PATTERNS OF INDUCED MICROEARTHQUAKES AT THE
SULLIVAN MINE, KIMBERLEY, B.C.

by

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ABSTRACT

In June and July of 1980 a 12 station microseismic detection network was established over a 40 km² area about the Sullivan Mine, Kimberley, B.C. for the purpose of using hypocentre locations of mining induced earthquakes to delineate the position of fault planes in 3-dimensions.

During the experiment 1551 microseismic events were recorded by 2 or more digital seismographs, but only 366 events were large enough to be recorded by 4 or more stations. A regional velocity of 5.30 kms⁻¹ was determined from calibration explosions and a 3-dimensional least squares type location program was used. Based on explosions of known location within the mine a location accuracy of 180 m in epicentral position and 500 m in focal depth was attained. Recorded microseismic activity occurred entirely within the mine bounds, centered on the active working areas. An extremely close relationship between level of microseismic activity and mining cycles was observed.

The seismic array at the Sullivan Mine was found to be unsuitable for use as a geologic mapping tool, partly because of the lack of resolution. However several interesting features of the induced microseismicity have become apparent:

(i) Influence of mining activity at the Sullivan is extremely localized, with microearthquake activity confined to the working areas.

(ii) The correlation between mine activity and recorded microseismic activity was extremely high; the majority of microearthquakes, in particular the smaller events, occurred in
the first ten minutes after large mine blasts. These appear to be cavity relaxation events.

(iii) There appears to be an association between the epicentral locations and the edges of cave areas. The only activity which may be associated with faults occurs when they are quite proximal to the cave edges; that is where tensional stresses in the hanging wall are localized along these pre-existing planes of weakness.

(iv) It is believed that regional stress conditions are unsuitable to allow fault reactivation below the mine. Geologic evidence suggests that the regional stress in the vicinity of the Sullivan is either neutral or extensional, in which case fault reactivation below the mine will be suppressed by the load removal caused by mining.
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CHAPTER 1

1.1 INTRODUCTION

Earthquake activity occurs in response to changing stress conditions in the earth's brittle lithosphere. One class of earthquakes are those induced by the activities of man.

Several types of human activity have resulted in the stimulation of earthquakes, some as large as magnitude 6.5 (Simpson, 1976). These activities have been well documented recently in several major symposia (Milne, 1976; Hardy and Leighton, 1977)

The activities are as follows:

(i) Detonation of large underground explosions:

Kisslinger (1976) discusses seismic activity following explosions such as those detonated at the Nevada Test Site by the U.S. Atomic Energy Commission. The large number of small earthquakes that begin after detonation and continue for several weeks are attributed to collapse of the explosion-created cavity (Kisslinger, 1976). Observable displacements on nearby faults are reported in only a few cases. Kisslinger (1976) states that earthquakes, other than those associated with the cavity, will occur only if the medium is already highly stressed. In such a case the explosion serves to decrease the effective principal stresses either by momentarily increasing the pore fluid pressure or by creating a transient tensile stress that reduces
the normal stress on the fault plane, thus allowing slip to occur in response to the pre-existing stress.

(ii) Fluid Injection:

Tectonic movements have been induced at a number of sites where fluid injection is taking place through boreholes, such as the Rocky Mountain Arsenal well near Denver, Colorado. In this case waste fluids were being injected into the subsurface formations at flow rates of millions of gallons per month and at pressures up to 1000 psi ($7 \times 10^6$ Nm$^{-2}$) greater than the original formation pore pressure (Kisslinger, 1976).

Earthquakes may occur when injection is carried out in areas with a pre-existing tectonic stress. Increased pore pressure will reduce the effective principal stresses thus allowing pre-stressed fault planes in the region to become unlocked.

(iii) Reservoir Impoundment:

Earthquakes are recorded during initial filling of approximately 10% of all large reservoirs (dam height $\geq 100$ m, volume $\geq 1.23 \times 10^9$ m$^3$) and subsequent activity may occur during seasonal changes in water level (Simpson, 1976). It is generally felt that there must be a pre-existing tectonic stress close to the failure strength of the faults (Gough and Gough, 1970). This is clearly the case when we see magnitude 6 earthquakes induced when the added water pressure is no more than 10-15 bars (Kisslinger, 1976). Consensus now is in favour of this activity being principally due to changes in the pore
water pressure with the increased surface load itself only playing a minor role (Snow, 1973). Kisslinger (1976) believes that the effect of stress corrosion in silicate rocks may also play a role in weakening the medium.

(iv) Mining and Quarrying:

Mining gives rise to seismic activity ranging from microseismic events of magnitude -6 to rare events of magnitude 5 (Cook, 1976). Rock failures in the mine environment may be classified into three major categories (modified from Cook, 1976).

(a) Rockfalls—loosened rock falls under its own weight, commonly called roof or hanging wall collapse. When this occurs an associated air blast is generally felt throughout the interconnected mine tunnels.

(b) Rockbursts—violent failures of rock that tend to occur when the rock is unusually strong or unfractured and thus capable of storing large amounts of strain energy. These failures may cause extensive damage to the mine workings and also have an associated air blast.

(c) Outbursts—more typical to coal mines; occur when the rapid release of gas causes rock to be ejected into the excavation.

During underground mining, local areas of high stress develop as the overburden load is unloaded from a particular area (stope) and redistributed onto the nearby pillars and surrounding walls. The areas of highest stress are thus in the vicinity of the advancing mine faces, and it is in this region
that microearthquakes due to rock fracture will occur in order to relieve those stresses (McGarr et al., 1975).

In this study, we are interested in a fourth and smaller category of mining-induced microearthquakes which occur at some distance from the mine faces along planes of weakness, such as faults, joints, bedding, and foliation planes, existing in the rock.

1.2 SELECTED PREVIOUS STUDIES OF MINING INDUCED SEISMICITY

(a) East Rand Proprietary Mine, South Africa

At the East Rand Proprietary Mine in the Witwatersrand, some of the ore removal is taking place at 3.2 km depth, which corresponds to a confining pressure of 860 bars (McGarr et al., 1975). Seismic activity is generally confined to a region between 100 m in advance of the mine face and 30 m behind it, although occasional events do occur further from the mine face and are possibly associated with faults (N.G.W. Cook, personal communication). Most of the events are observed to occur during and in the first few hours immediately after blasting. The general level of seismic activity is high except on Sundays when no mining takes place.

McGarr et al. (1975) found that the total calculated stress field only exceeded the failure strength for quartzite within a very small region, approximately 10 m radius, about the mine face which only accounts for a small number of the total observed seismic events. McGarr (1971a) observed failure in
this region as two sets of en-echelon fracture systems that
develop about 10 m in advance of the mining face and to some
extent de-stress the rock. These are usually "non-violent"
failures but may occur as explosive "bursts" if the rock is
unusually strong or unfractured and thus capable of storing
larger amounts of strain energy before giving way. McGarr et al
(1975) suggest that the remainder of the events, those more than
10-15 m away from the mining face, are the result of
differential stresses due to mining triggering the release of
stored strain energy. Strain-relief measurements in boreholes
indicate that there are regions of "locked in" residual stress
in the Witwatersrand quartzites 600 to 700 bars larger than the
ambient virgin stress.

McGarr et al (1975) used a 3-dimensional, ten station array
concentrated about the advancing mine face, with the furthest
gephone about 2 km away. The system frequency response was
from 15 to 200 Hz and timing was on a common base, thus allowing
an arrival time accuracy of 0.001 to 0.002 s. A P-wave velocity
of 5.8 to 6.1 kms\(^{-1}\) was determined from calibration blasts which
were also used to determine that a location accuracy of 20 m in
plan and 30 m in depth was possible. Event locations were
calculated using a 3-dimensional least squares approach.

(b) Sunnyside Coal Mining District of Utah

In a seismic study of an area of the Geneva coal mine,
which is under 100 m of overburden, Smith et al (1974) found the
principal concentration of focal depths to be 0.5 to 1.5 km
beneath a portion of the active mining area which exhibited
floor and roof failures. The composite fault plane solution indicated a thrust faulting mechanism, and as the solution nearly parallels the dip of the footwall shales, bedding plane failure was suggested. A distinct correlation was observed between the number of events at this site and the weekly working cycle. Smith et al. (1974) note that the solution is in general agreement with the regional stress pattern created by the tectonic development of the nearby San Rafael Swell. They suggest that the main earthquake energy is from regional tectonic stress.

Smith et al. (1974) used a 6 station surface array, deployed in a 10 km by 10 km area. Three of the stations had WWVB radio time and the remainder had crystal clocks. The total arrival time error was estimated to be in the range from 0.02 s to 0.1 s. Event location was done using a two dimensional program capable of taking into account station elevations and different surface velocity models. A three layered velocity model was used, based on geologic sections of the area.

(c) Dolomite Quarry, Wappingers Falls, New York State

Following a magnitude 3.3 earthquake at Wappingers Falls, Pomeroy et al. (1976) found the focal depths of the aftershocks to be at 0.5 to 1.2 km below a major dolomite quarry in the region.

The composite fault plane solution for the main shock and the well located aftershocks indicates a thrust mechanism which supports the presence of a north-northeast trending maximum compressive stress in eastern North America. They believe that
the earthquake sequence, and possibly past earthquakes in the area, may have been triggered by crustal unloading due to quarrying, in the presence of high horizontal compressive stress.

Pomeroy et al (1976) used a surface array of five Sprengnether MEQ-800 drum recording seismographs in a 5 km by 6 km area about the quarry. Timing was done by crystal clocks that were calibrated once per day. A timing accuracy of ± 0.020 s was estimated for impulsive arrivals. Hypocentral locations were obtained using a two dimensional program, a modified version of HYPO71 (Lee and Lahr, 1972). A uniform velocity model was used, determined by using the value for dolomite from tables.

In the latter two studies discussed above, source mechanisms were consistent with thrust faulting in the region; however the locations were not attributable to any specific faults. This volumetric distribution of the foci may however be due, at least in part, to limitations in the experimental design. In particular, limitations of the two-dimensional array geometry used, as will be discussed later, sheds doubt on the calculated focal depths.

If these type of induced microearthquakes can be located with sufficient accuracy, say within 100 m, then their location would provide a valuable aid to geological interpretation in the mine environment. The location, dip and curvature of planes of weakness such as faults, shears and fractures, pre-existent in the mine region and consequently reactivated by ore removal would be clearly delineated by zones of concentrated seismic
activity.

1.3 INTRODUCTION TO THE 1980 SULLIVAN MINE PROJECT

The basic objective of the 1980 Sullivan Mine project is to determine whether or not it is feasible to delineate fault planes using mining induced earthquakes and any natural events in the mine area. The field experiment was carried out at the Sullivan Mine which is located near Kimberley, British Columbia (Figure 1.1). The Sullivan orebody, outlined in Figure 1.2, is one of the world's greatest stratiform lead-zinc sulphide deposits with an areal extent of 3 km² and a thickness ranging from about 30 to 90 m. The orebody is surrounded by major faults and cut by numerous smaller faults. Figure 1.2 shows the four major faults bordering the ore lens; they are the Kimberley, Sullivan, Hidden Hand and Lois Creek faults. In three dimensions the ore body has the shape of an inverted saucer dipping to the north-east (Figure 1.3).

The type of mining activity taking place at the Sullivan is described by P. Ransom (personal communication, 1982):

i) Primary blasting - the initial pillar blast involving some tonnes of explosive. There is only one blast of this type per block.

ii) Secondary blasting - done while a block is producing, generally during the last half of the block's production life. One or several drawpoints are blasted at a time, generally involving 10 to 50 pounds of explosive per drawpoint. The objective is to break up large chunks of rock blocking the 6 ft by 6 ft openings.
Figure 1.1 Location of the Sullivan Mine, Kimberley, British Columbia. Kimberley is situated in the Rocky Mountain Belt of the Canadian Cordillera (adapted from Monger and Price, 1979).
Figure 1.2 Location of the Sullivan Orebody in relation to the Surface Traces of Major Faults in the Region.

- The U.B.C. seismograph network is also shown with the station locations indicated as diamonds, each with a standard three letter title. For convenience the axes on this, and all subsequent diagrams will use the mine coordinate system in feet.
The orebody is represented as a surface projection and two cross sections, one north-south and the other east-west. Seismic stations D39 and D27 are located within the underground workings.
iii) Development blasting—Involves preparation of ramps and drifts prior to ore extraction blasting.

iv) Chute blasting—If chutes become blocked and trains cannot be loaded, the hangups have to be blasted down. About 10 pounds of explosives might be used in such cases.

Explosions of the above nature will be confined to well-defined producing areas.

1.4 PREVIOUS STUDIES AT THE SULLIVAN MINE

Two previous studies conducted at the Sullivan Mine indicated that there were sufficient locatable microearthquake events to warrant a further 1 to 2 month recording program to examine the possibility of fault delineation by this means.

(a) Senturion Sciences Study

In 1971, Cominco Limited engaged Senturion Sciences Incorporated to carry out two brief microearthquake studies near Kimberley, B.C. with one test area centered on the Sullivan Mine and another on a wider area of the Rocky Mountain Trench (Senturion Sciences Inc, 1971). In the Sullivan program a 4 seismograph surface array of approximately 5 km by 5 km was operated for 8 1/2 days. During this period, a pillar blast was recorded and although details are not provided, the report implies that the origin time of the blast was known as well as the shot coordinates. Compressional wave velocities ranged from 5.03 kms\(^{-1}\) to 5.89 kms\(^{-1}\) with a mean of 5.41 kms\(^{-1}\). Velocities in their hypocentre program were then varied and the minimum deviation of the computed hypocentre from the blast location was
found for a velocity of 5.48 kms$^{-1}$. The epicentral error was 150 m and the depth error 110 m. This is a rather misleading error estimate since the velocity was allowed to vary. In subsequent hypocentral calculations, the 5.48 kms$^{-1}$ velocity was used and corrections applied to calculated hypocenters based on the errors found in the blast coordinates.

From the data collected during the Sullivan program, 24 hypocentres and 32 epicentres were determined. Interpretation of the earthquake locations in terms of structure did not agree in detail with geological thinking. However the results were sufficiently interesting to suggest that faults could be mapped using microearthquakes, provided the monitoring period was sufficiently long.

(b) UBC 1976-77 Program

During the period November 1976 – January 1977 a single chart recording seismograph was operated in the Morrison subdivision, approximately 4 km from the mining activity (Ellis, 1977). The objectives of this program were firstly to determine the rate of occurrence of locatable seismic events, and if possible the source-receiver distance and Richter magnitudes, and secondly to further examine the feasibility of using earthquakes to locate faults at this site.

The principal findings were that the occurrence rate of locatable events was about 70 per month in the range from Richter Magnitude 0.0 to 1.4 ie. similar to the rate found by Senturion; that the activity dropped very significantly on weekends when the mine was not in operation; and that the
seismicity was not highly correlated with shift end blasting periods. The upper size limit of most events was approximately magnitude 1.4, which is less than the upper size limit of 2.5 to 3.0 observed by McGarr et al (1975) for events at the East Rand Proprietary Mine.

A standard way of presenting the data is to plot event magnitude versus the log of the number of events recorded at that magnitude (log frequency). The slope of the line is known as the b-value, the higher the slope the more events recorded at the lower magnitudes versus the higher magnitudes. A b-value of -1.0 was determined for the Sullivan Mine area which is higher than those found by McGarr and Green (1978) in the East Rand Proprietary Mine. Scholz (1968) shows that the b-value is strongly dependent on the state of stress. As stress is increased the events become statistically larger, that is the b-values become lower. Although shallow it could not be determined whether the observed seismicity was closely related to the active mining faces or more broad scale. From this program it was clear that additional studies at the Sullivan Mine were required to determine whether hypocentre locations are a viable way of fault location at this site.

The UBC 1980 Sullivan Mine field experiment, which is the subject of this thesis, is a subsequent thorough investigation based on the findings of the 1976-77 program.
CHAPTER 2: THE SULLIVAN MINE

The geology of the Sullivan Mine will be dealt with from three basic aspects for the purposes of this study, ranging from the local scale to the regional scale and concentrating on the structural features. The first section discusses briefly the local mine geology and summarizes the information to date on the local faults in and around the mine area; the second section is a summary of the structural history reconstructed for the mine region; and the third section discusses on a broad scale the setting and development of the Sullivan orebody in the tectonic history of western Canada in terms of a plate tectonic model.

