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**ANALYSIS OF MICROSEISMICITY AND HAZARD
ASSESSMENT OF THE SELIBE PHIKWE CU-NI MINE (BCL),
BOTSWANA**

by

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ABSTRACT

Seismic Monitoring is a technique that uses vibration monitors in the detection and analysis of dynamic stress waves, generated from failure of rock mass. This technique was applied at the Selibe-Phikwe Cu-Ni mine (BCL) and surrounding areas to study the seismic activity. Shaking of the ground destabilizes both manmade and natural structures like, buildings, pillars and faults, through weakening and causing cracks on buildings, crushing pillars and awakening dormant faults. The main aim of the research project was to provide information about the seismic activity taking place within and around the Selibe-Phikwe Cu-Ni mining area with specific objectives of determining the locations of the seismic events, determining the seismic source mechanisms and other source parameters and providing a seismic hazard assessment. Data for this project was acquired from the Botswana Geological Institute (BGI). BGI had set up a temporary seismic monitoring system using seismic equipment from the Institute of Mine Seismology (IMS). These included; surface mount sensors that record vibrations, an enclosure with seismic monitoring equipment that digitizes and processes data as well as a Wi-Fi radio for communication to the server. Data processing was accomplished using IMS Trace™ and IMS Vantage™ software. IMS Trace™ was used for calculating source parameters, picking of phase arrivals and calculation of the location of the source energy (earthquake) while IMS Vantage™ is an analysis and visualization toolkit that was used to understand and explore seismicity both temporally and spatially within the mine. The data analyzed was for a period of 33 months (from 27th June 2019 to 11th March 2022). A total of 266,931 events were processed; these were

located in the south-eastern extension of the mine with majority of the events having occurred in 2019. Local and moment magnitude of all the events ranges from -2.7 to 3.6. Most large events occur below the 980m level. There are more small events (<0) than large events (>0). A correlation between the number of events per month and pumping activities was established. Events of magnitude >1.5 were used for moment tensor decomposition. The moment tensor decomposition of the amplitude and polarities together with the full waveform for the same event yielded a more diviatoric component with a much higher double couple in both cases. The source type plots showed a neither implosive nor explosive component and axes orientations of the two, were not very well constrained. An instability analysis was carried out that showed an increase in Cumulative Apparent Volume which indicates an increase in fracturing of parts of the rock mass within the south-eastern part of the mine, and as they become unstable and there might occur large scale rock mass deformation. Log Energy Index was greater than zero which indicates accumulation of stress, this can be regarded as a strain softening stage and it should be a warning indicator for potential damage. The frequency magnitude analysis showed a much gentler cumulation which indicates a higher proportion of large events in the study area; this therefore indicates a significantly noticeable degree of seismic hazard.

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1.0 CHAPTER ONE

1.1 INTRODUCTION

BCL Limited mine in Selibe-Phikwe has been prosperous throughout the years since it began its operation in 1956. It is a copper nickel mine (Vurayai et al., 2015) hosting a large mineralized deposit with an average production of over 40 000 tonnes per year since 1980. Among the private sectors it was the second largest employer with over 4200 employees. The mine started as an open cut mine which later became an underground mine where numerous underground tunnels were developed. The underground excavations are extensive such that almost the whole town is covered underneath.

A drastic decrease of copper nickel prices in previous years led to the mine not making profit. After it started operating at a loss, a decision of its closure was made in October 2016. Amongst the tragedies were people losing their jobs and the town losing its source of economic development, BCL Limited mine stopped pumping water from underground workings towards the end of 2018, and underground excavations started flooding with water.

In early 2019 approximately three years after mine closure, Selibe-Phikwe area started experiencing earth tremors. Tremors were minor at the beginning then became severe overtime. The severity was such that damages to buildings were reported by residents. In order to get an insight on the tremors experienced by Selibe-Phikwe residents,

21 Botswana Geoscience Institute (BGI) with help from Aqualogic (Pty) Ltd and Open
22 House Management Systems (OHMS) (Pty) Ltd deployed a temporary seismic
23 monitoring system in June 2019.

24 Water pumping activities were resumed in August 2019. The data from temporary
25 Seismic monitoring system brought realization of the significance of having a
26 monitoring system in a mining environment such as BCL Limited. Hence a permanent
27 seismic monitoring system was deployed in October 2020. Data from both the
28 temporary and permanent seismic monitoring systems was used for this research
29 project.

30 The aim of the deployment of the temporary and permanent seismic network by the
31 BGI was to monitor the microseismicity taking place at Selibe-Phikwe and provide risk
32 mitigation recommendations. This was the only seismic study carried out in the area
33 prior to this research project. The study was for a period of thirteen (13) weeks
34 (Aqualogic & OHMS, 2019) which confirmed the presence of microseismicity in the
35 area and concluded that the seismic activity was mine induced.

36 Prior to the discussed data acquisition there was no previous recording of seismic data
37 as well as important parameters such as pore pressure, porosity, hydrology and rock
38 mechanics. Therefore, the study confirmed the presence of mine induced seismicity
39 but there was no information on the sources of the seismic activity and the extent of
40 seismic hazard in the BCL Limited mine. Finding the source of these events was a major
41 mandate of this research project.

42 This research project provided an analysis of microseismicity by producing and
43 analyzing the distribution of events in 3D space, frequency of occurrence of events,
44 moment tensor decomposition and performed a seismic hazard assessment of the
45 area by using the frequency magnitude relation and carrying out an instability analysis.
46 Seismic activity in hard rock underground mines goes hand in hand with hydrological
47 analysis, but due to lack of hydrological data, hydrological analysis was not carried out.
48 Seismic monitoring equipment and software used were from Institute of Mine
49 Seismology (IMS).

50 **1.2 BACKGROUND**

51 A rock mass is in a stable stress condition prior to mining, subjected only to weathering
52 and tectonic pressures (Smith, 2018). As rock is mined, underground mine
53 development activities generate local changes in the stress state, and as greater
54 depths are reached, the stresses increases due to gravity loading. Localized failure and
55 associated seismic activity depend on the quality of the rock mass, the presence of
56 geological features, increasing depth, and mining activities (Smith, 2018).

57 A seismic event occurs when inelastic deformation in a rock mass causes a dynamic
58 stress wave (Hudyma, 2008). Seismic events in mines, also known as mining-induced
59 seismicity, are a common resultant of mining, especially in hard, brittle rock. In severe
60 cases, extreme rock mass damage may be related to mining-induced seismicity. There
61 are a number of rock mass failure mechanisms that may produce seismic events in

62 mines. A complicated relationship between discrete geological features, rock mass
63 characteristics, and mining-induced stress causes rock mass failure in mines.

64 Rock bursting and seismicity have been reported in most of the world's main mining
65 zones in hard rock mines. For nearly a century, it has been a serious concern in deep-
66 level South African gold mines (Hudyma, 2008). Equipment damage, reduced
67 production, loss of ore reserves, workforce injuries, fatalities, and mine closures have
68 all been reported as a result of seismicity in mines.

