 36 53 6.76
+ 234 1 48 24 6.52
- 237 5 3 17 6.87
- 269 17 57 30 6.96
- 277 19 58 5 6.08
- 287 1 36 18 7.04
- 306 11 18 40 6.84
- 308 18 29 44 6.60
- 308 20 26 1 6.15
- 311 12 30 39 6.92
- 318 12 30 39 6.85
- 319 11 30 39 6.48
- 334 11 22 32 6.49
- 336 10 47 19 5.96
- 337 6 6 25 6.63
- 337 11 11 16 7.03
direction show unusually weak signals. Nor do the effects appear to be related to the instrumentation, since individual geophones have an equal propensity for either situation for different events. The most reasonable explanation, therefore, is that these unexpected amplitudes are the result of the micro-fracture source mechanism. In other words, the physical process that gives rise to the observed seismic signal is oriented with respect to the array of geophones. For example, a geophone situated along the strike of a fault will register stronger ground motions than a geophone set up off the line of the fault slip direction.

A histogram showing the number of events for various K magnitudes is given in Figure 37, along with the cumulative number of events greater than the specified magnitude, is plotted in Figure 38. The frequency of occurrence of earthquakes as a function of magnitude can be represented by the Gutenberg-Richter relationship (Lee and Stewart, 1981, pp. 216-218):

$$\log(N) = a - b \cdot K$$  \hspace{1cm} (31)

where: \(N\) = the number of earthquakes of magnitude greater than or equal to \(K\).

\(K\) = relative magnitude (equation (28))

\(a\) = a constant

\(b\) = a constant, referred to as the "b-slope".

The b-slope describes the rate of increase in the number of earthquakes as magnitude decreases. The value of the b-slope
is approximately 1, with observed values usually in the range 0.6 to 1.2 (Lee and Stewart, 1981, p. 216). Values for b have been noticed to vary between foreshocks and aftershocks of a major earthquake (Suyehiro, 1966, for example), and for events located in different regions of a mine (Kuzmi et al., 1982).

Fitting a straight line to the points plotted in Figure 38, which cover a 40 month recording period, gives a b-slope of 1.01. The first four points (for small K magnitude) in Figure 38 were omitted in the b-slope determination since this region of the magnitude range is considered to be inadequately sampled: it is more likely that small events were missed than larger events. Extrapolation of the straight line fit to the data set can be used to estimate how many small events were in fact missed. For example, only 69 events were recorded that were greater than or equal to magnitude 5.8, yet the extrapolated line crosses 5.8 at 125, which suggests that \((125 - 69) = 56\) events (rather than the 5 recorded) occurred in the magnitude range 5.8 to 5.95.

Extrapolating the b-slope line to the large magnitude end of Figure 38 allows estimation of how often large events can be expected to occur. The line crosses the horizontal axis, \(N = 1\), at \(K = 7.9\): events greater than or equal to magnitude 7.9 can thus be expected to occur about once every 40 months, (the duration of recording at Cory). But two
macro-earthquakes of K-magnitude 9.0 occurred in the 40 month recording period. Further extrapolation of the b-slope line suggests that events of magnitude 9.0 should occur less than once every 10 recording periods, or once every 400 months (which is 33 years). This unexpected result may be indicating that the mechanisms that cause micro-earthquakes are not the same as the mechanisms that generate the larger events.

The K value magnitudes listed in Figures 36a - 36g are plotted as magnitude of individual events, and six month running average, versus date in Figure 39. If the peaks in the running average at October, 1982 and July, 1983 are discounted a very subtle variation is apparent. Event magnitudes were greater than the average in late 1981 and into early 1982, and then below average until the fall of 1984 when event signal strengths rise above average once again. As was the case with event frequency, there seems to be a correlation of higher event magnitudes with times of higher potash extraction.
FIGURE # 39 : "K" MAGNITUDES WITH TIME
(DASHED LINE IS SIX MONTH RUNNING AVERAGE)
A seismic monitoring array was set up over the Potash Corporation of Saskatchewan Mining, Cory Division potash mine to help gain further understanding of the noticeable earthquakes that apparently resulted from mining activity. The array was operated from October, 1981 through December, 1984. Over the three year recording period, 83 micro-earthquakes were recorded and two macro-earthquakes occurred, one of which was recorded.