In order to ascertain the present broad scale stress pattern in the Sullivan Mine area, it is particularly important to understand the development of the regional stress regime through to the last extensional phase in the southeastern Cordillera which took place 55 to 5 million years before present (Ma) during the Eocene to Miocene (Price, 1977).
2.1 GEOLOGY AND STRUCTURE OF OREBODY

The Sullivan orebody is located in lower Purcell sediments of Helikan age (1500 to 1000 Ma) at the contact between the Lower Aldridge and Middle Aldridge formations (Ransom, 1977). The Aldridge formation is a 4,500 m thick stack of flyschoid sediments consisting of argillites, silts and quartz wackes ranging in thickness from fine laminae to massive units 12 m thick (Ransom, 1977). The Aldridge formation is metamorphosed to middle to upper Greenschist facies (Hoy et al, 1981).

The orebody and surrounding sediments are cut by numerous faults. The major ones are shown in Figure 1.2 and Figure 2.1 provides a more detailed picture of the faults within the mine area. The faults are classified into two major types by Ransom (1977):

(i) North dipping, east-west striking normal faults such as the Kimberley and Hidden Hand faults. The Kimberley fault dips 55°N with an apparent stratigraphic displacement of 2000 m, north side down. Dragfolds in the beds on either side of, and close to the fault indicate however that the fault was initially a thrust with the north block riding over the south. Rice (1937) explains that the fault started as a thrust, probably of no great displacement, and later when forces changed from compressive to tensile the direction of movement reversed and it became a normal fault of much greater displacement.

(ii) Northerly trending normal faults that dip steeply west, such as the Sullivan, Burchett, Smith and East faults (Figure 2.1). The faults strike 10° to 20° east of north and exhibit west side down displacements in the ore of up to 25 m
Figure 2.1 Faults within the Sullivan Mine, Footwall Trace. The dashed line indicates the orebody edge and the dotted line shows the extent of the open pit. Number adjacent to the fault trace indicate the dip of the fault plane, (modified from Hamilton et al, 1982).
with larger displacements on similarly oriented faults located east of the orebody (Hoy et al., 1981). The faults in this class are known as Sullivan-Style.

2.2 STRUCTURAL HISTORY

The structural history of the mine region is of particular interest to the present study and is summarized from various studies as follows:

(i) Northeast trending syndepositional basement faults are believed to have locally controlled the initial deposition of the Purcell sediments (Hoy, 1979). Evidence suggesting this includes local variations in sediment thicknesses, rapid lateral facies changes and intraformational conglomerates (Hoy et al., 1981, 1982) and tourmalinization near these faults (Ethier et al., 1976).

(ii) The current and most widely held model for Sullivan ore deposition is described in detail by Ransom (1977) and Hoy et al. (1981). The Sullivan deposit formed as metal-bearing solutions ascended through a synsedimentary fault and fracture system. Discrete sulphide crystals were spewed out, as well as metal ions which combined with sea water sulphate under reducing conditions to precipitate as sulphides on the Aldridge sea floor. The metal zonation, consistent with the above model, indicates deposition of lead, silver and tin closer to the vent, thought to be represented by areas of chaotic breccia, with zinc becoming more concentrated than lead further away from the vent (Hoy et al., 1981).
(iii) McClay (1981) describes three phases of faulting and folding that occurred following ore deposition; these are
Phase 1: isoclinal folds with axial planes parallel to bedding planes and north trending fold axes.
Phase 2: relatively open folds with gentle north or south plunges with westerly dipping axial planes and westerly dipping thrusts. The first two phases are of pre-early Cretaceous age and correlate with the development of the Purcell Anticlinorium.
Phase 3: folds are associated with easterly dipping thrust faults which displace Early Cretaceous lamprophyre dykes dated at 150 Ma.
(iv) The Sullivan-style normal faults shown in Figure 2.1 cut all the earlier features and are believed to be due to regional extension during the Eocene (K. McClay, personal communication, 1981)

2.3 SETTING IN THE TECTONIC HISTORY OF WESTERN CANADA, A PLATE TECTONIC MODEL

The Canadian Cordillera consists of five distinct geological and physiographic provinces or belts (Figure 1.1) which are, from east to west; the Rocky Mountain Belt, Omineca Crystalline Belt, Intermontane Belt, Coast Plutonic Complex and Insular Belt. The belts form sub-parallel zones occupying much of British Columbia from the edge of the North American craton, located roughly at the B.C.-Alberta border, to the present coastline.

With the exception of the Rocky Mountain Belt, the present
configuration of the remainder of British Columbia is believed to be due to the collision and accretion of allochthonous terranes rafted in from the south-west (Monger and Price, 1979).

Evolution of the Canadian Cordillera began approximately 1500 Ma in the middle Proterozoic with initial Atlantic-type rifting of an older Precambrian continental land mass into the North American craton and its counterpart, the Siberian Platform (Monger and Price, 1979).

Figure 2.2 spans the time period from middle Proterozoic (1500 Ma) to mid Triassic (230 Ma) and summarizes, in simplified form, the material presented by Monger et al (1972), Monger and Price (1979), and others. Figure 2.2 shows schematically the initial formation of tensional rift blocks (in parts A and B) during the middle Proterozoic; progradation from the North American continental margin of a north-easterly tapering miogeoclinal wedge of Purcell sediments which discordantly overlaps earlier structures of the cratonic basement (parts B and C); continued progradation of the Windermere sediments during the later Proterozoic until the Middle Devonian, 380 Ma (part D); subsidence of the craton edge during the Late Devonian followed by the onlap of carbonate shale and chert facies stratigraphically on top of the older miogeoclinal strata (part E).

It is interesting to note that the duration spanned by Figure 2.2 represents over 4/5 of the total time of formation of the Cordillera of western Canada as it stands today.

The origin of a change from basically extensional to a compressional regime with overthrusting and subduction as shown
Domal uplift, formation of Atlantic-type tensional rift blocks sometime before 1500 Ma.

Development of a north-easterly tapering wedge of Purcell Sediment prograding from the North American cratone (Modern analogue: East African rift system).

Continued progradation of the Purcell during the middle Proterozoic; development of sea floor; intrusion of basic volcanics. (Modern analogue: Red Sea).

Truncation of the Purcell, continued deposition of Windermere sediments west of the Purcell from the later Proterozoic until the Middle Devonian, (-380 Ma).

Subsidence of the craton possibly due to movement away from the spreading ridge; onlap of shale and carbonate facies of the Late Devonian to Middle Triassic (380 - 230 Ma).

Figure 2.2 Schematic Evolution of the Canadian Cordillera (1500 - 230 Ma), based on the descriptions of Monger and Price, 1979.
1. Development of westerly thrusting, or subduction under the North American craton; possibly in response to initial opening of the Atlantic Ocean prior to 165 Ma.

2. Emplacement of the Stikine and associated terranes in the period from latest Triassic to Middle Jurassic (230 - 165 Ma).

3. Associated intrusion of granitic rocks in the Omineca Crystalline Belt during the Middle to Late Jurassic.

4. Emplacement of Wrangellia during the Middle Jurassic to Middle Cretaceous (165 - 95 Ma).

5. Associated intrusion of granitic rocks in the Coast Plutonic Complex during, and just prior to, the Late Cretaceous to Paleocene interval (95 - 20 Ma).

6. Associated folding and thrusting in the Rocky Mountain Belt.

Figure 2.3 Schematic Evolution of the Canadian Cordillera (230 - 95 Ma). The plan map shows the present configuration and areal extent of the major allochthonous terranes, modified from Monger et al, 1972; Monger and Price, 1979.
in Figure 2.3 is uncertain. This change occurred sometime in the period from latest Triassic to Middle Jurassic (230 Ma to 165 Ma) which is roughly coincident with the initial major opening of the Atlantic Ocean at about 165 Ma (Monger and Price, 1979). Monger and Price (1979) feel that these compressional features may reflect relative plate motion changes between the North American Plate and oceanic plates to the west in response to the opening of the Atlantic Ocean. They describe two major accretion events, each one followed by westward stepping of the subduction zone. This is idealized in Figure 2.3. Emplacement of the first exotic terrane, the Stikine Block (located almost wholly within the present Intermontane Belt) occurred in latest Triassic to Middle Jurassic (230 to 165 Ma) with associated uplift and intrusion of granitic rocks in the Omineca Crystalline Belt in the Middle and Late Jurassic (165 to 140 Ma), (Figure 2.3 parts 1,2,3) The second exotic terrane, Wrangellia (located in the Insular Belt) was emplaced during the Early Cretaceous (140 to 100 Ma) accompanied by uplift and subduction related magmatism in the Coast Plutonic Complex (Figure 2.3 parts 4,5). This was accompanied by major crustal shortening in the form of imbricate thrust faulting and folding in the Rocky Mountain Belt (Figure 2.3 part 6).

Figure 2.3 spans the period from Late Triassic to Late Cretaceous (230 to 95 Ma) after which time "widespread subduction of oceanic crust ceased and a transform boundary was established, now represented by Queen Charlotte - Fairweather fault system" (Monger and Price, 1979).

During Eocene, Oligocene and Miocene time (55 to 5 Ma)
regional extension, possibly in response to the cessation of subduction, led to the formation of listric normal faults, offsetting older structures in the Cordillera of southeastern British Columbia (Price, 1977).

Summary

(a) The Sullivan orebody is believed to have been hosted in the deepwater portion of the Atlantic-type continental terrace wedge of Purcell sediments prograding from the ancient North American craton during the period represented by Figure 2.2 C (Ransom, 1977).

(b) The phases of compressional deformation in the Sullivan from pre-Early Cretaceous to late-Early Cretaceous, described by McClay (1981), are coincident with emplacement of Wrangellia during the Middle Jurassic to Middle Cretaceous, and consequent deformation in the Rocky Mountain Belt.

(c) K. McClay (personal communication, 1981) believes Sullivan-style normal faulting occurred in response to regional extension in the south-eastern Cordillera during the time from the Eocene to Miocene described by Price (1977). It is possible that the change from thrust to normal motion along the Kimberley fault, as described by Rice (1937), was also facilitated at this time.
2.4 ANALYSIS OF CONDITIONS NECESSARY FOR FAULT REACTIVATION AT THE SULLIVAN

Let us now examine the possible mechanisms of fault reactivation that would generate microearthquake activity in the mine environment. Figure 2.4 explains intuitively how we would expect microearthquake activity to be induced by mining. As the ore is removed, material will move into the void space from both above and below. Above the orebody, collapse will occur along normal faults which may be pre-existing planes of weakness, although their distribution is generally controlled by the stopes below. The surface expressions of the larger of such occurrences are oval shaped depressions of concentric,
en-echelon normal faults. Below the orebody, material will move upwards by reverse faulting in response to the decreased overburden pressure. The microearthquakes will locate where stress release, in the form of rupture and sliding, occurs; and it is logical to assume that this movement will occur along pre-existing planes of weakness. Note that Figure 2.4 ignores those fracture-generated events, discussed earlier, that occur at the immediate mine faces in response to the load strength of the rock being exceeded in these highly stressed regions.

A more detailed look at the magnitude of the stress changes involved at the Sullivan Mine can be considered firstly by estimating the distributed load removed.

\[
\begin{align*}
\text{Total mass removed} &= 114,000,000 \text{ tonnes} \\
&(1920-1980) \\
&= 11.4 \times 10^{10} \text{ kg} \\
\text{Area of Mine} &= 3 \times 10^6 \text{ m}^2 \\
\text{Force} &= \text{mass} \times \text{gravitational (9.8 ms}^{-2}) \text{acceleration} \\
&= 11.4 \times 10^{11} \text{ newtons (N)}
\end{align*}
\]

The force acting in an upward direction perpendicular to the rock surface over an area of \( 3 \times 10^6 \text{ m}^2 \) means a distributed load removed of \( 4 \times 10^5 \text{ Nm}^{-2} \) or 4 bars. This figure is of the same order of magnitude as that of 7 bars calculated by Pomeroy et al (1976) for the distributed load removed from Wappingers Falls Quarry in a 20 year period; and also that of about 7 bars calculated by Gough and Gough (1970) for the downward normal stress under the deepest part of Lake Kariba formed by the damming of the Zambezi River in Africa. These figures, however, are significantly less than the load applied
by an average woman (mass 60 kg) wearing stiletto heels (each of 1 cm² area), that is 30 bars.

This is as far as researchers like Gough and Gough (1970) and Pomeroy et al (1976), dealing with only surface loading and unloading, could carry their calculations; the induced stresses alone are insufficient to cause failure. The implications of their findings will be discussed later.

In the case of an underground mine the differential stresses between various areas will be far higher. For example, at a particular point in, say, the floor of a large stope, the pressure removal corresponds not only to the removal of the column of ore but also the unsupported column of rock above that point. An increased stress is of course felt elsewhere in nearby pillars (Figure 2.5).

In the deeper parts of the Sullivan at 900 m depth the weight of a 1 m by 1 m column of rock of density 2.5 gm cm⁻³ is \(2.25 \times 10^6\) kg. The pressure it applies is \(2.25 \times 10^7\) Nm⁻² or 225 bars. So for a stope to pillar ratio of 1 to 1 there could be a load difference of up to 500 bars between certain points. This is now within the range of the shear failure strength of quartzites (Jumikis, 1979, p.108). It seems that sliding could occur particularly if pre-existing planes of weakness do exist.

Pomeroy et al (1967) and Gough and Gough (1970) suggest that the man-made activity is merely a trigger for earthquake activity observed at each of their study areas. Smith et al (1974) and McGarr et al (1975) arrive at the same conclusion in order to explain the seismic events observed away from the mining faces. A necessary criterion is either the pre-existence

of stored strain energy from a previous stress, tectonic or otherwise, or a presently active stress pattern.

Figure 2.6 shows the configurations of the tectonic stress field that would allow fault reactivation in the case of a load removal, such as caused by mining or surface quarrying. The diagrams show the Navier-Coulomb failure envelope given by the equation (Jumikis, 1979),

OVERLEAF:
FIGURE 2.6 Regional Stress Configurations necessary to allow Fault Reactivation due to Unloading. The stippled areas represent orebodies and the non-stippled areas indicate that the ore has been removed. The effect of unloading on the different possible stress configurations (A, B & C) is indicated by the dashed Mohr circles.
A. REGIONAL COMPRESSION
   \( \sigma_1 \text{ HORIZONTAL} \)
   WITH REMOVED LOAD

   \( \sigma_3 \)
   \( \sigma_1 \rightarrow \leftarrow \)

   \( \sigma_3' = \sigma_3 - \text{LOAD} \)

   THRUST FAULTING

B. REGIONAL COMPRESSION
   \( \sigma_1, \sigma_3 \text{ HORIZONTAL} \)
   WITH REMOVED LOAD

   \( \sigma_2 \)
   \( \sigma_1 \rightarrow \leftarrow \)

   \( \sigma_2' = \sigma_2 - \text{OVERBURDEN LOAD} \)

   STRIKE SLIP

C. REGIONAL TENSION
   \( \sigma_1 \text{ VERTICAL} \)
   WITH REMOVED LOAD

   \( \sigma_1' = \sigma_1 - \text{LOAD} \)

   NORMAL FAULTING SUPPRESSED
$$\tau = \tau_0 + \mu \sigma$$

where, $\tau = \text{the applied shear stress}$

$\sigma = \text{the applied normal or axial stress and}$

$\tau_0$ and $\mu$ are rock dependent parameters determined from loading experiments. The difference between the maximum and minimum principal stresses, $(\sigma_1 - \sigma_3)$, is also indicated in Figure 2.6 as the diameter of the Mohr circle. Three situations may occur (Figure 2.6 parts A, B & C):

A. In the case of an initial compressive regional stress (maximum principal stress $\sigma_1$, horizontal) uniform unloading due to mining activity would serve to decrease the downward directed minimum principal stress $\sigma_3$, enlarging the diameter of the Mohr circle until it becomes tangent to the Navier-Coulomb envelope at which point failure occurs by thrust faulting. An increased load in this case would merely serve to stabilize the situation by increasing $\sigma_3$, and thus decreasing the radius of the Mohr Circle.

B. In the case of both $\sigma_1$ and $\sigma_3$ being in the horizontal plane with $\sigma_2$ acting downwards, a load removal, or decrease in the effective overburden pressure, has the same effect as lowering the confining pressure. $\sigma_1 - \sigma_3$ remains the same but the Mohr circle is displaced towards failure which would occur by strike slip faulting.