69 According to Goldbach (2010), due to the progressive rise of groundwater, many gold
70 mines will flood when they are closed. Following the closure of mines, the dewatering
71 procedure is also discontinued, resulting in the flooding of abandoned mines, which
72 result in "Acid Mine Drainage" (AMD). AMD is caused when water flows over or
73 through sulfur bearing materials forming solutions of net acidity. Mining-induced
74 seismic events have also arisen as a result of the flooding of abandoned mines.

75 Seismic monitoring can be utilized as a method to investigate and characterize the
76 source and the probable mechanism of recorded seismic events. Understanding the
77 events is essential for assessing hazards and damage potential in advance (Smith,
78 2018).

79 **1.3 PROBLEM DEFINITION**

80 Seismicity induced by mining is a great concern worldwide, since it has been attributed
81 to infrastructural damages and loss of lives. Shaking of the ground destabilizes both
82 manmade and natural structures like buildings, pillars and faults through weakening

83 and causing cracks on buildings, crushing pillars and awakening dormant faults. This
84 causes even more severe problems with time. Selibe-Phikwe residents who are
85 currently experiencing these tremors are at a greater risk since damages to buildings
86 have already been reported.

87 The mining industry is associated with benefits of increased employment, economic
88 development and foreign exchange reserves (Letshwenyo, 2016). Without
89 overshadowing or overruling the substantial benefits, it should also be considered that
90 terminating the dewatering process after mine closure does more harm than good as
91 evidenced by case studies in Johannesburg (Du Plessis et al., 2015; Reimer & Durrheim,
92 2012)

93 After termination of dewatering program, water fills up mine voids increasing pressure
94 underground. Geochemical and chemical reactions among rock surfaces, oxygen and
95 mine wastes leads to the water underground becoming acidic. The rate of oxidation of
96 sulphides in the mineralogy of the rocks determines the impact of acid mine drainage.
97 Acid generation also depends on the amount of flow through or over the mine rock
98 strata. The extent of corrosiveness of the acid mine drainage as compared to
99 uncontaminated water provides lubrication to structures and reduces clamping forces.
100 This lubrication coupled with high pressure underground destabilizes manmade and
101 natural fractures and faults thus generating seismicity (Du Plessis et al., 2015).

102 The BCL limited mine at Selibe-Phikwe has extensive numerous tunnels covering
103 almost the whole village underneath. The main concern with this is that seismicity was

104 increasing with time yet there was insufficient information on the seismic source and
105 the potential seismic hazard at the mine. There is also lack of previous information on
106 the seismicity of the mine to show how seismic activity varied with time especially
107 before and after mine closure.

108 **1.4 AIM AND OBJECTIVES**

109 The research project was aimed at the understanding of the seismic activities
110 experienced at the BCL Limited mine and provides the necessary information for the
111 implementation of mitigation strategies to benefit Selibe-Phikwe residents. The
112 specific objectives of the research are:

- 113 ➤ Determine the locations of the seismic events
- 114 ➤ Determine the seismic source mechanisms and other source parameters
- 115 ➤ Provide the seismic hazard assessment of the area

116 **1.5 SIGNIFICANCE**

117 A deeper understanding of the nature of seismicity associated with mining at the
118 Selibe-Phikwe Cu-Ni mine (BCL Limited) is acquired. Seismic source parameters provide
119 an understanding of the nature of seismic activity. Seismic source mechanisms provide
120 the failure mode that caused the ground vibrations. Seismic hazard provides the
121 susceptibility of the area to large and damaging ground vibrations. All this knowledge
122 paves a way to finding mitigation strategies to be implemented.

123 A study of this nature shows the extent of damage to the mining area clearly depicting
124 which areas are more or less damaged than the others. Minimally or no damaged
125 areas can be pinpointed where mining operations can safely take place should the
126 mine start mining operations. This can therefore motivate the commencement of
127 mining activities at certain areas of the mine should the prices of Cu and Ni be good
128 enough for profitable mining again at BCL mine.

129 This research project will provide insights on the impacts caused by mine induced
130 seismicity, with this information other mines or mining areas would be motivated to
131 have their own seismic monitoring stations so they are in a better place to deal with
132 such impacts and come up with solutions prior to any severe damages.

133 **1.6 PROJECT OUTLINE**

134 In Chapter one, the context of the study has been discussed, the research aim and
135 objectives identified and the significance of the research argued.

136 In Chapter two, literature is reviewed to identify key concepts in seismology,
137 specifically in mine seismology.

138 Chapter three discusses the process of data acquisition and gives a clear and concise
139 description of the processing of the data and the software used before obtaining the
140 final results.

141 Chapter four presents results in the form of distribution of events, seismic source
142 parameters, seismic source mechanism and seismic hazard analysis graphs.

143 Chapter five discusses the results and correlates them with published literature.

144 In Chapter six, conclusions of the study and recommendations for future studies as

145 well as improvements on the current study are provided.

2.0 CHAPTER TWO

2.1 LITERATURE REVIEW

2.1.1 GEOGRAPHICAL LOCATION

Selibe-Phikwe town is located in eastern part of Botswana approximately 400km north of the capital city, Gaborone (Letshwenyo, 2016) (Figure 2.1). It is 60km east of the A1 (Gaborone-Francistown road) and 150km south east of Francistown. Geologically Selibe-Phikwe forms part of the Phikwe Complex of the Central Zone of the Limpopo Belt.