The local geology near the Cory mine precluded linear strategies for calculating the hypocenter locations of the events recorded. Instead a non-linear location algorithm had to be developed to describe accurately seismic energy propagation in the Cory area. A method of iterative approximation was developed to fit calculated ray-path move-out times to the arrival times measured. The problem is illustrated by introducing the idea of the errorspace, a contour map of the difference between calculated and measured move-out times, (or error), for possible locations in space; the contours close about the point giving the smallest error, which then is the "best-fit" hypocenter location. The non-linear curve-fitting strategy involves moving through the errorspace to the center of the minimum error contours. The optimization procedure that gave solutions rapidly and with a minimum of computation was a Simplex stepping procedure. The Simplex
hypocenter location algorithm that has been presented gives solutions in reasonable lengths of time. It should therefore be possible to utilize the Simplex strategy for location calculations done using a micro-computer.

A brief analysis was carried out to determine an estimate of distance errorbars for the location solutions. This involved adding error to the various synthetic input parameters, and seeing how much the added error affected the location solution. For events within the seismometer array errorbars of ± 50 meters horizontal and ± 150 meters vertical were found. These values could be much greater for events outside the limits of the array. The error analysis carried out was simple, and did not consider the effects of correlated errors amongst the various input parameters. A more exhaustive study could change the errorbar estimates given here.

Results of monitoring seismicity at Cory have been presented as an event frequency histogram, maps showing location with respect to mine workings over time, and a plot of local magnitude estimates over time. Of the 83 micro-seisms recorded locations and local magnitude estimates were determined for 72. A location was also found for the single macro-earthquake that was recorded.
There appears to be a general correlation between the number of events recorded per month and level of mining activity for that time. As the volumes mined increase, microseismic activity increases, and alternatively as mining activity slows (or stops) then microseismic activity decreases. A similar pattern appears to hold for event magnitude: events are of greater magnitude at times of increased mining activity. These perceived relationships between mining and both frequency and magnitude should be addressed more quantitatively by Cory personnel who have access to detailed mine survey records.

The inconsistencies observed in signal amplitudes for most of the events recorded present interesting possibilities. The measured signal amplitudes appear to be affected by the event source mechanism. If this is in fact true, (after more in depth study of the signal), then it should be possible to extract a strike, dip, and slip for each of the "micro-faults" that gave rise to the measured signals. Such a study might be pursued by an approach of modelling signal amplitudes, or possibly by analysing the signals in the frequency domain.

Events were for the most part located near areas of active, or recent mining. In addition, eight events occurred near regions of local geological disturbances. There was no clear correlation between micro-seismicity and the two
macro-earthquakes that occurred during the recording period. This may indicate a different earthquake mechanism for micro and macro events. However, a more probable explanation is that the pattern of seismicity observed until the end of 1981 was changed drastically throughout 1982 and 1983 when the mine went into both short and extended periods of reduced production. The microseismic data, therefore, can not at this stage be used to explain the geological processes that lead to macro-earthquakes. However, the 83 events recorded at Cory are a quantitative measure of how the earth has dynamically reacted to the potash mining activity during the period October, 1981 through December, 1984. One could, therefore, possibly use the Cory data set to predict how the earth might react to a different method of mining, specifically a long-wall or total extraction method.

A future study, to complement the data set collected using the Cory surface monitoring array, would be to monitor microseismicity using a similar geophone array set up underground.
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APPENDIX A: CORY SEISMIC MONITORING ARRAY LIST OF EVENTS:

ALL DISTANCES ARE IN METERS.

DISTANCES NORTH AND EAST ARE GIVEN FIRST IN LOCAL GEOPHONE COORDINATES, THEN IN CORY MINE PLAN COORDINATES.

<table>
<thead>
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<th>EVENT/DATE</th>
<th>#GF</th>
<th>X - EAST</th>
<th>Y - NORTH</th>
<th>Z DEPTH</th>
<th>&quot;K&quot; MAG.</th>
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<td>928 51729</td>
<td>1004</td>
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<td>284 51085</td>
<td>2788</td>
<td>6.17 (NOV19)</td>
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<td>540 51341</td>
<td>984 6.14 (DEC06)</td>
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<td>Z DEPTH</td>
<td>&quot;K&quot; MAG.</td>
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