C. For an area under regional tension, that is $\sigma_1$, acting vertically, a decreased load will cause an effective decrease in $\sigma_1$ with respect to $\sigma_3$, reducing the radius of Mohr's circle and driving the system towards stability. Normal faulting will be suppressed, rather than triggered by this situation. An
increased load would be necessary to permit normal faulting in this case.

Unloading thus will allow triggering of thrust type events, as seen by Pomeroy et al (1976) and Smith et al (1974), or strike slip; whereas it will inhibit failure by normal faulting.

It is important to remember that in the case of reservoirs, the effect of the loading is considered secondary to that of pore water pressure (Snow, 1973). In permeable rocks there may be an increase in pore water pressure which causes the effective principal stresses to be reduced. Both normal and strike-slip faulting may be triggered during reservoir filling.

Summary

In summary, fault reactivation may occur at the Sullivan Mine due to differential shear stresses along planes of weakness close to the mine faces. Failure by thrust faulting below the mine will only occur if regional stress is present and if it is compressive, that is with the maximum principal stress being horizontal. If regional stress is not present, the unloading due to mining activity alone is insufficient to reactivate thrust faulting.
3.1 OBJECTIVES

Based on previous studies and discussion with Cominco personnel, the 1980 field experiment was designed with the following specific objectives in mind:

(i) to determine hypocentre location capability using known explosions;

(ii) to examine the distribution of events with respect to the active mine areas;

(iii) to determine the relationship between the level of microseismic activity and periods of mine activity;

(iv) to accurately locate those events away from the immediate mine faces and determine if faults can be delineated.

(v) To examine focal mechanisms and determine whether they indicate the presence of a pre-existing regional stress pattern as well as mining induced stress.
3.2 THE FIELD EXPERIMENT

The field program at the Sullivan Mine was conducted in the period from June 2 to July 17, 1980. Site inspections were carried out on the first day and the seismograph array, consisting of 7 digital and 5 analog stations was established in a 9 km by 6 km area about the mine within the following six days. By June 10 the network was operating smoothly and data was collected at a high rate in the following 4 weeks. The areal distribution of the seismographs is shown in Figure 1.2. The geophone location at each site was surveyed in to a known control point in the mine reference grid so that the error in station location is no more than about 6 m (20 feet). Station co-ordinates in terms of the Sullivan Mine grid and descriptive locations are given in Table 3.1. The immediate mine area was well surrounded by a 3 km by 3 km inner net of stations (D39, D27, PMP, NAD, LOI, and PIT, shown in Figure 1.2) as it was anticipated that many of the events would occur in that region. Seismographs D39 and D27 were located in the mine workings (Figure 1.3) with D27 being as deep as possible, some 600 m below the surface. The underground stations were necessary to improve the focal depth resolution since 2-dimensional surface arrays only provide weak constraints on the calculated focal depths. An outer net of stations (SUL, MOR, NCN, MAT and BOG) increased the region of coverage around the mine and extended it asymmetrically westward. This was felt to be important as the Kimberley Fault is a major regional fault that extends to the west in this area (Figure 1.1) and its delineation could be of economic interest. Mining induced stress would not be great
<table>
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<tr>
<th>STATION</th>
<th>LOCATION</th>
<th>INSTRUMENTATION*</th>
<th>REGION</th>
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</thead>
<tbody>
<tr>
<td>X (ft)</td>
<td>Y (ft)</td>
<td>Z (ft)</td>
<td></td>
</tr>
<tr>
<td>SHF</td>
<td>3940</td>
<td>9020</td>
<td>3900</td>
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</tr>
<tr>
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<td>16860</td>
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</tr>
<tr>
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<td>-850</td>
<td>4190</td>
</tr>
<tr>
<td>MRK</td>
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<td>12185</td>
<td>4630</td>
</tr>
<tr>
<td>BOG</td>
<td>-14250</td>
<td>16427</td>
<td>5457</td>
</tr>
<tr>
<td>PIT</td>
<td>2908</td>
<td>7690</td>
<td>4638</td>
</tr>
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</table>

* D - Digital Geotech MCR 600 Seismograph  
A - Analog FM Tape Recording Seismograph

Table 3.1 Seismograph Locations in terms of the Mine Coordinate System.
enough to allow fault reactivation at this distance from the mine, as indicated by the selected studies in other mining areas. However, if there is any natural movement at present on any fault away from the influence of the mine, we would like to be able to locate the associated seismic activity as accurately as possible. Calculations based on the "continental area" (Vancouver Island, Puget Sound and Lower Mainland as defined by Milne et al., 1978), indicate the unlikelihood of recording any such natural events during the period of the experiment. For a 9 km by 6 km area (the size of the study area) we would expect only 1 event of magnitude zero or greater per 10 years.

A Sprengnether MEQ-800 drum recorder was maintained at station NCN for the duration of the experiment so that rapid visual observations of events could be made. In particular, their character, relative size and timing with respect to the background mine activity levels, could be seen at a glance. For example, shift break blasts occurred at scheduled times, were larger than the other events and their arrivals typically showed a maximum amplitude within the first few cycles (front end loaded).
3.3 ARRAY INSTALLATION AND MAINTENANCE

The areas for each site were carefully selected with the lowest possible cultural and background noise. Each seismometer was installed on bedrock, thus minimizing local natural noise and ensuring the best coupling to the ground. For the stations in the mine, sites were chosen in areas away from mining activity. At one stage reoccupation of the 3920 shifters station by mine workers required temporary resiting of SHF to D39. Where possible, the seismometer cable was raised off the ground and run through the trees after several disconnections as a result of animals gnawing the wires. The recording system and power supply, two 12 volt car batteries, had to be roped together as bears were causing disturbances and terminating recording by moving or overturning the equipment at all but the two underground sites. Further, repellent was sprayed on the equipment casings following repeated attempts by porcupines to eat the wooden battery and amplifier boxes at one site. The stations were covered with plastic sheeting to keep out moisture and aid camouflaging.

The analog sites required servicing every 5 days to change tapes and batteries. The digital systems however required more constant maintenance as sufficient events were recorded to fill up the tapes every 2 to 3 days. Also the crystal clocks had a significant drift rate (Appendix 1) such that it was desirable to visit the sites as often as possible, and at most 2 days apart, to calibrate the clocks with WWV radio time. The digital systems in the mine were visited twice a week. As radio reception was impossible underground, their clocks were set by
carrying in another system that was calibrated to WWV immediately prior to, and following the underground visit. The drum recorder required a daily chart paper change.

3.4 INSTRUMENTATION

(i) Analog Systems: The output of a 1 Hz seismometer is amplified and presented to a 7-channel FM tape recorder at 4 gain levels separated by 12 db to extend the basic 35 db dynamic range of the recording system. The maximum gain setting was chosen to bring the seismic background noise well above the tape noise level. Primary timing is by recording of WWVB signal with secondary timing provided by a crystal controlled clock in case of the radio signal fading. The frequency response of this system is shown in Figure 3.1 A. One disadvantage of this system is the extended low frequency response. The sharp high frequency onsets therefore ride on top of the longer period energy.

(ii) Digital Systems: The digital seismographs are Geotech MCR-600 digital event recording seismographs with 72 db dynamic range for which input was provided by 1 Hz seismometers. The sampling rate was set at 150 Hz and passbands either 5 to 25 Hz or 10 to 25 Hz. The frequency response of this system is shown in Figure 3.1 B. Typically the criterion used for event detection was that the short term (0.213 s) average to long term (6.83 s) signal ratio was greater than or equal to 6. This provided high quality records and filled digital tapes at a maximally serviceable rate (i.e. every 2 to 3 days). This was our first field deployment of these new digital instruments and
A Velocity sensitivity of UBC FM System at amplifier gain of 106 db (i.e. HI = 94 db).

B Velocity sensitivity of UBC GEOTECH MCR 600 system at 90 db gain for low-cut frequencies of 5 Hz and 10 Hz as used in the experiment.

Figure 3.1 Velocity Sensitivity of UBC Seismograph Systems.
indeed one of the earliest applications of MCR-600's. As expected, some time was spent defining the appropriate parameters for triggering and several technical problems arose, typical of early model equipment (our lowest serial number was 006).

In a microseismicity experiment, the weakest part of the system is the crystal clock which systematically drifts due to temperature variation and aging of the crystal. The drift measurements made on Unit 008 are shown by the symbols in Figure 3.2. A typical drift rate of about 0.050 s per day is observed with significant variations from linearity. During the data processing, the observed time of each first arrival was corrected assuming linear drift between time checks. Appendix 1 shows that this assumption is adequate with respect to crystal aging and also linear drift due to departure of the mean temperature from the crystal calibration temperature. The problems arise due to the diurnal temperature cycle which is undersampled and not obviously visible in Figure 3.2. For example the climatological data for Kimberley suggest a daily sinusoidal-like variation with an amplitude of 0.013 s. Variations of the mean daily temperature cause errors of similar size. Thus the clock drift curves of Figure 3.2 are explainable in terms of thermal drift plus aging. The errors introduced by these variations are of the same order as measurement errors for the digital systems (discussed in Section 3.6).
Clock Drift

Figure 3.2 Clock Drift Curve for Digital Unit 008 at PMP. Symbols indicate times at which the drift was monitored using WWV radio time. The lines are linear interpolations of the drift rate from which arrival time corrections were made.
3.5 DATA EDITING

The data recorded during the field experiment was contained on 83 digital cassettes and 38 analog tapes i.e. about 13,600 station records in digital form and 190 station days of continuous analog recording. This presented a formidable data handling problem and required significant programming, particularly since it was the first experiment with the digital systems.

As the inner network consisted largely of MCR-600 units and due to the relative ease in data handling, the digital data was processed first. The cassettes for each station were sequentially transferred onto standard 9 track digital tape. The 21 byte record headers which contain the record start times were then stripped into a computer working file. This allowed a search between sites for coincident events (i.e. those whose record start times were within 5 seconds of each other) and subsequent regrouping of the records onto a tape by event rather than station, with only the first 8 second record of each event retained. Since 4 observations are needed to locate an event and the analog stations were generally on the periphery of the array, only the 366 events recorded on 4 or more digital seismographs were used in the analysis. These events have been digitally plotted.

The estimated time to find and then play back these events from the analog tapes is about 200 hours with comparable time required for basic analysis. Therefore, only critically located analog stations have been played onto chart records. Station PIT (see Figure 1.2 p 10.) was initially played back due to its
critical location at the southern end of the inner net. It was a particularly important southerly constraint as the NCN digital station was malfunctioning for most of the experiment. Station MRK was required as a westerly constraint, then SUL was also played back for about a third of the events in order to show that hypocentre locations would not be moved significantly by addition of a further arrival time. It also provided a northerly constraint for those events locating in the vicinity of, and beyond, D27. The effect of station constraint on event locations will be further discussed in later chapters. Figure 3.3 is an example of the data available for one event which shows 7 digital and 3 analog records. As expected, arrivals recorded on the analog systems contain lower frequencies.

Preliminary analysis of the data involved
(i) picking and reading P-wave arrival times, and S where possible
(ii) making clock drift corrections to those arrival times at digital stations
(iii) determining the first motion of the P-waves.
Figure 3.3 Typical Event recorded by 7 digital and 3 analog stations. The time scale is in seconds, note that the analog recordings (SUL, MRK and PIT) consist of lower frequencies.
3.6 ERRORS IN EVENT ARRIVAL TIME MEASUREMENTS

Digital records are plotted at a scale of $1" = 1 \text{s}$ and with a $0.02"$ measuring scale sharp onsets can be picked to $0.01 \text{s}$ or better i.e. approaching the sample interval of $\Delta t = 0.0066 \text{s}$. In the case of less sharp, but still good, arrivals the error band could be as large as $0.020$ to $0.030 \text{s}$, that is $\pm 0.015 \text{s}$. Another source of error arose from a paper stretch of $0.3\%$ and as most events occur in the first $3 \text{ seconds}$ of the plot there is an error of $0.00$ to $0.01 \text{s}$ or $\pm 0.005 \text{s}$. Coupled with the error due to the nature of the crystal clocks as discussed earlier, the total error in arrival time for good digital records is $\pm 0.03 \text{s}$.

Analog records are played back at $4 \text{ mm} = 1 \text{s}$ and using the $0.016"$ scale and a magnifying glass on the analog records, the reading error, or half the smallest measuring unit is, $\pm 0.01 \text{s}$. Chart pen thickness of $0.01 \text{s}$ made it impossible to pick sharp arrivals and time channel deflections to better than this. Another source of error was due to possible pen misalignment, between channels. These factors lead to a total arrival time error of about $\pm 0.03 \text{s}$ which is similar to that for the digital arrivals.

We note that $0.03 \text{s}$ corresponds to a P-wave propagation distance of $160 \text{ m (500' )}$ assuming a velocity of $5.3 \text{ kms}^{-1}$.

Errors in the arrival times for S-waves tended to be higher due to the difficulty in seeing their first arrival, often buried in the P-waves coda.
3.7 INSTRUMENT POLARITIES

Instrument polarities were calibrated using the test blasts and other large mine explosions. As expected, a positive polarity or compressional first arrival was generally observed at each station with the exception of the two underground stations, D39 and D27. They recorded negative polarities in the cases when they were located below the level of the explosion; that is since the cavity containing the seismometer is small with respect to the P-wavelength (discussed in Chapter 5) the whole cavity and seismometer have an initial displacement downwards.
CHAPTER 4: VELOCITY MODEL FOR THE SULLIVAN MINE AREA

In this chapter the basis of a uniform velocity model for the Sullivan Mine area is analysed and the suitability of the model for use in the hypocentre location program is justified. A safeguard against error that may be introduced due to geologic structure is discussed in terms of a station weighting factor; and the possible effect of mine workings on seismic wave propagation is examined.

4.1 DEVELOPMENT OF A UNIFORM MODEL

During the period of the experiment, four test explosions were used to obtain a velocity model for the Sullivan Mine area.

T1: June 20, 1980 Open Pit blast (4475, 8120, 4485) recorded at 9 stations (Figure 4.1).

T2: July 3, 1980 Open Pit blast (4360, 8140, 4485) recorded at 8 stations (Figure 4.2).

T3 & T4: July 8, 1980 Two timed blasts at #10 pit (-3550, 9900, 4587), the first being recorded by 9 stations and the second by 8.

As the location was the same for both #10 pit blasts, and the origin time known, both were plotted on the same travel time diagram (Figure 4.3). Only the location, and not the origin time, is known accurately for the open pit blasts.
Figure 4.1 Travel-Time Diagram for the June 20, 1980 Open Pit Blast.

The time intercept is unknown but was arbitrarily set to zero as the explosion was in solid rock. The height of the symbols indicate the probable error or uncertainty in the arrival time.

**T1: Open Pit Blast**

- **VELOCITY** = 5.54 ± 0.19 km s⁻¹
- **TIME-INTERCEPT** = 0.000 ± 0.013 s
- **PROBABLE ERROR OF DATA POINTS** = 0.011 s
Figure 4.2 Travel-Time Diagram for the July 3, 1980 Open Pit Blast.
The time intercept is unknown but was arbitrarily set to zero as the explosion was in solid rock. The height of the symbols indicate the probable error or uncertainty in the arrival time data.

VELOCITY = 5.25 ± 0.09 km/s
TIME-INTERCEPT = 0.000 ± 0.009 s
PROBABLE ERROR OF DATA POINTS = 0.011 s
Figure 4.3 Travel-Time Diagram for the July 8, 1980 Number 10 Pit Blasts. The blasts were monitored so the origin time is known exactly. The height of the symbols indicate the probable error or uncertainty in the data.

VELOCITY = 5.28 ± 0.15 kms⁻¹
TIME-INTERCEPT = 0.034 ± 0.018 s
PROBABLE ERROR OF DATA POINTS = 0.019 s
We will assume for simplicity that in the following analyses we can ascribe the uncertainty of the measurement totally to the dependent parameter (travel time). This is a valid assumption as the instrumental and reading error in the arrival time calculation is about an order of magnitude more than the error in station and test explosion locations. That is 50' or 0.0028 s error in station location compared with 0.030 s, the total arrival time error.

A standard least-squares approach was used to fit a straight line to the data points in the time-distance graphs. The velocity, time-intercept and probable error of the data points were determined using standard procedures (Bevington, 1969).