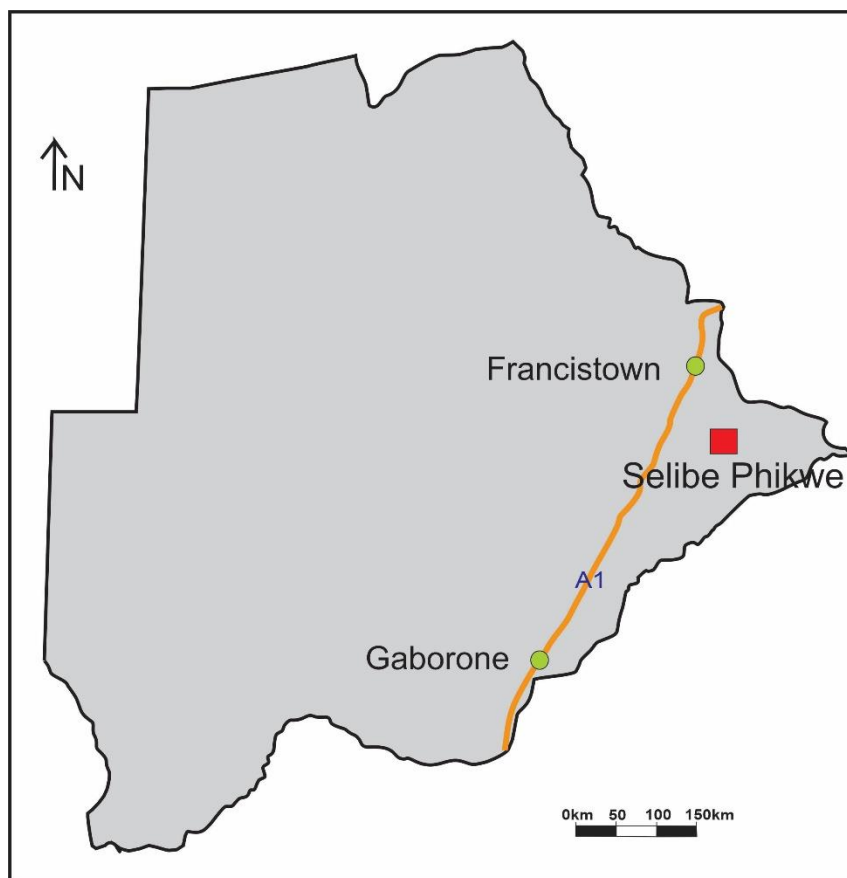
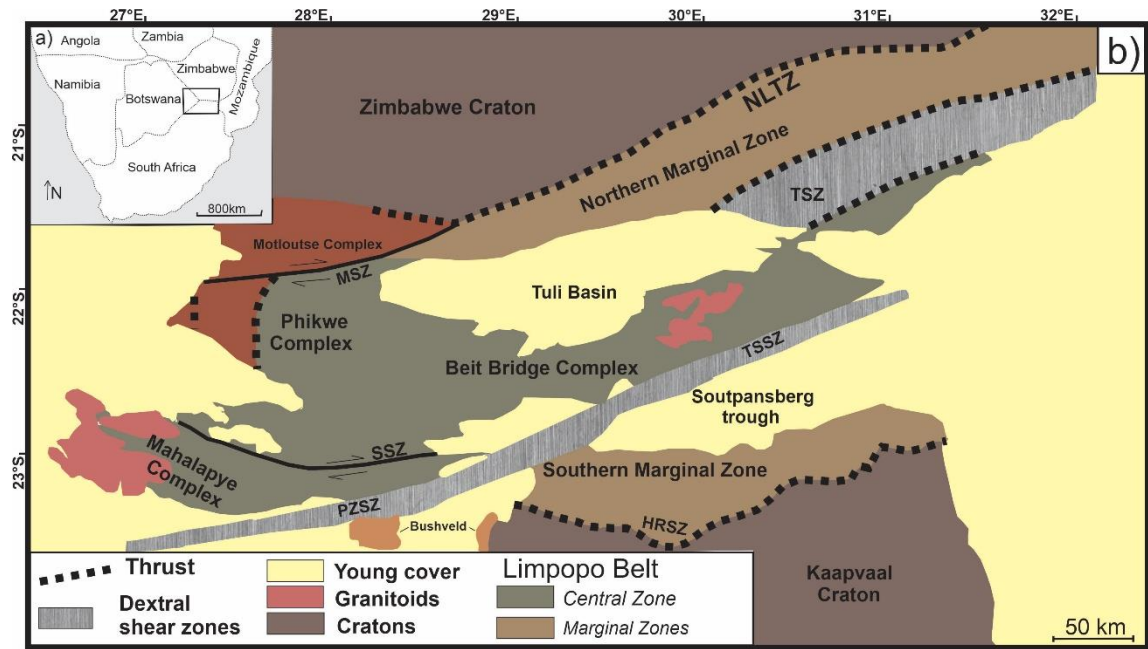


Figure 2.1: Map showing the location of Selibe-Phikwe.

156 **2.1.2 GEOLOGICAL SETTING**

157 **2.1.2.1 REGIONAL GEOLOGY**

158 Southern Africa is home to the Zimbabwe Craton, Kaapvaal Craton and the Limpopo
159 mobile Belt, these are zones separated by major shear zones (Figure 2.2). These zones
160 experienced different tectonic styles, different pressures and different temperatures
161 associated with different orogenic processes (Millonig, 2009). In Botswana the
162 Kaapvaal Craton is in the south of the Zoetfontein Fault. The Zimbabwe Craton is a
163 granitoid-greenstone terrain with 26 greenstone belts and their associate granitoids.
164 The south-western part of the Zimbabwe Craton extends into Botswana as the
165 Maitengwe, Matsitama and Tati-Vumba granitoid greenstone terraines. The Limpopo
166 mobile Belt is a granulite gneiss terrain trending east-northeast, located between the
167 Zimbabwe and Kaapvaal Cratons (McCourt et al., 2004). The belt has long been
168 considered to be a result of the collision between the Zimbabwe and Kaapvaal cratons
169 (Millonig, 2009). The Limpopo Belt is divided into three crustal domains; the Northern
170 Marginal Zone, the Central Zone and the Southern Marginal Zone (Figure 2.2). The
171 North Marginal Zone is represented by the Semolale Complex; the Central Zone is
172 divided into the Mahalapye and Phikwe Complexes. The northern boundary of the
173 Limpopo Belt against the Zimbabwe Craton in Botswana is a matter of debate
174 (McCourt et al., 2004).



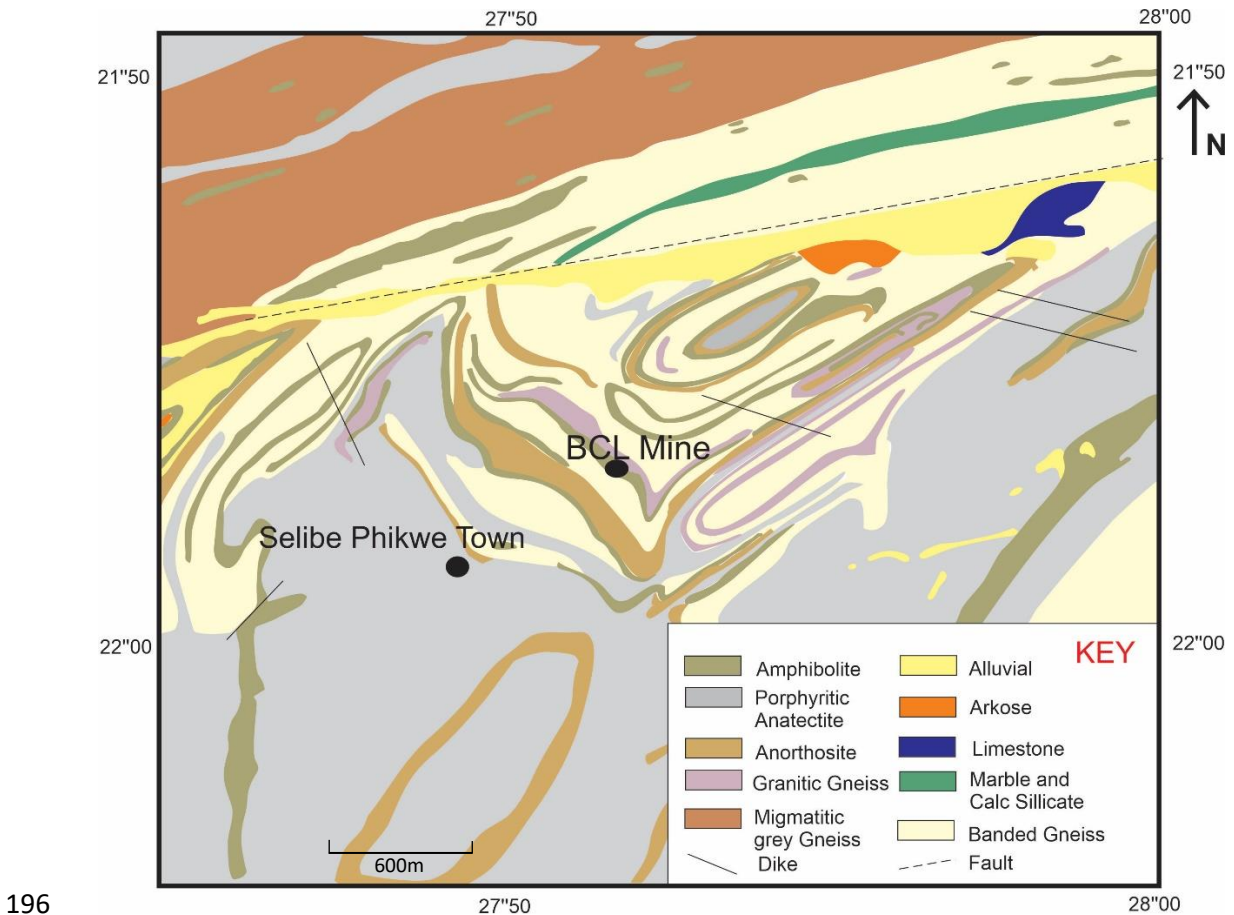
175

176 Figure 2.2: Detailed regional geologic map of Selibe-Phikwe and surrounding areas, a)
 177 Southern Africa b) regional geology, modified from Millonig, (2009).

178 2.1.1.2 GEOLOGY OF THE AREA

179 The study area lies in the Phikwe Complex of the Central Zone of the Limpopo Belt,
 180 which consists of gneisses hosting mafic-ultramafic intrusions contained in the Selibe-
 181 Phikwe Belt (Motswaiso et al., 2019; Maier et al., 2007). The gneisses are Archean
 182 quartz feldspathic tonalitic hornblende bearing and trondhjemitic (Maier et al., 2007)
 183 (Figure 2.3). The gneisses are characterized by fold patterns with large amplitudes and
 184 planar fabrics trending north to northeast at Phikwe and north to south at the
 185 southern part of the Complex (Motswaiso et al., 2019). Amphibolites and minor
 186 ultramafic rocks are found having variable foliation and intrusive contacts. The
 187 northern boundary is formed by the Mogogaphate shear zone (McCourt et al., 2004).

188 According to Maier et al., (2007) the protoliths to the hornblende gneisses are shallow
 189 intrusions and volcanics while those of the quartz feldspathic gneisses are calkline
 190 volcano-sedimentary rocks. Granitic gneisses are aged between 2.6 and 2.65 billion
 191 years (Maier et al., 2007). The central Phikwe, Selibe and Selibe north make the Phikwe
 192 copper deposits which are intrusive (Maier et al., 2007). According to Motswaiso et al.,
 193 2019 (citing Maier et al., 2007) the study area comprises major and minor sulfide
 194 minerals. The major sulphide minerals include pentlandite, pyrrhotite and chalcopyrite
 195 while the minor are marcasite, bravoite, violarite and pyrite.



196
 197 Figure 2.3: Detailed geologic map of Selibe-Phikwe and surrounding areas, modified
 198 from Motswaiso et al, (2019).

199 **2.1.3 SEISMOLOGY**

200 Seismology is the study of seismic wave generation and propagation (Udías, 1997). It is
201 based on seismograms, which are records of mechanical vibrations that provide the
202 fundamental data for seismologists (Lowrie, 2018). Seismology can also be defined as a
203 study of elastic waves in the earth's crust and the sources that cause them. Seismology
204 has traditionally been defined as the science of studying earthquakes in a broad sense
205 (Båth, 1979); their occurrence as well as their characteristics. As a result, many
206 disciplines such as physics, chemistry, geology, and engineering come into play
207 (Agnew, 1989). Seismology, according to Richter (1957) as cited by (Udías, 1997), is a
208 field that straddles the divide between geology and physics.

209 Understanding the earth's interior and the source of earthquakes has relied heavily on
210 the study of elastic (seismic) waves (Båth, 1979). After large earthquakes, seismic
211 waves analysis combined with geological field observations provide valuable
212 information about earthquake source mechanisms. Without the incorporation of
213 tectonics, a correct interpretation of the seismicity and source mechanisms of
214 earthquakes in a region is unlikely (Udías, 1997).

215 **2.1.3.1 SEISMIC WAVES**

216 Seismic waves are elastic strain energy parcels that propagate outwards from a seismic
217 source. The strain associated with a seismic pulse's immediate passage is very small
218 and can be assumed to be elastic (Kearey et al., 2002). Normal and shear strains are
219 caused by earthquakes, resulting in a variety of seismic waves. The wavelength and

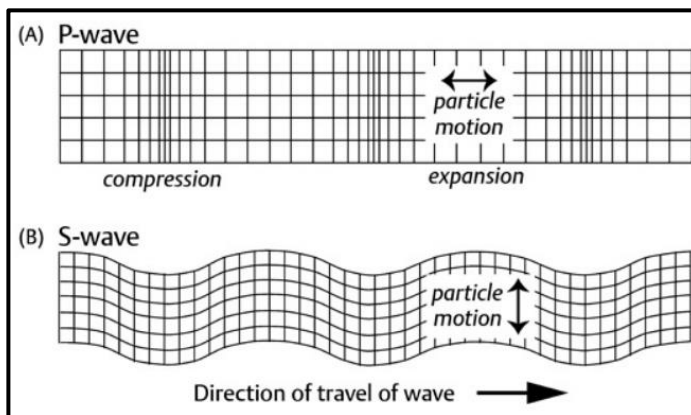
220 frequency of each type of wave are used to describe it, and their product is the wave's
221 speed (Lowrie, 2018). Their speeds depend on elastic moduli and the density of the
222 rocks (Kearey et al., 2002; Lowrie, 2018). There are two main groups of seismic waves;
223 body waves and surface waves but for this research project we focus mainly on the
224 body waves.

225 **2.1.3.1.1 BODY WAVES**

226 Body waves travel through an elastic solid's internal volume and there are of two types
227 (Kearey et al., 2002).

228 **2.1.3.1.1.1 Primary wave (P wave), also called longitudinal or compressional**

229 P waves propagate through compressions and rarefactions produced by particles in the
230 ground moving backward and forward in the direction of wave propagation (Kearey et
231 al., 2002; Lowrie 2018) (Figure 2.4A). It is the fastest seismic wave and can travel
232 through fluids, though at a slower rate. A P-wave normally causes nearly vertical
233 motion when it reaches the Earth's surface (Lowrie, 2018).



234
235 Figure 2.4: Body waves (A) P waves and (B) S waves, Adapted from Lowrie, (2018).

236 **2.1.2.1.1.3 Secondary wave (S wave), also called transverse or shear**

237 S waves propagate through shear strain in the direction right angled to the direction of
238 propagation of the wave (Keary et al., 2002) (Figure 2.4B). S waves travel slower than P
239 waves and cannot propagate through a fluid, because fluids do not have shear
240 strength. Because S-waves have components in both vertical and horizontal planes,
241 they shake buildings up and down and from side to side when they reach the Earth's
242 surface (Lowrie, 2018).

243 **2.1.4 MINE SEISMOLOGY**

244 Seismology induced by mining is described as the occurrence of seismic events
245 triggered by failures of rock as a result of changes in the stress field within the rock
246 mass near mine openings (Hudyma, 2008). Locating seismic occurrences is the initial
247 step in understanding mine seismicity. Accuracy is one of the most important factors in
248 such investigations. The spatial structure of seismic networks, the precision of seismic-
249 wave arrival data, and the suitability of the assumed velocity model all influence the
250 accuracy of seismic event locations. (Gibowicz & Kijko, 1994).