Figures 4.1, 4.2 and 4.3 show the travel time diagrams for the four test explosions and the results of the least squares fit. A time intercept of 0.034 s was found for the #10 pit explosions, as they were located in an area of poorly sorted, unconsolidated glacial material. Assuming a reasonable velocity for the glacial material of $v_0 = 1.5$ to $1.8$ kms$^{-1}$ overlying solid rock with $v_1 = 5.3$ kms$^{-1}$, then its thickness can be easily calculated as follows:

$$z = \frac{t_1}{2} \frac{v_0 \cdot v_1}{\sqrt{v_1^2 - v_0^2}}$$

$$= 27 \text{ m to 33 m}$$

Thus the glacial debris extends to a depth of about 30 m (100 ft), assuming the simple two-layer case described above is valid. The time intercepts for the open pit explosions were arbitrarily set to zero, and that point taken to be the origin time as both open pit blasts occurred in solid rock.
An independent estimate of the error in the data can be determined from the data itself by its own scatter (Bevington, 1969). That is, if we assume that the uncertainties are all instrumental, hence the standard deviation for all data points are equal, then we can estimate them from the data. The uncertainty or standard deviation of the arrival time data is indicated in Figures 4.1, 4.2 & 4.3 by the size of the data point symbol. The total height of each symbol is equal to twice the probable error (where P.E. equals 2/3 the standard deviation) to indicate that the true arrival time value lies within plus or minus the P.E. with a probability of 50%. This figure (± 0.01 to ± 0.02 s from Figures 4.1, 4.2 & 4.3) will only be a rough estimate of the true error in data as the standard deviations for the data points are in reality not equal. Since a uniform velocity model has been chosen for the region, part of the probable error for each point that we have assumed to be instrumental will in fact be due to variations in the geologic structure.

A mean regional velocity for the Sullivan Mine area was calculated as a weighted average (Bevington, 1969). The slope of the line $a_k$, determined for each test event, is weighted by the inverse of its own variance $\sigma_{a_k}$ in the sum.

$$a' = \frac{\Sigma (a_k/\sigma_{a_k})}{\Sigma (1/\sigma_{a_k}^2)} = 0.1886 \text{ km}^{-1}\text{s}$$

$$\sigma = 1/a' = 5.30 \text{ km}^{-1}\text{s}$$

The mean slope has a variance given by,

$$\sigma_{a'}^2 = \frac{1}{\Sigma (1/\sigma_{a_k}^2)} = 0.0025$$
so we have a P-wave velocity, $c = 5.30 \pm 0.07 \text{ kms}^{-1}$

Unfortunately an S-phase was either absent or very difficult to observe on the test explosion records, as is expected for an explosive source. Therefore the relationship $\beta = c/\sqrt{3}$, corresponding to a Poisson's ratio of 0.25, was used yielding an S-wave velocity, $\beta$, of 3.06 kms$^{-1}$. This seems a reasonable value to use as a summary of crustal Poisson values indicate a range from 0.23 to 0.26 (Cumming et al, 1979).

4.2 JUSTIFICATION FOR A UNIFORM VELOCITY MODEL: DISCUSSION OF DEVIATIONS DUE TO GEOLOGIC STRUCTURE

Geologic variation will lead to a systematic departure of arrivals from the straight line of the uniform velocity model. For example in the case of the #10 pit blasts. (Figure 4.3), arrivals recorded at MRK, BOG and SUL are consistently early which suggests that the travel paths to these stations, north of the Kimberley Fault are through slightly higher velocity material.

Travel time compensation corrections may be applied in the hypocentre location program, to those points that depart from the straight line by more than their probable error, (the probable error being consistent with the record reading error of 0.01 to 0.02 s). Table 4.1 lists the departure of P-wave arrival time at each station from the uniform velocity curve for each test event. Those that depart from the straight line by more than the probable error are underlined and it will be assumed that such departures are due to real geological variation.
Care must be taken when attempting to compensate for departures from the regional velocity as different travel paths to the same station will yield different velocity estimates. Thus for the stations in the immediate mine area, (D27, D39, SHF, PIT and NAD), where the events are likely to be at various orientations with respect to the stations, a meaningful correction cannot be applied. This is apparent in Table 4.1; travel time corrections for the closer stations are inconsistent in sign and magnitude between the different test event locations.

For stations outside the immediate vicinity of the mine area the travel path will not vary much over the whole zone in which the majority of events are expected to occur and the corrections are consistent between the different test event locations (Table 4.1).

Since most of the events occur in the mine area, the magnitude of the travel time corrections from the nearby open pit blasts (T1 & T2) are more meaningful. The average corrections for the open pit blasts exceed the probable error of the data points in three cases:

- MOR: +0.014
- LOI: +0.017
- MRK: -0.015

and it is these that were tried in the hypocentre location program.

Figure 4.4 shows the location of hypocentres for test events calculated both with and without travel time corrections. There is a systematic shift in the epicentral (x,y) position;
<table>
<thead>
<tr>
<th>STATION NAME</th>
<th>TRAVEL TIME CORRECTION (Milliseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHF</td>
<td>T1 -0.012</td>
</tr>
<tr>
<td></td>
<td>T2 +0.019</td>
</tr>
<tr>
<td></td>
<td>T3 +0.029</td>
</tr>
<tr>
<td>D27</td>
<td>T1 -0.022</td>
</tr>
<tr>
<td></td>
<td>T2 +0.037</td>
</tr>
<tr>
<td>PMP</td>
<td>T1 +0.012</td>
</tr>
<tr>
<td></td>
<td>T2 +0.0005</td>
</tr>
<tr>
<td></td>
<td>T3 -0.005</td>
</tr>
<tr>
<td>MOR</td>
<td>T1 +0.010</td>
</tr>
<tr>
<td></td>
<td>T2 +0.017</td>
</tr>
<tr>
<td></td>
<td>T3 +0.025</td>
</tr>
<tr>
<td></td>
<td>T4 +0.019</td>
</tr>
<tr>
<td>NAD</td>
<td>T1 -0.009</td>
</tr>
<tr>
<td></td>
<td>T2 -0.012</td>
</tr>
<tr>
<td>LOI</td>
<td>T1 +0.024</td>
</tr>
<tr>
<td></td>
<td>T2 +0.010</td>
</tr>
<tr>
<td></td>
<td>T3 +0.019</td>
</tr>
<tr>
<td></td>
<td>T4 +0.014</td>
</tr>
<tr>
<td>SUL</td>
<td>T1 -0.004</td>
</tr>
<tr>
<td></td>
<td>T2 -0.052</td>
</tr>
<tr>
<td></td>
<td>T3 -0.038</td>
</tr>
<tr>
<td>MRK</td>
<td>T1 -0.015</td>
</tr>
<tr>
<td></td>
<td>T2 -0.023</td>
</tr>
<tr>
<td></td>
<td>T3 -0.022</td>
</tr>
<tr>
<td>BOG</td>
<td>T1 -0.006</td>
</tr>
<tr>
<td></td>
<td>T2 -0.018</td>
</tr>
<tr>
<td></td>
<td>T3 -0.033</td>
</tr>
<tr>
<td>PIT</td>
<td>T1 -0.005</td>
</tr>
<tr>
<td></td>
<td>T2 -0.016</td>
</tr>
<tr>
<td></td>
<td>T3 +0.007</td>
</tr>
<tr>
<td></td>
<td>T4 +0.023</td>
</tr>
</tbody>
</table>

Table 4.1 Departure of the P-Wave arrival time at each station from the uniform velocity curve for each test event. Those underlined depart from the straight line by more than the probable error; these are assumed to be due to real geological variation.
generally less than 80 ft easterly of the position calculated without the correction. This is as expected; the correction lengthens the P-wave travel time from an event to MRK, to the west, and shortens the time to LOI and MOR, to the east, thus moving the calculated epicentre in an easterly direction. The improvement in epicentral location is debatable; the corrections lead to an improvement when the calculated epicentre is to the west of the true location and a worsening, as in the case of T2, the July 3 open pit blast, when the calculated hypocentre is east of the true position.

Even for these events which were used as the basis for deriving the travel time correction, the improvement in the epicentral location was at best marginal; and as these possible corrections lie within the total arrival time error range of ± 0.03 s (as will be discussed in Chapter 5), there appears to be no justification for using them.

Summary
(i) A regional P-wave velocity of 5.30 kms\(^{-1}\) was derived from calibration explosions for the purpose of hypocentre calculation
(ii) A regional S-wave velocity of 3.06 kms\(^{-1}\) was determined using a Poisson's ratio of 0.25
(iii) The uniform regional model was used in the hypocentre location program; systematic travel time corrections were not applied as they did not lead to a significant improvement in event location.
Figure 4.4 Location of the calibration events T1, T2, T3 and T4 and their calculated epicentres. The calculations were done both with and without travel time corrections.
4.3 THE STATION WEIGHTING FACTOR

A weighting factor, \( WF = \frac{A}{B + d_i} \),

where \( A = 10000 \)
\( B = 600 \)

and \( d_i \) is the distance in metres from the source to the detecting station, was applied to the Sullivan Mine array. Constants \( A \) and \( B \) are arbitrary and in this case were chosen to be the same as those used by Spottiswoode (1980) at the East Rand Proprietary Mine.

For example, Consider as an example, an event occurring in the open pit: The closest stations SHF, NAD and PIT have the highest weighting which is about 4 times the weighting given to MRK, the furthest station in the inner net, and 7 times that given to MAT and BOG, the most distant outer net stations.

The weighting assumes that errors in the arrivals at the more distant stations are likely to be higher; the two reasons for this are:

(i) seismic waves travelling longer distances through the earth would be more affected by departures from the assumed uniform velocity model.

(ii) attenuation of the higher frequencies at this distance will lead to less sharp first arrivals and thus less reliable arrival time picks.
4.4 EFFECT OF THE MINE WORKINGS ON THE MODEL

Intuitively it is expected that if the wavelengths are long compared to the size of the cavity, the cavity will have little effect. The calculations of Greenfield (1977) show that at higher frequencies a cavity will distort the radiation pattern to the extent that it would make those frequencies unobservable in some directions. An opening is shown to effect wavelengths shorter than approximately 15 cavity radii (Greenfield, 1977).

In the case of the Sullivan Mine we have;

\[ v = 5.3 \text{ kms}^{-1} \]
\[ f = 10 - 20 \text{ Hz} \]

now \[ v = f\lambda \]

so \[ \lambda = 260 - 530 \text{ m} \]

That is, a cavity of radius 17-30 m would be necessary to affect the wave propagation. All the Sullivan Mine tunnels (radius 1-2 m) and all except the largest stopes are smaller than this; thus the majority of mine workings do not significantly effect the wave propagation. The largest stopes have dimensions of approximately 50 m by 70 m by 100 m high (P. Ransom, personal communication, 1982) which are large enough to affect the wave propagation from certain directions. None of the stations in the inner net show evidence of being consistently shielded from wave radiation. However wave amplitudes, particularly those of the higher frequency components, may be lowered by the presence of these large stopes depending on the stope, source and receiver geometry (Greenfield, 1977). This aspect will not be dealt with any further in the present study.
5.1 EVENT CLASSIFICATION:

Figure 5.1 shows the breakdown of all 1551 events recorded on 2 or more digital seismographs during the experiment. Events recorded by 4 or more stations, hence used in the analysis, are divided into major observable types. An event was classified according to its coda shape, frequency content, phase separation and time of occurrence. The different types are as follows:

(i) Emergent Events

A typical example is seen in Figure 5.2. The signal emerges slowly from the background noise, taking on average between 1 and 2 seconds to reach a maximum amplitude, then decays to background level producing a characteristic diamond shaped coda. The event duration is no longer than about 5 seconds. Signal frequencies (determined from arrivals at LOI) are commonly in the range from 8 to 10 Hz with some reaching 12 Hz; which is in general lower than that observed in the other event types.

Their emergent onsets and lower frequency content indicate that they are not the result of an abrupt energy release as would be expected for an explosion or sudden rupture in virgin or tightly locked rock. Instead these events represent a more gradual release of energy. The uncertainty in the first arrival
Figure 5.1 Event Classification.
Events recorded by 4 or more stations are shown divided into major observable types. The "other" group consists of an unknown combination of explosion and microearthquake events of which the "weekend" events form a basically explosion free subset.
Figure 5.2 Example of a Seismic Event with an Emergent First Arrival.
The bounds of a plausible first arrival pick are indicated by triangles. Events of this nature are not useful in our application due to large location errors.
time picks is extremely high, as indicated by the triangles on Figure 5.2. The 0.2 seconds shown here corresponds to a P-wave travelling in excess of 1 km so clearly this type of event cannot be located accurately. Emergent events constitute about 1/3 of the data set or 118 events as shown in Figure 5.1, and of these about 1/2 were discarded because of the extreme error in picking first arrivals; an attempt was made to locate the remaining 60 events.

(ii) Multiple Blasts and Explosion Events

Multiple blasts are distinctly characterized by energy bursts throughout the seismogram as shown in Figure 5.3. This complex coda shape has been attributed to the long delay firing sequences that are used in ore extraction blasting.

The other explosion events were distinguished primarily by their timing. Large amplitude events observed at the end of mine work shifts were clearly "shift change blasts" and others were determined by their correspondence with the times on a list of mine explosions provided by Cominco.

The Explosion events show front-end loaded codas, that is maximum amplitudes within the first few cycles of the waveform, and tend to have frequencies in the range from 13 to 16 Hz (based on arrivals at LOI) with some of the smaller events containing frequencies as low as 9 Hz. It is interesting to note the higher recorded frequencies (17 to 20 Hz) at sites D27 and NAD due to their proximity to the mine workings. Figure 5.4 is a typical example of an explosion event.

As shown in Figure 5.1 known multiple blasts and explosion
Figure 5.3 Example of a Multiple Event:
The onset of energy bursts are indicated by triangles. Events of this type are attributed to a complicated blasting sequence. This particular event took place on Monday June 23, 1980 at 6:09 am in the #1 surface ramp development area.
Figure 5.4 Example of a Explosion Event.
This particular explosion took place on Friday June 20, 1980 at 5:45 pm in the L-11-30 working area.
events make up 22% of the data set. Although not of direct interest to this study, the majority of these events were retained to serve as a control on hypocentre location accuracy.

(iii) **Distant Events**

Although very few in number, events of this type were recognizable by the clear separation of the P and S phases. The S wave to P wave travel time difference can be written in terms of the P and S wave velocities, assuming propagation through homogeneous material:

$$t_s - t_p = t_{s-p}$$

$$\frac{x}{p} - \frac{x}{s} = t_{s-p}$$

where

- $x = $ hypocentral distance
- $p = 3.06$ kms$^{-1}$ S-wave velocity
- $s = 5.30$ kms$^{-1}$ P-wave velocity

then

$$x = 7.24 t_{s-p} \text{ km}$$

Therefore if $t_{s-p}$ is greater than 1.5 s, the epicentre is likely to be outside the array. Figure 5.5 shows an event with $t_{s-p} = 2.5$ s which is clearly not of interest in this experiment.

(iv) **Events of Interest**

The remaining 46% of the events used, or "other" events as indicated in Figure 5.1, consist of mine explosions as well as the microearthquake events of interest. Further division may be carried out on a temporal basis:

(a) "Weekend" Events

By selection of those events that occur on weekends we can
Figure 5.5 Example of a "Local" Seismic Event outside our Region of Interest.

The S phase arrival is chosen by analysing arrivals at all stations, the S-P arrival time difference of 2.5 s indicates an epicentral distance of about 20 km.
be reasonably well assured of an explosion free subset; 47
events occur at this time. The weekend events have a simple
coda shape, the energy is front-end loaded decaying to
background in 3 to 4 seconds. They range in frequency from 10
to 18 Hz, with a predominant number of events around 13 to 14
Hz. This encompasses the range shown by the explosion events.
Occasionally a small separation between S and P phases is
evident on some of the records. Figure 5.6 shows a typical
weekend event.

(b) "Weekday" Events

Following separation of the above mentioned event types we
are left with 120 "weekday" events (Figure 5.1). The events in
this group are sharp and thus well locatable but still consist
of mine explosions as well as microearthquake events. The
similarity between the character of these and explosion events
makes their separation very difficult. Thus we would like to be
able to determine some form of discrimination criterion in order
to increase the useful working set of microearthquake events.
Figure 5.6 Example of a Typical Weekend Event.
A small S-P phase separation is visible in this case. This particular event occurred 21 minutes after the July 11, 1980 pillar blast and was seemingly triggered by the large blast.
5.2 EXPLOSION-MICROEARTHQUAKE DISCRIMINATION PROBLEMS

When considering a spherical explosion in a homogeneous elastic medium compared to a rupture along a fault plane of finite size, one would expect to see the following differences:

(a) The explosion, involving an extremely rapid energy release at a single point in the medium, would show a higher frequency content compared to the lower frequencies involved in a rupture propagating along a finite length slip surface and occurring over a much longer time period.