251 Within the surrounding rock mass, mining excavations cause elastic and ultimately
252 inelastic deformation. During the process of inelastic deformation, the potential
253 energy accumulated in the rock mass may be released quickly or gradually (Mendecki
254 et al., 1999). Three essential factors govern the degree and consequences of failure:
255 stress state, geomechanical conditions, and mining activities. The phrase
256 "geomechanical conditions" refers to intact rock with geological structures (folds,

257 faults, joints, and so on), and it is defined by the strength and stiffness of the intact
258 rock, water pressure and joints (Smith, 2018). The interaction of all three factors is a
259 requirement for failure to occur. Different failure modes occur depending on the
260 characteristics of the variables.

261 Rock failure and seismic activity are common occurrences in large-scale deep
262 underground mining (Gibowicz & Kijko, 1994). The research and quantification of
263 seismic source factors such as radiated seismic energy and coseismic inelastic
264 deformation has allowed us to progress beyond simple event location and time
265 analysis to routine rock mass stability interpretation (Mendecki et al., 1999). Seismicity
266 caused by underground mining has been documented in a number of mining districts
267 across the world (Gibowicz & Kijko, 1994).

268 **2.1.5 SEISMIC MONITORING**

269 Seismic monitoring is a technique that uses vibration monitors for detecting and
270 analyzing dynamic stress waves that are a result of failure of rock mass, often known
271 as seismic events. Understanding mine seismicity can be accomplished by gaining
272 knowledge of two factors: seismic hazard and seismic source mechanism. In order to
273 execute an effective seismic analysis, populations of seismic events are used to tie rock
274 mass failure mechanisms to patterns in seismic data (Hudyma, 2010). Different seismic
275 analysis methods use seismic source parameters such as event location, event time,
276 seismic moment, source size, and seismic energy to evaluate the seismic hazard and
277 the seismic source mechanism (Hudyma, 2010; Abolfazlzadeh, 2013).

278 **2.1.5.1 SEISMIC SOURCE PARAMETERS**

279 **2.1.5.1.1 SOURCE LOCATION**

280 A seismic source's location is a point at the source that triggered seismic sites used to
281 locate it. It provides information on how the ground is changing and how the rock
282 mass responds to mining (Mendecki et al., 2010). Accurately locating the seismic
283 source provides insights into how rock mass responds to mining and where ground
284 conditions are shifting (Abolfazlzadeh, 2013). The quality of the seismic data collected
285 can also be checked by accurately locating the source. If the locations of seismic events
286 are frequently distributed or unstable during seismic data processing, the data
287 captured by the seismic system is most likely of poor quality. Because the quality of
288 most other seismic event source parameters is reliant on the source location, if the
289 quality of the location of the source is unreliable, the quality of the other seismic
290 source parameters may be unreliable as well (Mendecki et al., 2010).

291 **2.1.5.1.2 EVENT MAGNITUDE**

292 The energy generated by a rupture is used to determine the magnitude of a seismic
293 event. It is the most commonly used criterion for describing seismic activity (Alaneme
294 & Okotete, 2018; Gibowicz & Kijko, 1994). The Richter scale, created in the 1930s by
295 seismologist Charles Richter to define the sizes of local earthquakes in California, has
296 been used to classify magnitudes in the past. Later, it was expanded to include sources
297 that are distant (Lowrie, 2018; Smith, 2018). The Nuttli Magnitude scale, which is
298 commonly used in Eastern Canada to measure earthquakes and seismic events, and

299 the Moment Magnitude scale, which is a measure of the seismic moment and is best
 300 associated with the size of a fault slip event, are two more commonly known
 301 magnitude scales that have been developed (Smith, 2018). Local Magnitude (ML) is a
 302 word that has been frequently used to designate a magnitude scale calibrated from
 303 the moment magnitude of events recorded on a local seismic monitoring system,
 304 which is common in underground mining, and used to quantify events within the
 305 localized system (Smith, 2018; Glazer, 2018; Nthaba et al., 2018). Hudyma, (2010)
 306 presents a qualitative description of earthquake activity on the Richter scale.

307 **Table 2.1: Qualitative description of seismic activity relative to the Richter and Local**
 308 **magnitudes (Adapted from Hudyma, 2010).**

Approximate Local Magnitude	Approximate Richter Magnitude	Qualitative Description
-3.0	-2.0	➤ Most microseismic monitoring systems cannot detect events ➤ Events are audible, but vibrations are generally too small to be felt ➤ This degree of seismic noise is usual after development blasts in stressed ground ➤ Small bangs or bumps heard nearby ➤ Only those who are relatively close to the

		source of the event can hear it.
-2.0	-1.0	➤ Often detectable using a microseismic monitoring device ➤ Felt like good thumps or rumbles. ➤ Ground shaking may be sensed from a distance of more than 100 meters from the source of the occurrence.
-1.0	0.0	➤ Similar vibration to a distant subterranean secondary blast ➤ Significant ground shaking reported near to the occurrence ➤ Should be observable by a seismic monitoring system ➤ Often felt by many mine personnel
0.0	1.0	➤ Vibrations similar to those produced by a development ground are felt on the surface. ➤ Bump may be felt on the surface (from hundreds of meters away), but not audible. ➤ Vibrations can be felt and heard all over the mine.

1.0	2.0	➤ Vibrations felt on the surface akin to a huge manufacturing blast ➤ Felt and heard extremely clearly on surface by regional seismological sensors located a few hundreds of kilometers distant
2.0	3.0	➤ The geological survey of Canada is generally capable of detecting events of this magnitude. ➤ The vibrations felt on the surface are higher than those caused by massive production blasts.
3.0	4.0	➤ Earthquake monitoring across the province are capable of spotting the event.

309

310 **2.1.5.1.3 SEISMIC MOMENT**

311 The area of ruptured segment of a fault, average amount of slip, and the elastic shear
312 modulus of the ruptured rocks all contribute to seismic event size. Multiplying these
313 three quantities together produces the seismic moment (Lowrie, 2018). Also known as
314 a scalar that represents the source of coseismic inelastic deformation. The integral of
315 the far field displacement pulse is proportional to the seismic moment; therefore, it is
316 easy to calculate from waveforms (Mendecki et al., 2010). Moment-magnitude is a

317 scalar that converts seismic moment to magnitude of a seismic event (Mendecki et al.,
 318 2010). The following formula (Equation 2.1) (Gibowicz & Kijko, 1994) can be used to
 319 determine the seismic moment:

$$320 \quad M_o = 4\pi\rho_o c_o^3 R \frac{\Omega_o}{F_c} \dots\dots\dots \text{Equation 2.1}$$

321 Where, M_o is the seismic moment in Nm, ρ_o is the density of the rock in kg/m³ at the
 322 region of the earthquake, c_o is the wave velocity in m/s for either P-wave or S-wave, R
 323 is the distance from receiver to seismic source in m, Ω_o is the low frequency plateau of
 324 the frequency spectrum of a seismic waveform and F_c is the coefficient of the
 325 empirical radiation pattern for either P-wave or S-wave. The low-frequency plateau
 326 refers to a relatively flat or constant energy level observed in the lower frequency
 327 range of the seismic spectrum. It signifies that the seismic signal has significant energy
 328 content in the lower frequencies and remains relatively constant in that range
 329 (Gibowicz & Kijko, 1994).

330 **2.1.5.1.4 SEISMIC ENERGY**

331 The energy released from the rupture of rock mass at the source. The radiated seismic
 332 waveforms released at the source are used to calculate seismic energy. An increase in
 333 seismic moment increases seismic energy. Gibowicz & Kijko's, 1994 formula (Equation
 334 2.2) for calculating seismic energy is used.

$$335 \quad E = 4\pi\rho_o c_o \langle F_c \rangle^2 \left(\frac{R}{F_c R_c} \right)^2 J_c \dots\dots\dots \text{Equation 2.2}$$

Where, E is the radiated energy in joules, ρ_r is the density of the rock in kg/m^3 , c_r is the wave velocity in m/s , R is the seismic source distance in m , J_c is the integral of the square of the ground velocity, F_c is the coefficient of the empirical radiation pattern and R_c accounts for the free surface amplification.

2.1.5.1.5 APPARENT STRESS

Apparent stress is the measure of relative energy release per unit of deformation that is used to infer increasing rock mass stress conditions. Apparent stress of mine seismic data typically exhibits a scale dependence. As the event size (moment) increases, apparent stress increases at a greater rate. There is a reciprocal relationship between apparent stress and apparent volume. A stress change measurement at the seismic source that is model independent of the dynamic stress release. The formula is as follows (Wyss & Brune, 1986):

$$\sigma_a = \frac{\mu E}{M_0} \dots\dots\dots \text{Equation 2.3}$$

Where, σ_a is the apparent stress, M_0 is the seismic moment, E is the kinetic or dynamic (seismic) energy, and μ is the shear modulus of rigidity.

Due to large clamping forces, high stress zones tend to release more seismic energy while allowing less deformation (Abolfazlzadeh, 2013). As a result, Apparent Stress episodes are substantially higher. Low Apparent Stress occurrences could be caused by places that have shed load due to previous rock mass fracturing. Seismic data can be used to track the relative stress levels.

356 **2.1.5.1.6 APPARENT VOLUME**

357 Because of its scalar character, Apparent Volume (V_A) may be manipulated in contour
358 or cumulative plots. V_A also expresses the relationship between an individual event's
359 energy and its moment (Mendecki et al., 2010). It is defined as a co-seismic inelastic
360 strain estimation of the rock volume. It provides insights into the rate and the
361 distribution of co-seismic deformation and/or stress transfer in the rockmass (Ryder
362 and Jager, 2002). Given an event, the radius of a sphere with volume equal to the
363 apparent volume is comparable to Brune source radius r_0 . The following is the formula,

364
$$V_A = \frac{M_o}{2\mu E_R} \dots\dots\dots \text{Equation 2.4}$$

365 Where, V_A is the Apparent Volume in m^3 , M_o is the Seismic Moment in Nm, E_R is the
366 Radiated Energy in Joules and μ is the Rigidity Modulus in Pa.

367 **2.1.5.1.7 INTENSITY**

368 The seismic intensity is describing the intensity of ground vibrations as determined by
369 structural damage and the perceptions of people who were present during the quake.

370 The Mercalli scale, which goes from I to XII, is the most widely used scale today. The
371 modified, Mercalli Intensity Scale, named after Giuseppe Mercalli, is used in North
372 America (Lowrie, 2018).

373 **2.1.5.1.8 STRESS DROP**

374 The average difference in stress over the fault before and after an earthquake is
375 known as stress drop (Shearer, 1999). Seismic data can be used to calculate the
376 dynamic stress drop, defined as the difference between the kinetic friction on the fault
377 and the initial shear stress. Using the following relationship, the static stress drop may
378 be determined.

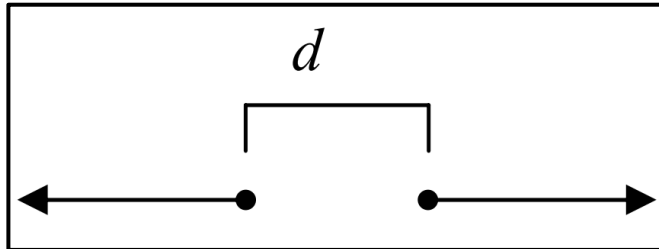
379
$$\Delta\sigma = \frac{7M_o}{16r_o^3} \dots\dots\dots \text{Equation 2.5}$$

380 Where the seismic moment is M_o , and the radius of the circular fault is r_o . The
381 relationship is based on complete stress release. The stress release at the seismic
382 source is estimated by the stress drop $\Delta\sigma$. It gives good estimates and a fair
383 comparison among different sources recorded by the same seismic system from the
384 same region (Mendecki et al., 2010). The size of an earthquake's stress drop varies
385 greatly from one event to the next. The range for mining tremors is 0.01 to 10 MPa
386 (Gibowicz & Kijko, 1994). The average stress decrease for earthquakes at plate
387 boundaries (interplate earthquakes) is 3 MPa, while those within a plate (intraplate
388 earthquakes) have an average stress drop of about 10 MPa (Shearer, 1999).

389 **2.1.5.1.9 SEISMIC MOMENT TENSOR**

390 The distribution of forces due to inelastic deformation describes the process at the
391 seismic source (Udías, 1997). If change in moment per unit volume, is described as a
392 change in strain, then change in moment per unit volume, is proportional to the

393 change in strain. The seismic moment tensor is the total moment integrated over the
394 source volume. The basic force couple or dipole (Figure 2.5), which has no net
395 moment, is the simplest force system that conserves angular momentum.



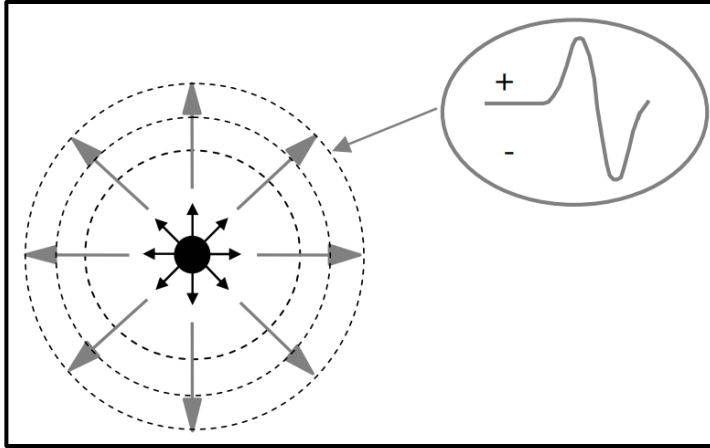
396
397 Figure 2.5: A simple force couple or dipole.

398 The momentum is no longer conserved when a distance, d , separates forces in the
399 direction opposite that of the force orientation until another force pair balances the
400 momentum. Pair of force couples, called double-couple ensures angular momentum
401 conservation, i.e., the net torque is zero, as shown in Figure 2.6.