(b) The explosion mechanism would not generate any shear waves and hence is characterized by a simple front loaded coda; the rupture would generate both P and S phases which propagate at different velocities and thus produce a more complex coda.

(c) The explosion mechanism would generate a spherically spreading compression wave whereas in the case of the rupture event, the recording stations may experience either a compressive or rarefactive first arrival depending on their position with respect to the rupture plane and the direction of motion along the rupture plane.

In the mine environment however, the above criteria, with the exception of polarity, tend to fail as firstly, the microearthquake events are rather small, that is the rupture dimensions come close to being a point source, and secondly the explosions are not single burst, point sources in a homogeneous medium.

(i) **Frequency Content**

It appears that the source dimensions of the
microearthquake events are too small to allow discrimination based on frequency content. Hence this is not a useful criterion as borne out by the Sullivan Mine data. Both explosion events and microearthquake events (i.e. weekend events) showed a similar range in frequency.

(ii) **Generation of Shear Waves**

Explosions, particularly in the development areas, are detonated in groups with an ordered delay pattern. An initial blast is detonated creating a cavity (i.e. free faces) after which several further charges are detonated around the cavity. Breakage occurs by tensional failure, as the compressional wave changes phase upon reflection off the free surface, and material moves into the cavity. The differential stresses created lead to the generation of S-waves. In fact, this principal is used by the oil industry to generate S-waves from explosive sources; the technique is called SEISLAP (Tatham et al, 1980).

(iii) **Coda Shape**

Due to the explosion time delays, the coda shape criterion is no longer applicable.

(iv) **Polarity**

The direction of first motion could not be determined sufficiently well to enable its use as a discrimination criterion.

The most serious problem in event discrimination was the lack of polarity information. It was hoped that a first motion
analysis of the microearthquakes would enable the construction of fault plane solutions and hence allow some more conclusive comments to be made on the style of the failure in the mine area and on the nature, or absence, of a stress regime. Unfortunately, with the rest of the data set being of lower magnitude than the test events, first arrivals were often not as distinct. An examination of 55 known explosion events showed that for each station used there was roughly a 50:50 distribution of positive and negative first arrival polarities; (the only exception being PIT, located above the southern edge of the mine, which generally recorded positive polarities). The reason for the problem is obvious when we consider the orientation of the vertical seismometers with respect to the zone in which the majority of events occur. Figure 5.7 shows the radial distance of the seismometers and their elevation with respect to the open pit. In the case of a uniform velocity model, that is assuming straight line travel paths, it becomes clear from the diagram that the component of motion which the vertical seismometers are able to measure is much smaller than the radial horizontal component. Consider three cases evident in Figure 5.7; firstly the stations above the plane of the open pit blast experience a small direct upward vertical component of first motion. Secondly, the surface stations below the plane of the explosion should experience a small direct vertical component of first motion downwards. In practice however (as indicated by the positive test explosion polarities) diffraction effects due to surface topography, and the fact that a slight vertical velocity gradient probably does exist, means that the
Figure 5.7 Station Elevation and Radial Distance with respect to the Open Pit. Star represents elevation of open pit blasts and the dashed line separates those stations located above the plane of the blast from those located below.
rays arriving at these stations are largely horizontal with a small upward vertical component. Finally, in the case of the two underground stations the cavity containing the seismometer is small with respect to the P-wave length of 260 - 530 m so when the plane of the explosion is above the stations (Figure 5.7), the whole cavity would have an initial displacement downwards resulting in negative first arrival polarities.

In all cases the vertical component of first motion is only sufficiently large for the closer surface station PIT to record unambiguously. The more distant stations record a much smaller vertical component such that it could only be reliably picked in the case of the larger test explosions.

Note that caution is required when using underground stations for polarity analysis in the case where source depth with respect to the recording stations is unknown. Ambiguity will arise as the recorded first motion will be influenced by both the location of the source with respect to the recording stations and the nature of the source. Had the Sullivan polarity information been usable, further serious problems would have arisen due to poor focal depth determination.

In summary, a detailed examination of the data failed to yield any useful event discrimination criteria, apart from separation on a temporal basis. Further separation of the "weekday" events (Figure 5.1) is beyond the scope of this present study. In order to use polarity information in future experiments, horizontal seismometers oriented towards the area of expected activity should be deployed.
5.3 HYPOCENTRE LOCATION

A seismic event that is recorded by an array of 4 stations can be located both spatially and in time as follows:

Take the unknown coordinates of an event hypocentre \( (x_0, y_0, z_0) \) and its unknown origin time \( t_0 \) and let the known coordinates of the \( i \)th recording geophone be \( (x_i, y_i, z_i) \). The distance to each geophone \( d_i \) can be written in two ways,

\[
d_i = (x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2
\]

\[
d_i = v(t_i - t_0)
\]

where \( t_i \) is the arrival time at the \( i \)th geophone of a particular phase, and \( v \) is its velocity. Equating the two equations above,

\[
(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = v^2(t_i - t_0)^2
\]

and with 4 seismic stations recording the event, it is possible to solve uniquely for the 4 unknowns \( x_0, y_0, z_0 \) and \( t_0 \). This is known as the "direct solution".

A summary of the various three-dimensional source location techniques is given by Leighton and Blake (1970) which includes the "standard direct solution". A further paper by Leighton and Duvall (1972) contains excellent discussion on the merits of using a "least squares" approach over the "standard direct solution" method in terms of location accuracy when there are more than 4 arrival times available. The most recent development of algorithms for a 3-dimensional distribution of stations includes work by Spottiswoode (1980), Cete (1977) and the mineral engineering group at Pennsylvania State University (Mowrey, 1977; and Harding, 1970).

Two least squares type programs were obtained for this
study from Spottiswoode (1980) and Mowrey (1977). That of Spottiswoode, which is based on Seidel's method has been implemented on the U.B.C. computer. A discussion of Seidel's method and a listing of the program is included in Appendix 2. The program allows the use of both P and S arrivals, weights stations according to distance, and can take account of velocity variations directly or through time delays. The program iterates quickly to a final solution removing stations from the computation which have time residuals larger than a specified value.

The time residual for the Sullivan Mine project, above which rejection would occur for a station in the inner net, was chosen to be about equal to the total arrival time error of ±0.03 s. The seismograms of the rejected arrivals could then be re-analysed for mistakes in the first arrival picks or for timing errors. In the case of the emergent events the time residual for all the stations was generally much higher, often as much as 0.1 s to 0.2 s and it was usually impossible to obtain an improved first arrival pick.
5.4 NON-LOCATABLE EVENTS

From the initial data set of 366 events, 266 events were used in the hypocentre location program for reasons discussed in section 5.1. Initially locations could not be determined for 55 of them yet their character indicated that they should be within the array area.

After repicking difficult first arrivals in 22 cases and eliminating misidentified S arrival picks in 6 cases, 28 non locatable events remained of which 15 were emergent events. The remaining 12 events would not converge due to an insufficient number of station constraints. They were all recorded by only 4 digital stations and of these arrivals at D27 could not be used because of unresolvable timing problems.

5.5 IMPORTANCE OF CONSTRAINING CALCULATED HYPOCENTRES

It is extremely important that an event be completely surrounded by recording stations in order that its hypocentre may be determined accurately. The problem is highlighted in Figure 5.8 which shows the epicentres of events calculated without the arrival at MRK included; for comparison Figure 5.9 shows the epicentral locations calculated using the arrivals at MRK. Figure 5.8 shows the events, rather than a cluster in the mine area as they really are, but as a band of activity extending out of the mine area both to the east and west. A number of events extend some 2000' (600m) to the west of their true locations.

Without station MRK east-west constraint is poor compared
Figure 5.8 Epicentral Map of all Events Located with arrival MRK
Excluded from the Calculations.
The spread of the epicentres compared with Figure 5.9 indicates the effects of poor station constraint.
Figure 5.9 Epicentral Map of all Events Located with arrival MRK Included in the Calculations. When compared with Figure 5.8 the importance of MRK as an east-west constraint can be seen. The significance of the event locations will be seen later.
to that in the north-south direction and in order to minimize the squares of the distance residuals the program can move calculated epicentres quite easily along this line of weakest constraint. These observations have an important bearing on the discussions concerning focal depths to follow in the next sections and Chapter 6.

5.6 HYPOCENTRAL ACCURACY BASED ON EXPLOSIONS

The expected location capability may be determined by comparing the calculated hypocentres of events with their known locations. A suite of 12 explosions in the mine area enabled this to be done. Figure 5.10 shows the calculated epicentres of all known explosions and the active mining areas in which they are most likely to have occurred (J. Hamilton, personal communication 1981). Those explosions of known location are shown circled and their areal distance from the true location in the mine workings are indicated. Figures 5.11 and 5.12 show the projection of explosion hypocentres and mine working areas onto a north-south and east-west plane respectively. Those explosions of known location are again circled and the displacement of their calculated focal depths from the true location shown. The difference between the known and calculated parameters is also listed in Table 5.1, column 5.3 kms⁻¹.

From the Figures and Table we see that the epicentral error varies from 0 to 600' (180 m) with the depth being much more poorly determined but generally deeper than the true depth. The error band ranges from 200' (60 m) above to 1600' (500 m) below the true depth.
Figure 5.10 Calculated Explosion Epicentres.
Circled epicentres are of known location, displacement from their true position in the working areas is indicated as a solid line.
Figure 5.11 Calculated Explosion Hypocentres projected onto a North-South Cross Section.
The locations of those events circled are known from explosion records, displacement from their true position in the working areas is indicated as a solid line.
Figure 5.12 Calculated Explosion Hypocentres projected onto a East-West Cross Section. The locations of those events circled are known from explosion records, displacement from their true position in the working areas is indicated as a solid line.
<table>
<thead>
<tr>
<th>EVENT NUMBER AND LOCATION</th>
<th>VELOCITY (\text{kms}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>EPI</td>
</tr>
<tr>
<td>73 (P-9-1)</td>
<td>230</td>
</tr>
<tr>
<td>74 (P-9-1)</td>
<td>280</td>
</tr>
<tr>
<td>94 (#1 RAMP)</td>
<td>310</td>
</tr>
<tr>
<td>52 (P-9-1)</td>
<td>380</td>
</tr>
<tr>
<td>49 (L-11-30)</td>
<td>325</td>
</tr>
<tr>
<td>47 (P-9-1)</td>
<td>+180</td>
</tr>
<tr>
<td>45 (# RAMP)</td>
<td>40</td>
</tr>
<tr>
<td>10 (3710 29)</td>
<td>-1570</td>
</tr>
<tr>
<td>261 (PILLAR)</td>
<td>1070</td>
</tr>
<tr>
<td>75 (OPEN P)</td>
<td>610</td>
</tr>
<tr>
<td>199 (OPEN P)</td>
<td>0</td>
</tr>
<tr>
<td>70 (#1 RAMP)</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 5.1 Difference between the calculated explosion hypocentres and their true position, for velocities ranging from 5.1 to 5.5 \(\text{kms}^{-1}\). EPI is the epicentral displacement and Z is the difference in depth.
The extremely large hypocentral error and tendency for event foci to cluster below their known position is rather disconcerting, but it can be explained in terms of station geometry. When we ask why there is such a large error in the z-direction alone it becomes clear that the same situation is occurring as was seen in Figure 5.8 when locations were calculated without MRK. In this case, the arrival time errors in the residual equation are being minimized most easily by variation in the z-direction. Looking again at Figure 5.7 showing station elevation versus radial distance, we see that even though an attempt was made to create a 3-dimensional array of stations at the Sullivan Mine, there is still a plane (close to horizontal) in which the station constraint is strongest. Due to caving and hence restricted access above the Sullivan Mine the station locations tend to form a ring around the area of greatest activity. If we consider the theoretical case in which the stations form a perfect circle, recording P-arrivals from an event occurring at the centre of the array, then there will be no constraint at all in the z-direction. In the case of the Sullivan array the underground stations are at the mining level and thus place some constraint on the focal depths; travel-time differentials between them and the surface stations constrain most hypocentres to lie at and below the orebody.
5.7 THE EFFECT OF CHANGES IN THE VELOCITY MODEL

What is the importance of the velocity model in hypocentral determination and what would be the effect of changing the velocity from that of 5.30 kms\(^{-1}\) derived from the calibration explosions? The explosion events with known origin co-ordinates were again used and the velocity iterated from one end of a reasonable range to the other, i.e. 5.1 to 5.5 kms\(^{-1}\). The effects on the epicentral and depth errors are listed in Table 5.1 and can be seen on Figures 5.13, 5.14, and 5.15. The dashed lines indicate the change in calculated position as the velocity is changed from 5.1 to 5.5 kms\(^{-1}\).

As expected in the horizontal plane of maximum station constraint, there is very little effect across the whole range of velocities. The epicentral locations (Figure 5.13) are rather insensitive to velocity with the positions changing by 0 to 300 ft (90 m), but in most cases less than 200 ft (60 m). The focal depths, on the other hand, vary up to 1600 ft (500 m) with the velocity changes. An increase in velocity is seen to pull the focal depths closer to the plane of maximum station constraint, both from above and below the plane (Figures 5.14 \\& 5.15). The reason is apparent geometrically, as the arrival time differential, \(\Delta t\), between stations is fixed and \(v = \Delta d/\Delta t\), where \(\Delta d\) is the distance differential between the source and the various station locations. An increased velocity therefore requires a larger distance differential between stations; this is facilitated by moving the source closer to the plane of station elevation.

It is clear that the velocity chosen does not play a very
Figure 5.13 Effect of Velocity Changes on Epicentral Location. The dotted lines indicate the change in calculated epicentral position of the explosion events as the velocity is iterated from 5.1 kms⁻¹ to 5.5 kms⁻¹. The cross is the position at 5.3 kms⁻¹.
Figure 5.14 Effect of Velocity Changes on Hypocentral Location, North-South Cross Section.

The dotted lines indicate the change in calculated hypocentral position projected onto a north-south plane. The position changes in the direction of the arrows as the velocity is increased from 5.1 to 5.5 km/s.
Figure 5.15 Effect of Velocity Changes on Hypocentral Location, East-West Cross Section.
The dotted lines indicate the change in calculated hypocentral position projected onto an east-west plane. The position changes in the direction of the arrows as the velocity is increased from 5.1 to 5.5 kms⁻¹.
important role in epicentral location, provided the source is well surrounded by stations. To use an artificially high velocity to pull the focal depths into the plane of maximum station constraint, rather than the more appropriate value of 5.3 km/s determined from the test explosions, merely serves to disguise the error scatter. This would not provide better depth resolution.
CHAPTER 6: ANALYSIS AND INTERPRETATION

6.1 EVENT LOCATION, AN OVERALL PICTURE

Figure 6.1 is an epicentral map of all events located during the six week experiment. The most noteworthy feature is that all the events, with the exception of some explosions and emergent events, lie well within the boundaries of the mine area, and as we shall see are concentrated on the active mining zones. Small clusters of explosions to the immediate south of the mine area correspond to activity in the open pit and development of the #1 surface ramp. The four explosions near MRK, to the west of the mine were detonated in #10 pit. There is a scatter of emergent events within and to the north and west of the mine.

Figure 6.1 illustrates that the Sullivan Mine is having an extremely localized effect on its surroundings. There is no activity on the Kimberley Fault (KF) to the west of the mine workings nor on the Sullivan Fault (SF) to the south of the mine.

Figure 6.2 is a block diagram showing the location of all the events in the mine area and their projections onto a north-south and an east-west cross section. One notices two distinct clusters of hypocentres on the east-west cross section at, and below, the level of the mine workings. We recall that an event hypocentre may be located anywhere between 200 ft (60 m) above to 1,600 ft (500 m) below its true position. In view
Figure 6.1 Epicentral Map of all Events Located at the Sullivan Mine, June-July, 1980.

The events labelled as "other" consist of an unknown combination of mine explosions and microearthquake events.
Figure 6.2 Three Dimensional Representation of all Event Hypocentres at the Sullivan Mine. The event hypocentres are projected onto the east-west, north-south and horizontal planes.
of the lack of constraint on focal depth, the data is suggestive of two source regions at the working level (Figures 5.11 & 5.12).

The fact that Pomeroy et al (1976) and Smith et al (1974) obtain focal depths of 0.5 - 1.2 km and 0.5 - 1.5 km in their respective study areas with equivalent or weaker time constraints than in this experiment suggests that they may also be seeing the spurious manifestation of their arrival time errors in the vertical direction. Their focal depths may also be at, or immediately below the mining level.

6.2 THE EMERGENT EVENTS

Figure 6.3 shows the "locations" of the emergent type events discussed in the previous chapter, 10 of which lie within the mine area and 12 outside; their statistical centre is to the north and east of the mine. There is no reported human activity in this region (P. Ransom, personal communication, 1982). However the location error of these events (discussed in Section 5.1) is such that it would be foolish to attempt to ascribe them to a particular fault. One could suggest that the emergent events may originate from the Kimberley Fault but the shortcomings of this hypothesis will be discussed later.

Figure 6.4 is a frequency histogram of events per day for the subset of 118 emergent events that were recorded by 4 or more digital seismographs. A clear weekly cycle with almost no activity on weekends is evident, indicating a strong relationship between these events and mining activity. As
Figure 6.3 Epicentres of Locatable Emergent Events at the Sullivan Mine. 
Their scatter is the result of difficult to pick first arrivals.
Figure 6.4 Histogram, Number of Emergent Events per Day. Each day runs from 10:30 pm to 10:30 pm and the weekends, or periods when there is no mine activity, are shaded.
discussed in Chapter 5, their emergent onsets and lower frequency content indicate that they are not the result of an explosion or sudden rupture, as is the case for a typical front-end loaded event. It thus seems clear that they are some form of microearthquake event related to mining-induced earth movement.

As the emergent events form a significant proportion of the data set (Figure 5.1), it is unfortunate that nothing more definite can be said. Frantti (1977) observed similar events at the White Pine Copper Mine, Michigan but was also unable to ascertain their nature.

6.3 EVENTS WITHIN THE MINE AREA, A DETAILED PICTURE

Now let us analyse in more detail the events occurring within the mine area. Figures 6.5 and 6.6 are enlargements of the mine cross sections in Figure 6.2 affording a more detailed view of the relationship between the calculated focal depths and the production or development areas. On the east-west section (Figure 6.6) the two clusters of events are again clearly seen, dipping in a westerly direction and separated by an area in which there is very little activity. The cluster below D39 appears to be due to activity associated with mining in the upper levels, in particular the L-11-30 and P-9-1 (4290 P SCRAM) working areas. The lower cluster, closer to and east of D27, appears due to activity in the deeper workings such as 3905 A

1Note that the foci are not actually below D39, only apparently so because of the projection.
Figure 6.5 Event Hypocentres projected onto a North-South Cross Section.
Figure 6.6 Event Hypocentres projected onto an East-West Cross Section.
RAMP and 3710-29 SCRAM. The band-like nature of the clusters is due to the lack of constraint in the vertical direction as described earlier.

The south-westerly dip visible in the east-west section (Figure 6.6 and also in Figures 5.11 and 5.12) seems to be attributable to the station geometry. The plane of maximum constraint is actually one dipping to the north-east so the direction of weakest constraint, at right angles, is that indicated by the band of events. It is important to note that projection of the hypocentres onto the horizontal plane will lead to an apparent south-westerly displacement of the epicentres as has been observed in some cases (Figure 5.10).

Figure 6.7 is an enlargement of the mine area and epicentre locations seen earlier in Figure 6.1. No distinct lineations of the event epicentres are apparent, and recalling that an epicentral error of up to 600 ft (180 m) may exist, it would thus be unwise to attempt to define any previously unmapped faults on this basis. Figure 6.8 is a map showing the footwall trace of known faults within the Sullivan Mine. This figure may be directly overlain upon Figure 6.7 so that a direct comparison can be made between the event epicentres and the fault traces. It is possible that stress release within the mine area may be occurring along portions of the Sullivan (SF), Number-two (N2), Burchett (BF), Alpha-Beta pair (AB), Jonel (JF) and Hamlet (HF) faults. An interesting feature is the abrupt termination of activity to the west of the Sullivan fault footwall trace. This is also clear in the east-west mine cross section (Figure 6.6).
Figure 6.7 Event Epicentres in the Mine Area.

Figure 6.8 Faults in the Mine Area.

Figure 6.9 Active Blocks, June-July, 1980. The solid line is a 600 ft distance contour around the working area.
It is apparent that there was no activity on any fault outside the mine boundaries and that if any activity was occurring on faults within the mine area, it was confined to those portions very near to the working areas. Figure 6.9 is a map showing the blocks in which active ore removal, or mine development, was taking place during the period June-July, 1980. A line of radius 600 ft (180 m), corresponding to the maximum epicentral location error determined in Chapter 5, has been drawn around the active areas. On this basis, any event occurring within the error boundary can be ascribed to mining activity or associated stress release totally within the active blocks. Figure 6.9 overlays directly onto Figures 6.8 and 6.7 and it is clear that almost every event is located within this region. Only seven events, excluding the emergent types, locate outside, but very close to, the 600 ft error boundary.

Figure 6.10 shows the location of cave areas in the Sullivan Mine, that is areas in which the removal of ore has led to hanging wall slumping. The teeth on the lines point inward to the downdropped portion. Figure 6.11, event epicentres in the mine area, when overlain upon Figure 6.10 shows that there is an apparent correlation between event location and the edges of the cave areas, particularly in the large northwestern most cave. A concentration of epicentres lie near the eastern and southern edges of this cave area and also the western edge which is coincident with the Sullivan fault. Four of these events are those whose epicentres locate outside the 600 ft error boundary about the active areas, described above. The northeastern edge of this cave area which is coincident with the Number-two fault,
Figure 6.10 Cave Areas above the Sullivan Mine.

Figure 6.11 Event Epicentres in the Mine Area.
also shows some activity.

The easternmost cave area is bounded by a portion of the Burchett fault and the Alpha-Beta fault pair earlier described as showing activity associated with possible reactivation. The events near the northern Hamlet fault seem to occur where the fault intersects a portion of the southern cave area.

Figure 6.12 shows epicentral locations of the subset of events occurring on the weekends, that is from 10 pm on Fridays (following the last afternoon shift) to 10 pm on Sundays (the beginning of the Monday morning graveyard shift). We can be reasonably sure that the weekend events contain no explosions and that they probably represent the random release of stress that has built up in various areas of the mine due to activity during the week. About 60% of the events occurring at this time locate within ±200 ft of the edges of the cave areas.

6.4 EVENT ORIGIN TIME ANALYSIS

A detailed knowledge of exactly when each event occurs is important, particularly in determining the overall relationship between microseismic activity and mining cycles. It allows us to examine factors such as rates of microearthquake activity following large explosions and the stress relaxation time.

Analysis was done using the 1651 events recorded by 2 or more stations and an extremely close correlation with mining activity was found.

Figure 6.13 is a frequency histogram of the number of events recorded per day over the period of the experiment where
Figure 6.12 Epicentral Locations of the Weekend Events.
The numbered triangles indicate the calculated position and timing of the larger events triggered by the pillar blast. The true location of the pillar blast is shown as a star.
each day runs from 10:30 pm to 10:30 pm and includes the three 8 hour shifts, graveyard, morning and afternoon. The most striking feature is the weekly cycle with distinct lows corresponding to the weekends. The number of events that occur on a Saturday is greater than on a Sunday in all cases as stress relaxation events from the immediately preceding afternoon shift are tailing off into the Saturday period. This is especially apparent on the final Saturday of the experiment which has an extremely high average rate of activity as the Friday afternoon shift ended that week with the enormous July 11, 1980 pillar blast.

Figure 6.14 shows a portion of the histogram (Figure 6.13) with an expanded time scale where each day now consists of three columns, each corresponding to an 8 hour shift period. The changing amounts of activity in each shift is clearly reflected in the recorded microseismic activity. In general the graveyard shift shows the lowest level of activity, 2.0 events/hour, with the average rate increasing in the dayshift to 3.0 events/hour. The afternoon shift tends to have the highest average rate of activity, 3.5 events/hour. At the end of the day there is always a marked drop in the average activity with the commencement of the graveyard shift. The weekends have an average rate of 1 event/hour.

A detailed examination of the data showed that in 70% of all the shift periods examined there was a drop in the number of events observed in the first hour of the new shift. This is consistent with the fact that during this first hour the miners are still travelling to and preparing their working areas. In
Figure 6.13 Histogram, Number of Events per Day. Days run from 10:30 pm to 10:30 pm and the weekends are shaded to indicate that work is not taking place in the mine at this time.
Figure 6.14 Histogram, Number of Events per 8 Hour Shift Period.
Each day is broken up into the three 8 hour shifts, graveyard, morning and afternoon. The weekends are shaded to indicate that no work is taking place in the mine at this time.
general there was no pattern within each shift due to the fact that mining and small blasting takes place throughout this period.

Figure 6.15 allows us to study in detail the way in which mining induced stress is released; it is a graph showing the number of events occurring per hour. The spikiness of the graph, (i.e. from 0 up to 29 events may occur in the space of an hour), indicates the quantized nature of the stress release. The correlation of many of the spikes with shift break times and Cominco records, as well as their notable absence on weekends, suggests that they represent extremely high rates of microearthquake activity immediately following large mine explosions. The "size" of the events making up the spikes is shown as a pie diagram above each spike and as one can see, the majority of these events were recorded by only 2 or 3 digital seismographs which means that they were generally small and not suitable for location on our array. Examination of some of the larger spikes shows that about half the events making up the spike for that hour occur in the first 10 minutes following a major mine explosion. Figure 6.16 shows the number of events occurring per 10 minute period following an afternoon shift break blast at 10:05, July 9, 1980. It is clear from the figure that some 20 microearthquakes were induced in the first 10 minutes. Another good example is seen in Figure 6.17, a histogram which shows the number of events occurring per hour at the time of the July 11, 1980 pillar blast. The blast took place immediately prior to the start of a weekend so that it was possible to observe an explosion free decay period. The
Figure 6.15 Histogram, Number of Events per Hour.
Pie diagrams above spikes indicate the size of the stress release events following a mine explosion. The number above each diagram indicates the percentage of events recorded by four or more stations.
Figure 6.16 Histogram, Number of Events per 10 minute Period during the July 9, 1980 Afternoon Shift Break Blast. The pie diagram above the spike indicates that only 5% of the events in this 10 minute period were large enough to be recorded by 4 or more digital stations.
Figure 6.17 Histogram, Number of Events per Hour following the July 11, 1980 three stage Pillar Blast. An expanded time scale also shows the number of events occurring per 10 minute period following the blast.
majority of the stress release occurred in the first hour following the blast and, in fact, the first 10 minutes as seen on the expanded time scale. It took however approximately 8 hours for the ground to completely relax, that is for the number of events per hour to drop to the normal weekend level of about 1 event/hour. Only 5 events occurred in this period that were large enough to be located and their areal distribution (Figure 6.12) indicates that at least 4 did not occur within the explosion cavity. The three-stage pillar blast was the largest event recorded during the experiment. A more typical relaxation time for the normal week endings can be seen in Figure 6.18; the level of activity returns to background after the first hour.
Figure 6.18 Histogram, Number of Events per Hour for the Start of the Weekends commencing 10:30 pm on June 20, June 27 and July 4, 1980. Shaded portions represent weekend hours.
CHAPTER 7: CONCLUSIONS, SPECULATIONS AND SUMMARY

The findings of the 1980 Sullivan Mine experiment may be summarized as follows:

(i) The influence of mining activity at the Sullivan Mine is extremely localized. There is no evidence to suggest that the microearthquakes are occurring at any significant distance from the mine faces or cave areas; 97% of the events occur within the 600 ft (180 m) error contour about the active working areas and all events occur within 600 ft of both the working areas and cave zones.

(ii) The only types of stress release events that we can say with certainty are occurring at the Sullivan Mine are:

(a) Stress release in immediate response to the explosion activity, as indicated by the large number of small events following large mine blasts (Figures 6.16, 6.17 & 6.18). The events are probably due to relaxation of the rock in the severely strained walls of the newly formed cavities and probably also include those resulting from shear failure caused by differential loading and unloading at the cavity edges.

(b) Stress release in the zone of induced tensile stress above the mining created cavities. Such stress release is supported by the physical presence of cave zones above the mine, reports of air blasts following major mine explosions and the possible association of calculated epicentral locations with the edges of the cave zones.

The large epicentral location error and the inability to calculate fault plane solutions weigh strongly against making
any more definitive statements; it is impossible to determine what proportion of the "weekday" events are microearthquakes and also the exact nature of their source mechanisms.

(iii) Figure 7.1 is a summary of the figures in Chapter 6 highlighting the relationship between cave zones, faults and calculated event epicentres. There appears to be a more definite association between the epicentral locations and the edges of cave areas and it is interesting to observe that when activity does seem to occur along faults, they are proximal to cave edges. In fact it appears that the faults may be controlling the cave boundary shape in these areas. The suggestion is that some of the larger mine explosions may trigger the release of unstable hanging wall blocks in the vicinity of cave areas. Consider as an example the 5 locatable events following the July 11, 1980 pillar blast (Figure 6.12). All but one are more than 600 ft from the pillar location implying that they do not originate from within the explosion cavity; and all except one locate within 300 ft of the cave zone edges. The triggering is not immediate with the events occurring 8 min, 12 min, 21 min, 125 min and 160 min after the pillar blast. Figure 5.6 is a seismogram of the 21 minute event.

The suggestion that these events represent hanging wall collapse is in accordance with reported activity during the hours following the pillar blast; there were several "bumps" with associated air blasts which were interpreted as "sloughs of ground"; that is collapse of the mine roof (H. Pearson, personal communication, 1980).
Figure 7.1 Relationship between Event Epicentres, Cave Areas and Faults.
For clarity only those portions of cave zones and faults apparently activated by mining have been included.
(iv) There is no evidence to suggest the presence of any "locked in" or stored stresses similar to those observed by McGarr et al (1975) at the East Rand Proprietary Mine, nor the presence of any regionally compressive tectonic stresses such as required by Smith et al (1974) and Pomeroy et al (1976). In the above cases some of the earthquake events involved more energy release than that provided by the man-made activity that triggered them. This is reflected also in the higher b-values (or more small events compared to big ones, as would be expected in a collapse environment) calculated by Ellis (1977) for the Sullivan Mine area compared to those calculated by McGarr and Green (1978) for the East Rand Proprietary mine.

The lack of activity on any of the faults outside the mine area, lack of definite lineations of activity within the mine, other than possibly along cave edges, and lack of events of any significant magnitude (that is, magnitude greater than the mine explosions) all suggest that mining activity is not acting as a trigger for any pre-existing regional stresses which would have to be horizontal and compressive as discussed in Chapter 2.

The geologic evidence discussed in Chapter 2 suggests that regional stress in the vicinity of the Sullivan Mine is either neutral or extensional. (Figure 2.6 part C, $\sigma$, vertical) which suggests that activity on the faults in the footwall will in fact be suppressed by mining. The apparent correlation between microearthquake activity and portions of the Sullivan, Number-two, Burchett, Alpha, Beta and Hamlet faults is due to an entirely different mechanism. I believe that only the fault plane between the roof of the mine workings and the surface is
affected within that zone above the mine shown in Figure 2.5 in which the induced stress is primarily tensile. Here the stress pattern clearly manifests itself in the form of normal faulting and collapse in cave areas where the roof is either too weak or has additional stresses placed on it by pillar removal. The faults near the edges of cave areas represent planes that are essentially weaker than the surrounding rock and thus tensional failure will tend to occur preferentially along them.

(v) The emergent events remain a mystery. Based on their character and timing however we now can state quite definitely what they are not due to; this only leaves a few reasonable possibilities for their origin. The earlier suggestion that they represent mining triggered activity on the Kimberley fault is not in keeping with the suggestion that regional stress at the Sullivan Mine is either neutral or extensional:

(a) Normal faulting can never be induced by unloading alone in this case and the Kimberley fault is also clearly away from the cave areas;

(b) Thrust or strike slip faulting that is triggered by mining would require the existence of a horizontal, compressive regional stress.