402
403 Figure 2.6: Balanced double-couple (right) and unbalanced force couple (left).

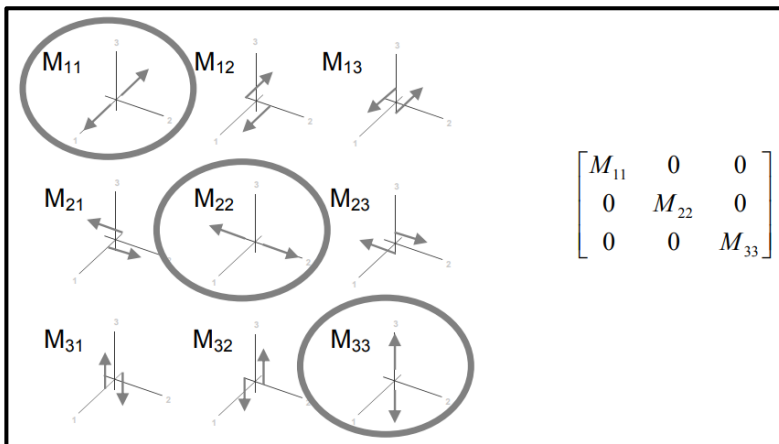
404 Shear fractures are represented by force couples, which are employed in the
405 formulation of the moment tensor. Figure 2.7 shows a force diagram of an explosion at
406 the source, as well as an illustration of the wave's first motion.



407

408 Figure 2.7: First motion of resulting wave and explosion force diagram (Andersen,
409 2001).

410 Force-couples are used to characterize the wave's motion. Figure 2.8 depicts the three
411 force couples required to describe an explosive source, as well as the other six force
412 couples that make up the moment tensor.

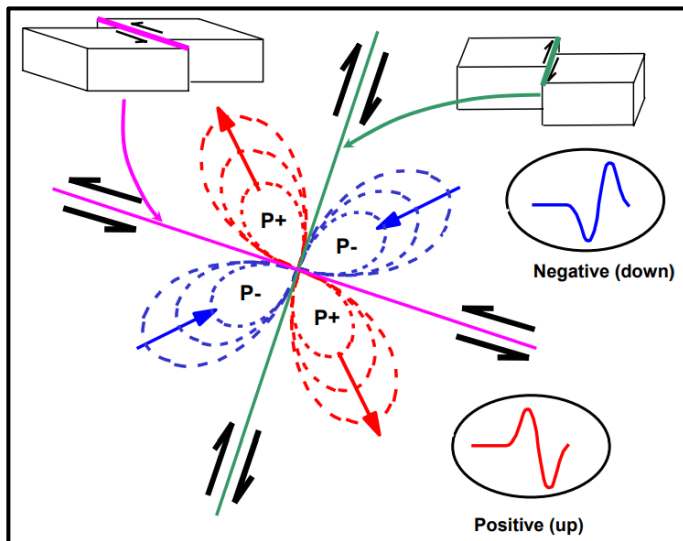


413

414 Figure 2.8: The moment tensor with circled force couples representing explosion
415 (Andersen, 2001).

416 Force couples can be used to describe any shear type movement depending on their
417 combination. P-waves spread outwards from the source, a vertical fault along which

418 slip is initiated is assumed. Around the source, the P-wave first motion from the source
 419 creates movement away from the source (dilatational) and movement towards the
 420 source (compressional) quadrants. In Figure 2.9, the compressional quadrants are
 421 labelled P+, whereas the dilatational quadrants are labelled P-. This seems
 422 contradictory at first until you realize that the naming of the P and T axes refers to the
 423 strain radiated out away from the couples. The third principle stress axis, the
 424 intermediate axis, is orthogonal to both the compressional and tensional axes and is
 425 called the B axis. S waves are radiated with maximum amplitudes along the nodal
 426 planes, and with zero amplitudes along the P, T and B axes.



427
 428 Figure 2.9: P-wave quadrants around the source (Andersen, 2001).

429 At 45° to fault planes in the middle of each quadrant, the strongest movements are
 430 located (longitudinal P waves). The force system that leads to fault slip without
 431 shearing can be denoted by a pair of orthogonal dipoles. Two fault planes from Figure
 432 2.10 are denoted X_1 and X_2 , and the double-couples are drawn in an $X_1 - X_2 -$

coordinate system depicted in Figure 2.10. These are known as principal axes, and they are represented by the letters P and T, where P is compression axis and T is dilatation axis.

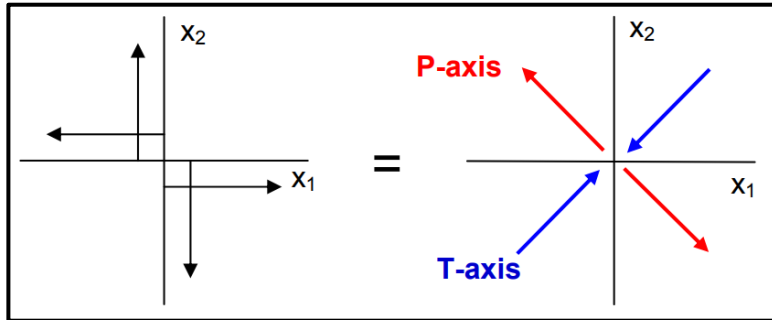


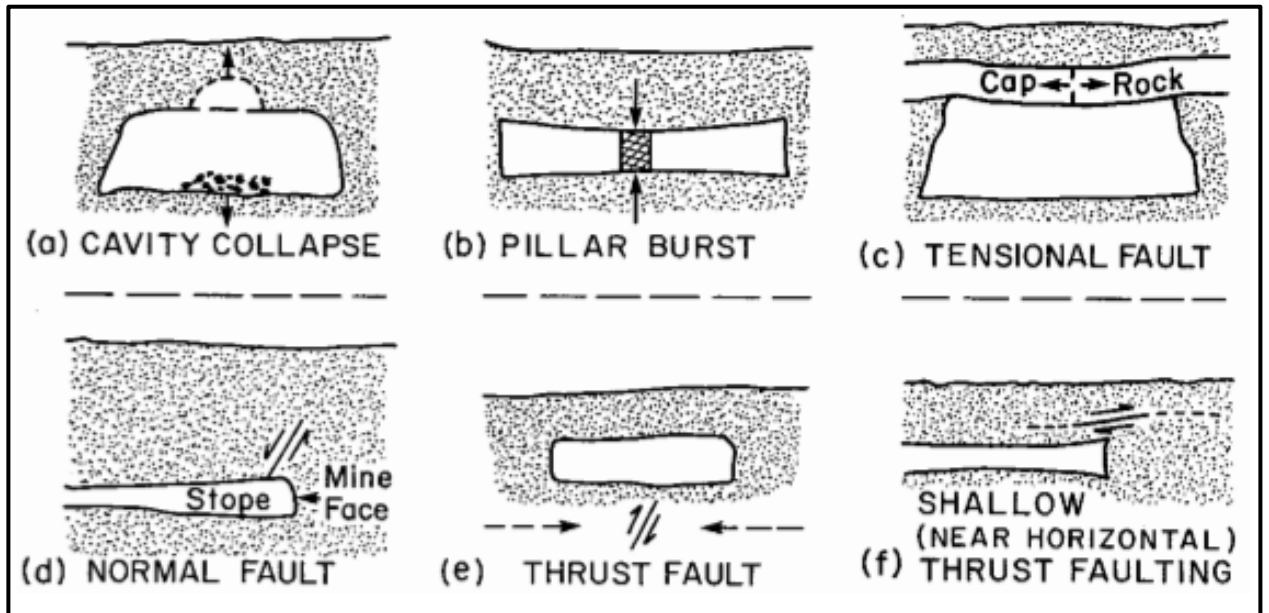
Figure 2.10: Principal axis representing double-couples (Andersen, 2001).