The emergent onset and lower frequency content of these events indicate that they are neither explosion events nor sudden failure type events. Their strong correlation with the weekly mining cycle suggests that they are mining related microearthquakes and in view of their arrival time errors we can suggest that they too belong within the mine area. The only two possibilities left are that they result from non-violent
tensional deformation of a slumping type in the hanging wall or non-violent shear deformation (i.e. "stable deformation", McGarr, 1971b) in the immediate vicinity of the mine faces.

The results of this study have shed much light on the nature and timing of microseismicity, and the regional and local influence of ore extraction at the Sullivan Mine. We are now aware of the areas of expected activity and have discussed the mechanisms involved. The use of microearthquake activity for the delineation of fault planes at the Sullivan Mine has failed, the implication being that regional stress conditions are unfavorable for fault reactivation, other than in the zones of tensional stress above the stope areas. In this zone, fault planes extending from the hanging wall to the surface may possibly be delineated with improved procedures, but it is also these portions that are easily accessible and have already been mapped by visual inspection.

7.1 FUTURE PROGRAMS

The following section is designed to aid future studies involved with induced microseismicity by suggesting various improvements to combat the problems encountered during the present study.

Careful attention should be paid to the geologic evidence implying the existence, or absence, of a regional stress field when formulating the experimental aims.

The array design and timing as it stands is basically not accurate enough to be used as a precise mapping tool and
recommendations for modifications to future programs are as follows:

(i) High Accuracy Clocks:

A common time base at all stations, would completely eliminate the errors introduced by thermal drift of the crystal clocks. This would reduce the total arrival time error by approximately 50% in the present study.

(ii) Horizontal Component Seismometers:

These would allow the use of polarity information as discussed in Chapter 5 thus enabling the discrimination between microearthquakes and explosions and also facilitating a focal mechanism study.

(iii) Wide Frequency Passband:

The desired frequency passband will vary depending on the experimental design. There is no point in having a high upper frequency cut for distant stations due to attenuation of the signal waveform, however for a station very close to the source, in a high resolution study, it would be advantageous for the upper frequency limit to be close to 100 Hz. this would yield extremely sharp first arrivals and perhaps also enable frequency discrimination between explosion and microearthquake events.

(iv) Array Configuration:

The desired array configuration will also vary depending on the aims of the experiment but it is clear that a truly
3-dimensional array is necessary to attain the same location accuracy in focal depth as in epicentral position.

Were a further experiment to be conducted at the Sullivan Mine, there would be several major array design changes based on the findings of the present study:

a: The outer net could be collapsed inward to provide a more detailed coverage of the mine area. As no microearthquakes were recorded outside the mine area during the present study, the wide coverage of the outer net is not necessary.

b: As a result of this study, areas of interest may be selected, and more stations set up in surrounding stopes within the mine. A station located on the surface, directly above the area of interest would also aid by providing further constraint on the focal depths.

In the case of further detailed surveys in the mine area, and if it is possible to implement the above suggestions, an epicentral location accuracy of about ± 20 m with about ± 30 m in depth, as found by McGarr et al. (1975) could be expected for the events with sharp first arrivals.
REFERENCES


Hoy, T. 1982. The Purcell supergroup in southeastern British Columbia; sedimentation, tectonics and stratiform lead-zinc deposits. in: Major Sulphide Deposits of Canada and Environments, the H.S. Robinson Memorial Volume, GAC (in press).


APPENDIX 1  CLOCK DRIFT ERRORS

We consider errors in clock times due to variations in the crystal frequency. Let

\( T = \text{clock time (s)} \)
\( f = \text{oscillator frequency (Hz)} \)
\( F = \text{correct oscillator frequency (Hz)} \)

Then after 1 s the clock would show

\( T = \frac{f}{F} \)

More generally, we can write

\[
T = \int_0^t \frac{f(t)}{F} \, dt
\]

Crystal frequency errors are normally due to

(i) Initial offset \( \Delta F_o \) (Hz)
(ii) temperature drift \( \Delta F_T \) (Hz/°C)
(iii) aging \( \Delta F_A \) (Hz/s)

Then

\[
T = \frac{1}{F} \int_0^t \left( F + \Delta F_o + \Delta F_T \Delta t + \Delta F_A t \right) dt
\]

\[
= t + \frac{\Delta F_o}{F} \, t + \frac{\Delta F_T}{F} \, \Delta t \, t + \frac{\Delta F_A}{F} \, \frac{t^2}{2}
\]

where \( \Delta t \) - temperature change

Notes:

(i) **Frequency Offset** \( (\Delta F_o) \)

The term is linear and can therefore be easily corrected by time checks during the experiment.
Notes: cont'd

(ii) **Aging rate** \( (\Delta F^A) \)

For the Geotech MCR-600 units the quoted aging rate is \( 5 \times 10^{-6} \) /yr \( (=1.369 \times 10^{-8}/\text{day}) \). i.e. the error per day

\[
\frac{1.37 \times 10^{-8} \times 1}{2} \times 24 \times 3600 = 1 \text{ millisecond (ms)}
\]

This is not significant.

(iii) **Temperature Drift** \( (\Delta F_T) \)

For the Geotech MCR-600 the quoted value is \( 1 \times 10^{-7}/^\circ\text{C} \).

Let us assume that the crystals have been set in a laboratory at temperature \( T_m \) and are operated in an environment with temperature given by

\[
T_m + A \sin \frac{2\pi t}{86400}
\]

\[
\Delta T = 1 \times 10^{-7} \int_0^t [T_L - (T_m = A \sin \frac{2\pi t}{86400})] \, dt
\]

\[
= 1 \times 10^{-7}[\left( T_L - T_m \right) t = \frac{86400}{2\pi} A \cos \frac{2\pi t}{86400}] \]

For \( T_L = 25^\circ\text{C} \) and using July temperature values for Kimberley obtained from Environment Canada, \( T_m = 17.7^\circ\text{C} \) and \( A = 9.5^\circ\text{C} \), we have

\[
\Delta T = 1 \times 10^{-7} \left( 7.3t + \frac{9.5 \times 86400}{2\pi} \cos \frac{2\pi t}{86400} \right)
\]

This gives a linear drift of 63 ms/day with a sine wave variation of 13 ms zero-to-peak. We further note that if the mean
(iii) cont'd

temperature were 5.3°C the drift rate would decrease to 46 ms/day. Thus in combination, the diurnal temperature cycle and variations in the mean daily temperature may lead to timing errors of several 10's of ms.

In future experiments, either improved crystals should be used or the temperature stability improved by the use of thermal insulation.
APPENDIX 2  HYPOCENTRE LOCATION

Most local earthquake hypocentre programs e.g. HYPOELLIPSE (Lahr, 1979) are written for a 2-dimensional array of seismographs with variations in elevation taken into account by the use of station delays. For hypocentre location in a mine environment a true 3-dimensional array of stations is generally employed. A 3-dimensional computational scheme is therefore required. The program used in this report is a modified version of the code written by Spottiswoode (1980) which is simple in concept and computationally efficient. Its basis is now described.

The arrival times \( t_i \) \((i = 1, \ldots, N)\) of compressional waves (P) and shear waves (S) are observed at seismographs located at \((x_i, y_i, z_i)\). It is assumed that the P and S wave velocities, \( \alpha_i \) and \( \beta_i \), to each station are also known. From this data we desire to find the hypocentre coordinates \((x, y, z)\) and the origin time \( t_0 \). Normally more observations exist than unknown parameters and one therefore desires to minimize an objective function, in our case the weighted sum of the squares of the distance residuals.

Assume that we have a trial hypocentre and origin time \( x_0 \) = \((x, y, z, t)\). Then the station hypocentre distances are given by

\[
d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}
\]

and the distances based on the origin times are

\[
D_{pi} = \alpha_i (t_{pi} - t)
\]

\[
D_{si} = \beta_i (t_{si} - t)
\]
The distance residuals can then be written

\[ R_{pi} = d_i - D_{pi} \]

\[ R_{si} = d_i - D_{si} \]

and the weighted sum of the squares of the distance residuals (the objective function) is

\[ R^2 = \sum_{i=1}^{N} K_i^2 (R_{pi}^2 + R_{si}^2) \]

where \( K_i \) is a weighting function

In the present program

\[ K_i = a/(b + d_i) \]

i.e. a function which lowers the weight of the more distant stations.

Without difficulty, it could be modified to include the quality of the arrival time pick.

Seidel's method is used to determine \( \mathbf{x}_o = (x_o, y_o, z_o, t_o) \), that is the values of \( \mathbf{x}_o \) which minimize \( R^2 \). Observations are assumed to satisfy within measurement error an equation of the form.

\[ R(\mathbf{x}_i, \mathbf{x}_o) = 0 \ 'The residual equation' \]

where \( \mathbf{x}_i \) are the independent variables (known)

\( \mathbf{x}_o \) are the dependent variables (unknown).
We may write the unknown true hypocentre and origin time $x_o$ in terms of the trial hypocentre and origin time $x_t$ plus an unknown difference $\delta x$. The residual equation becomes

\[ R(x, x_t + \delta x) = 0 \]

Expanding $R$ in Taylor's series and neglecting quadratic and higher order terms

\[ R = R(x_i, x_t) + \sum \frac{\partial R}{\partial x_t} \bigg|_{x_t} \delta x + \mathcal{O}(\delta x)^2 \]

We now choose $\delta x$ to minimize

\[ \sum_{i=1}^{N} (R_i)^2 \]

Taking partial derivatives and setting equal to zero we obtain $4$ equations.

\[ \sum_{i=1}^{N} \frac{\partial R_i}{\partial x_t} (R_i(x_i, x_t) + \sum \frac{\partial R_i}{\partial x_t} \delta x_t) = 0 \]

\[ j = 1, \ldots, 4 \]

These equations are then solved simultaneously for the unknown $\delta x$ which provide an improved trial solution.

\[ x_t' = x_t + \delta x \]

This process can be repeated until $\delta x$ is sufficiently small.

In this case

\[ x_o = x_t'. \]
HYPOCENTRE LOCATION PROGRAM

DIMENSION SKU(24), VEL(24), EVENT(3), ARTM(24), DF(4), SS(12), RR(4), NARR(16), RES(16), DIS(16), XA(12), YA(12), ZA(12), SIN(9), STN(5)

C **** THIS PROGRAM WAS DEVELOPED BY S.M. SPOTTISWOOD
C DURING 1977 FOR LOCATING E.R.P.M. SEISMIC EVENTS
C SEIDELS METHOD OF SUCCESSIVE APPROXIMATIONS
C IS USED TO IMPROVE AN INITIAL GUESS LOCATION
C
C TO COMPILE THIS PROGRAM......
C
C RUN *FTN SCARDS=SPOTTI SPUNCH=SPOTTI.O
C TO RUN
C
C RUN SPOTTI.O+IMSL:8S 4=SPOTTI.DATA 5=SPOTTI.DATA2 6=OUT1 7=OUT2
C WHERE OUT2 IS THE INPUT FILE FOR 3DMAP
C
C **** MODIFICATIONS BY R.R. COENRAADS DURING 1981 FOR
C APPLICATION OF THE PROGRAM TO THE SULLIVAN MINE
C PROJECT ARE AS FOLLOWS ;
C - STATION COORDINATES AND EVENT LOCATIONS ARE
C IN FEET TO COMPLY WITH THE MINE COORDINATE
C GRID
C - UP TO 12 STATIONS ARE ACCEPTED
C - INPUT AND OUTPUT FORMAT MODIFICATIONS
C
REAL RDIR(6)/.028,-.071,.176,-.168,.420,1.0/
LOGICAL LEAR, LDONE

DIST(X,Y,Z)=SQRT(X*X+Y*Y+Z*Z)
WRITE(6,201)
201 FORMAT('I X',7X,'Y',7X,'Z  HEAD SKEW*,4X,'P',6X,'S',7X,'1 GEOPHONE')

DO 87 I= 1 , 12
READ(4,10)XA(I),YA(I),ZA(I),SKU(I),SKU(I+12),

1 VEL(I),VEL(I+12),STN

C*************************
C FEET CONVERSION
XA(I)=XA(I)*0.3048
YA(I)=YA(I)*0.3048
ZA(I)=ZA(I)*0.3048

C*************************
10 FORMAT(3F6.0,2F5.3,2F5.3,5X,5A4)
10 FORMAT(5F5.0,2F5.3,5X,5A4)

C **** 12 GEOPHONES ARE USED FOR LOCATIONS
C LABELLED 1 TO 12
C (XA(I),YA(I),ZA(I),I=1,10) ARE X Y Z COORDINATES IN METRES
C MINE COORDINATES ARE USED : X+ :WEST,
C Y+ :NORTH,
C Z+ :DOWN
C
C SKU(I),I=1,12 : HEAD SKEW CORRECTIONS APPLIED TO P ARRIVALS
C SKU(I),I=13,24 : HEAD SKEW CORRECTIONS APPLIED TO S ARRIVALS
C IN GENERAL SKU(I+12)=SKU(I)
C STATION RESIDUALS CAN BE INCORPORATED BY CHANGING
C P AND/OR S HEAD SKEW CORRECTIONS.
C
C VEL(I),I=1,12 : P VELOCITIES TO EACH GEOPHONE
C VEL(I),I=13,24 : S VELOCITIES TO EACH GEOPHONE
C
C*************************************************************************
C METRES CONVERSION FOR WRITE
XA(I)=XA(I)/0.3048
YA(I)=YA(I)/0.3048
ZA(I)=ZA(I)/0.3048
WRITE(6,22)XA(I),YA(I),ZA(I),SKU(I),SKU(I+12),
1 VEL(I),VEL(I+12),STN
XA(I)=XA(I)*0.3048
YA(I)=YA(I)*0.3048
ZA(I)=ZA(I)*0.3048
C*************************************************************************
87 CONTINUE
22 FORMAT(3F8.0,2F7.3,2F7.2,5X,5A4)
NLINE=14
READ(5,13,END=99,ERR=99)EVENT,SCAL,NPOOR1,NPOOR2,NDAY,NHRS,MIN,
+NSYM,NEV
13 FORMAT(3A4,F4.1,212,4X,13,1X,12,1X,12,3X,12,16X,13)
SCAL=1.0
READ(5,14,END=99)ARTM
14 FORMAT(12F6.3)
READ(5,15)
15 FORMAT(1X,/,1X)
C
C**** EVENT : EVENT TITLE ; USUALLY DATE & TIME.
C SCAL : PAPER SPEED OF HARD-COPY RECORD IN MM/(FIELD) SEC
C ARTM(I),I=1,12 : 12 P ARRIVALS IN MM
C ARTM(I),I=13,24 : 12 S ARRIVALS IN MM
C P & S ARRIVALS ARE READ IN IN THE SAME ORDER AS
C USED FOR GEOPHONE COORDINATES, VELOCITIES & HEAD SKEWS
C NPOOR1 & NPOOR2 : GEOPHONE NUMBER (NPOOR=NPOOR+12 FOR S)
C OF UNCERTAIN ARRIVALS
C NPOOR2 = 0 IF ONLY ONE ARRIVAL IS CONSIDERED UNCERTAIN
C NPOOR1 = 0 IF ALL ARRIVALS HAVE BEEN READ WITH CONFIDENCE
NLINE=NLINE+12
IF(NPOOR1.GT.0)NLINE=NLINE+8
IF(NPOOR2.GT.0)NLINE=NLINE+8
C
C 100 C
C 101 C
C 102 C
C 103 C
IF(NLINE.GT.115)NLINE=0
660 FORMAT('11')
66 IF(NLINE.EQ.0)WRITE(6,660)
661 FORMAT('///')
C
C**** NLINE IS USED TO SKIP TO A NEW PAGE OF OUT PUT
C NEAR THE END OF EVERY SECOND PAGE
C
CWRITE(6,20)EVENT,NDAY,NHRS,MIN,NEV
20 FORMAT(2X,3A4,5X,13,1X,12,:':',12,5X,'NUMBER = ',13,
+/,' ************',5X,'************',5X,'************')
WRITE(6,17)ARTM
17 FORMAT(1X,12F6.2)
IF(SCAL.LE.0.)GO TO 70
IF(NPOOR1.GT.24)NPOOR1=0
IF(NPOOR2.GT.24)NPOOR2=0
ARRIVAL TIMES ARE CONVERTED FROM MM TO MILLISECONDS
HEAD SKEW CORRECTIONS ARE ADDED
EARLIEST ARRIVALS ARE IDENTIFIED

DO 1 I=1,124
   IF(ARTM(I).EQ.0.)GO TO 1
   ARTM(I)=1000.*(ARTM(I)/SCAL+SKU(I))
   IF(ARTM(I).GE.TM)GO TO 1
   TM=ARTM(I)
   M=I
   CONTINUE
1 73 MM=M-12*((M-1)/12)

THE FIRST (GUESS) LOCATION IS CHOSEN CLOSE TO THE GEOPHONE AT WHICH FIRST ARRIVAL IS READ.

THE ORIGIN TIME OF THE EVENT IS DETERMINED FROM EACH GEOPHONE FOR WHICH BOTH P & S ARRIVALS WERE READ.

DO 2 I=1,12
   IF(ARTM(I+12).LE.0. .OR. ARTM(I).LE.0.) GOTO 2
   VR=VEL(I+12)/VEL(I)
   TO=(ARTM(I)-ARTM(I+12)*VR)/(1.-VR)
   EVT=TO
   WRITE(6,221) I, TO, ARTM(I), ARTM(I+12)
221 FORMAT(15,' , TO =',F7.0,2F8.0)
   NLINE=NLINE+1
   IF(TO.GT.TM)  WRITE(6,222) M
222 FORMAT('+',35X,'THIS IS AFTER ARRIVAL',13)
   CONTINUE
LDONE=.FALSE.

THE ITERATIVE PROCEDURE USED FOR IMPROVING THE GUESS COORDINATES START HERE.
FOR MOST EVENTS FEWER THAN SIX ITERATIONS ARE REQUIRED FOR SATISFACTORY CONVERGENCE.
CONVERGENCE IS CONSIDERED TO BE SATISFACTORY IF THE MOVEMENT BETWEEN SUCCESSIVE ITERATIONS IS LESS THAN 1 METER.
ALL THE TERMS OF THE MATRICES SS AND RR (USED FOR IMPROVING THE LOCATION) ARE SET TO ZERO.

DO 161 J=1,12
   SS(J)=0.
161 DO 1610 I=1,4
   RR(I)=0.
1610 N=0
   NN=0

N ARRIVALS WERE READ.
NN ARRIVALS ARE USED TO LOCATE THE EVENT DURING EACH PASS.
(n-3 <= NN <= N)
ERROR=0.
DO 164 I=1,24
IF (ARTM(I).EQ.0.) GOTO 164
IF (N.EQ.15) GOTO 164
C**** NO MORE THAN 15 ARRIVALS ARE USED.
N=N+1
II=I-12*((I-1)/12)
X=EVX-RA(II)
Y=EVY-YA(II)
Z=EVZ-ZA(II)
D=DIST(X,Y,Z)
IF (IT.GE.3 .AND. I.EQ.M .AND. D.GT.5000.) LEAR=.TRUE.
V=VEL(I)
P VELOCITIES ARE FIXED AT 6.1 KM/SEC.
CS VELOCITIES ARE FIXED AT 3.8 KM/SEC FOR DISTANT EVENTS.
IF (LEAR) W=6.1-2**3*I/I
W: DISTANCE RESIDUAL = (THEORETICAL-OBSERVED) DISTANCE
FROM EVENT TO GEOPHONE, METERS.
N=(EVT-ABS(ARTM(I)))*V
NARR(N)=ISIGN(I,IFIX(ARTM(I)))
RES(N)=W/V
IF (I.EQ.NPOOR1) RES1=W
IF (I.EQ.NPOOR2) RES2=W
DIST(N)=D
IF (ARTM(I).LT.0.) GOTO 164
NEGATIVE ARRIVAL TIMES ARE NOT USED FOR LOCATIONS
NN=NN+1
ARRIVALS FROM CLOSE GEOPHONES ARE GIVEN A GREATER EMPHASIS
THAN ARRIVALS FROM MORE DISTANT GEOPHONES.
THE WEIGHTING FACTOR USED HERE (WT) IS CHOSEN TO BE CONSISTENT WITH ERRORS IN VELOCITIES
TO EACH GEOPHONE AND ERRORS IN PICKING ARRIVALS.
WT=10000./(600.+D)
WW=ABS(W)*WT
THE LEAST CONSISTENT ARRIVAL IS IDENTIFIED.
IF (WMAX.GT.WW) GOTO 170
IMAX=I
WMAX=WW
ERROR=ERROR+W*W
DF(1),1=1,3 ARE THE DIRECTIONAL COSINES
FROM EACH (IMPROVED) LOCATION TO EACH GEOPHONE.
DF(1)=X/D
DF(2)=Y/D
DF(3)=Z/D
DF(4)=V
RR(I),I=1,4 & SS(I),I=1,10 ARE THE COEFFICIENTS OF THE MATRICES USED TO CALCULATE THE CORRECTION FACTOR USED TO IMPROVE THE LOCATION.
JK=0
DO 165 J=1,4
RR(J)=RR(J)+DF(J)*W*WT
DO 165 K=1,J
JK=JK+1
165 CONTINUE
164 CONTINUE
IF (NN.GT.2) GOTO 166
EVENTS WITH ONLY 3, 4, OR 5 READ ARRIVALS ARE LOOSELY CONstrained.
TO 100 M. ABOVE (HERCULES) REEF.
W=EVZ-4554.-.168*EVX+.420*EVY
RR(1)=RR(1)-0.168*W
RR(2)=RR(2)+0.420*W
RR(3)=RR(3)+W

DO 167 JK=1,6
167 SS(JK)=SS(JK)+RDIR(JK)

N=N+1
NARR(N)=999
RES(N)=W
DIS(N)=W

IF(NN.LT.4) GOTO 70
C**** LEQT1P IS A SUBROUTINE IN THE INTERNATIONAL MATH AND
C AND STAT LIBRARY IMSL.
C LEQT1P SOLVES THE EQUATION A*X=B.
C WHERE A IS AN N BY N MATRIX STORED IN SYMMETRICAL STORAGE
C MODE, AND B IS AN M BY M MATRIX.
C FOR THIS PROGRAM N=4 AND M=1.
166 CALL LEQT1P(SS, 1, 4, RR, 4, IGDT, D1, D2, IER)
C**** THE AMOUNT OF MOVEMENT DURING EACH SUCCESSIVE ITERATION
C IS RESTRICTED BY "FIX". THIS GUARDS AGAINST OSCILLATORY
C BEHAVIOUR SOMETIMES FOUND USING SEIDELS METHOD.

FIX=1.2-FLOAT(IT)/20.

EVX=EVX-RR(1)*FIX
EVY=EVY-RR(2)*FIX
EVZ=EVZ-RR(3)*FIX
EVT=EVT-RR(4)*FIX

IF(NN.EQ.4)GO TO 185
ERROR=SQRT(ERROR/(NN-4.0))

185 IF(NN.EQ.4)ERROR=0.0

D=DIST(RR(1),RR(2),RR(3))

C**** EVENT IS CONSIDERED TO DIVERGE IF ITERATION IS >5 KM.
IF(D.GT.5000.) GOTO 999
C**** EVENT IS CONSIDERED TO CONVERGE IF ITERATION IS <1 M.
IF(D.GT.1.0 .AND. IT.LE.30) GOTO 71

220 FORMAT(' VELOCITIES OF 6.1 AND 3.8 KM/SEC USED')

C EVX,EVY & EVZ ARE THE MINE COORDINATES OF THE EVENT LOCATION
C EVT IS THE ORIGIN TIME RELATIVE TO THE COMMON REFERENCE TIME
C ON THE HARDCOPY RECORD IN MILLISECONDS
C ERROR = SQRT((SUM OF SQUARES OF DISTANCE RESIDUALS IN METERS
C /(NUMBER OF ARRIVALS USED FOR LOCATION - 4))

C METRES CONVERSION FOR WRITE

EVX=EVX/0.3048
EVY=EVY/0.3048
EVZ=EVZ/0.3048
EVT=EVX/1000.

WRITE(6,21)EVX, EVY, EVZ, EVT1, ERROR

C TEMPORARY OUTPUT FILE ADDITION

WRITE(7,990)EVENT, NDAY, NHRS, MIN, EVT1, NEV
990 FORMAT(' )  
WRITE(7,991)EVX, EVY, EVZ, NSYM, NN, ERROR
991 FORMAT(3F8.0,4X,'PLOT SYMBOL = ',',I2,5X,'ARRIVALS = ',',I2,3X,'ERR
+P5.0,/,1X)

C METRES CONVERSION FOR WRITE

EVX=EVX*0.3048
EVY=EVY*0.3048
EVZ=EVZ*0.3048
EVT1=EVX/1000.
EVZ = EVZ * 0.3048

141

C**********

21 FORMAT( 'OX = ', F7.0, ', Y = ', F7.0, ', Z = ', F7.0, ', T = ', F7.3,
1
', ERROR = ', F5.0)

25 FORMAT( '+ ', 60X, 'OVER', I3, ' ITERATIONS' )

250 FORMAT( 4X, 'DIST MOVED LAST ITER', F6.0, ' METRES' )

C

C***** NARR(N) : GEOPHONE NUMBER OF NTH ARRIVAL

N = 13 TO 24 FOR S ARRIVALS

IF( NARR .LT. 0 ) ARRIVAL IS NOT USED FOR THIS LOCATION

NARR = 999 EVENT IS LOOSELY CONSTRAINED TO 100M ABOVE(HERCU

REEF

WRITE( 6, 26 ) NN, ( NARR(I), I = 1, N )

26 FORMAT( /, I3, ' ARRIVALS', 16, I7 )

C

C RES : (THEORETICAL - OBSERVED) ARRIVAL TIME, MSEC

WRITE( 6, 27 ) ( RES(I), I = 1, N )

27 FORMAT( ' RESIDUALS ', 16F7.0 )

C

C**** DIS(I) = HYPOCENTRAL DISTANCE BETWEEN GEOPHONE I AND

C EVENT LOCATION

C

C************************

37 CONTINUE

DO 37 I = 1, N

DIS(I) = DIS(I) / 0.3048

37 CONTINUE

WRITE( 6, 28 ) ( DIS(I), I = 1, N )

28 FORMAT( ' DISTANCE ', 16F7.0 )

IF( NPOOR1 .EQ. 0 ) GO TO 171

C

C**** UNCERTAIN ARRIVAL TIMES ARE MADE NEGATIVE AND THE LOCATION

C IS REPEATED WITHOUT THEM

C IF TWO ARRIVALS ARE UNCERTAIN IE NPOOR.NE.0

C LOCATION IS REPEATED FIRST WITHOUT THE UNCERTAIN ARRIVAL

C WHICH HAS THE LARGER TIME RESIDUAL.

C

IF( ( NPOOR2 .EQ. 0 ) .OR. ( ABS( RES1 ).GT. ABS( RES2 ) ) ) GO TO 129

ARTM( NPOOR2 ) = - ARTM( NPOOR2 )

WRITE( 6, 29 ) NPOOR2

29 FORMAT( '0', ' RELOCATE WITHOUT DOUBTFUL ARRIVAL', I3 )

NPOOR2 = 0

GOTO 72

129 ARTM( NPOOR1 ) = - ARTM( NPOOR1 )

WRITE( 6, 29 ) NPOOR1

NPOOR1 = NPOOR2

NPOOR2 = 0

GOTO 72

171 CONTINUE

IF( NNEW .NE. 0 ) GOTO 173

C

C**** DOUBTFUL OR BADLY INCONSISTENT ARRIVALS ARE TESTED TO SEE

C IF THEY COULD HAVE BEEN PICKED AS THE INCORRECT PHASE.

C IF SO, THE LOCATION IS REPEATED WITH THE 'CORRECTED' DATA.
DO 172 I = 1, N
361 NOLD = -NARR(I)
362 IF (NOLD .LE. 0) GOTO 172
363 II = ISIGN(1, 21 - 2 * NOLD)
364 IF (ABS(II * DIS(I)/RES(I) + 10.5) .GT. 2.0) GOTO 172
365 NNEW = NOLD + 12 * II
366 ARTM(NNEW) = -ARTM(NOLD)
367 ARTM(NOLD) = 0.
368 WRITE(6, 272) NOLD, NNEW
369 272 FORMAT ('0', 'TRY ARRIVAL', 13, ' AS ARRIVAL', 13)
370 GOTO 72
371 172 CONTINUE
372 173 CONTINUE
373 GO TO 70
374
375 C IF((WMAX .LT. 600.) .OR. LDONE .OR. (NN .LE. 6)) GOTO 70
376 C**** IF ANY ARRIVAL IS INCONSISTENT BY MORE THAN ABOUT 50 M
377 C (AT 1 KM) COMPARED TO THE EXPECTED LOCATION,
378 C A FURTHER LOCATION IS DONE WITHOUT IT.
379 LDONE = .TRUE.
380 WRITE(6, 23) IMAX
381 23 FORMAT ('0', '****', 13, ' ???? ****')
382 ARTM(IMAX) = -ARTM(IMAX)
383 NLINE = NLINE + 8
384 GOTO 72
385 999 WRITE(6, 24) IT
386 24 FORMAT (40X, 'DIVERGES AFTER', 13, ' ITERATIONS')
387 C***********************
388 C METRES CONVERSION FOR WRITE
389 EVX = EVX/0.3048
390 EVY = EVY/0.3048
391 EVZ = EVZ/0.3048
392 EVT1 = EVT/1000.
393 WRITE(6, 21) EVX, EVY, EVZ, EVT1, ERROR
394 C TEMPORARY OUTPUT FILE ADDITION
395 WRITE(7, 990) EVENT, NDAY, NHRS, MIN, EVT1, NEV
396 WRITE(7, 991) EVX, EVY, EVZ, NSYM, NN, ERROR
397 EVX = EVX*0.3048
398 EVY = EVY*0.3048
399 EVZ = EVZ*0.3048
400 C************************
401 WRITE(6, 26) NN, (NARR(I), I = 1, N)
402 IF (NPOOR1 .EQ. 0) GOTO 70
403 C**** DIVERGENT LOCATIONS ARE REPEATED WITHOUT UNCERTAIN ARRIVALS.
404 ARTM(NPOOR1) = -ARTM(NPOOR1)
405 WRITE(6, 29) NPOOR1
406 NPOOR1 = NPOOR2
407 NPOOR2 = 0
408 GOTO 73
409 99 STOP
410 END

End of File
## TEST EXAMPLE

**T1 OPEN PIT BLAST**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>HEAD</th>
<th>SKEW</th>
<th>P</th>
<th>S</th>
<th>GEOPHONE</th>
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<td>4068</td>
<td>9705</td>
<td>3936</td>
<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>1. D39</td>
</tr>
<tr>
<td>5710</td>
<td>13000</td>
<td>2727</td>
<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>2. D27</td>
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<tr>
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<td>0.0</td>
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<td>3.06</td>
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<tr>
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<td>5. MOR</td>
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<td>5.30</td>
<td>3.06</td>
<td>6. NAD</td>
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<tr>
<td>8637</td>
<td>12706</td>
<td>4346</td>
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<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>7. LO1</td>
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<tr>
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<td>16860</td>
<td>5482</td>
<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>8. SUL</td>
</tr>
<tr>
<td>-15990</td>
<td>-850</td>
<td>4190</td>
<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>9. MAT</td>
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<tr>
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<td>4630</td>
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<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>10. MRK</td>
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<tr>
<td>-14339</td>
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<td>5457</td>
<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>11. BOG</td>
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<tr>
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<td>0.0</td>
<td>0.0</td>
<td>5.30</td>
<td>3.06</td>
<td>12. PIT</td>
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</table>

**EVENT(5):29**  
**NUMBER = 75**  

<table>
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<th>X</th>
<th>Y</th>
<th>Z</th>
<th>T</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.89</td>
<td>0.0</td>
<td>0.0</td>
<td>47.32</td>
<td>46.95</td>
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<td>47.24</td>
<td>47.40</td>
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<td>0.0</td>
<td>48.04</td>
<td>47.43</td>
</tr>
<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>46.96</td>
</tr>
</tbody>
</table>

X = 4074., Y = 8495., Z = 3392., T = 46.835, ERROR = 241. OVER 13 ITERATIONS

**ARRIVALS**  
| 5 | 6 | 7 | 8 | 9 | 10 | 12 |

**RESIDUALS**  

**DISTANCE**  
| 1326. | 8415. | 2223. | 6282. | 9529. | 22148. | 9928. | 1885. |