There are two different fault planes in the double couple model that correspond to the same seismic impressions. The actual fault plane is referred to as the primary fault plane, and the other fault plane is referred to as the auxiliary fault plane. Additional evidence, such as aftershock sites or observed surface ruptures, is required to determine which plane is which.

2.1.5.2 SEISMIC SOURCE MECHANISM

In mines, there are two types of seismic sources: those triggered by mining and those induced directly by mining (Gibowicz and Kijko, 1994). Those induced by mining rely on energy fluctuations in the mining process to produce rock mass failure, whereas those triggered by mining would already be in instability and would only require a tiny amount of energy to create large-scale catastrophes. Seismic occurrences can be divided into two categories: those that are directly related with stopes and those that

450 are associated with movement on major geologic discontinuities. Slip faults, pillar
451 bursts, and cavity collapses are typical mine- induced mechanisms (Hudyma, 2010)
452 (Figure 2.11).



453
454 Figure 2.11: Typical seismic source mechanisms of mine induced tremors (adapted
455 from Hudyma, 2010).

456 Techniques used to determine seismic source mechanisms are divided into two;
457 waveform techniques and inferred techniques. Inferred techniques use inference to
458 suggest the seismic source mechanism, while waveform techniques use interpretation
459 of data collected by seismic sensors (Hudyma, 2010).

460 The waveform techniques are the moment tensor inversion and first motion analysis.
461 The moment tensor inversion describes equivalent forces working at a seismic point
462 source. It is the best approach to study the seismic source mechanism of events but it
463 is rarely used because it demands high quality data which is mostly not available in

464 mines (Hudyma, 2010). The first motion analysis is applied to minor rock mass
465 discontinuities that have no history of shearing.

466 Inferred techniques include; event location, frequency magnitude relation, S: P energy
467 ratio and diurnal analysis. Spatial plotting of high resolution seismic data gives the
468 location of rock mass failure and this is usually in proximity with geological and mine
469 structures (Hudyma, 2010). The ratio of s-wave to p-wave energy, time of day of
470 occurrence and the slope of the frequency magnitude relation relates strongly to the
471 identification of seismic source mechanisms.

472 **2.1.5.2.1 STOPES RELATED SEISMIC EVENTS**

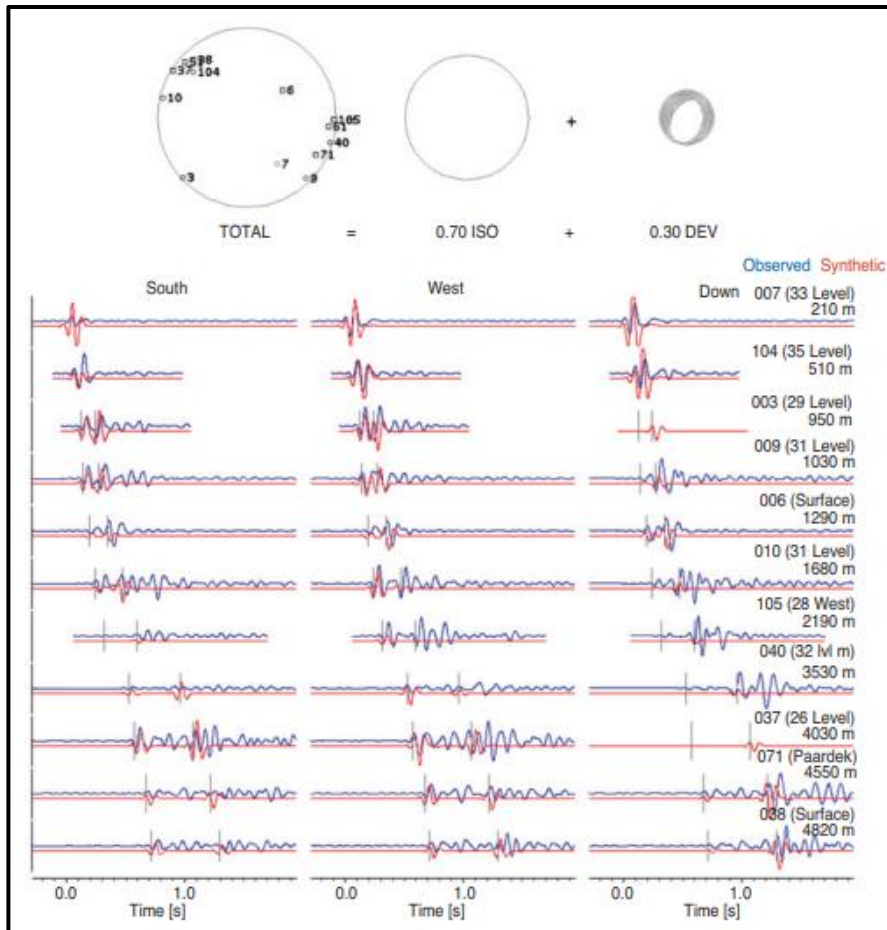
473 These kinds of phenomena take place around mine openings and are caused by
474 redistribution of stress around the mine opening. They're more prone to happen
475 where there is concentration of stress. The damage and the energy discharge are both
476 at the same location.

477 **2.1.5.2.1.1 STRAIN BURST**

478 In both mines and civil engineering buildings, strain bursts are the most prevalent type
479 of rock bursts. The word is used to characterize a failure event in which relatively small
480 bits of rock are released from the mine opening's perimeter. The ejected rock particles
481 are usually thin and have sharp edges (Gibowicz and Kijko, 1994). If the rock around
482 the excavation is jointed, the failure occurs through thin laminates of near-surface rock
483 rather than through entire rock. Because the quantity of energy released is usually
484 tiny, a strain burst normally causes very minor harm.

485 **2.1.5.2.1.2 PILLAR CRUSH**

486 Pillar crush is a term used to describe violent failure of pillars caused by localized stress
487 redistribution. Figure 2.12 shows an example of the moment tensor decomposition of
488 an event interpreted to be a pillar crush. Depending on the position of the failing pillar
489 and the state of nearby pillars and rock, the damage caused by a pillar crush can be
490 significant. Because energy released by a pillar crush is substantially more than that
491 released by a strain burst, the radiated seismic wave may cause damage in other
492 locations, such as loose rock shake-down (Hudyma, 2010). When one pillar fails
493 suddenly, stresses are shifted to other pillars, which may then fail violently depending
494 on how close it is to the burst. A cascade of pillar failures could occur, resulting in the
495 mining area's collapse.



496

497 Figure 2.12: Moment tensor decomposition of a 2.5ML event that was interpreted to
 498 be a pillar failure adapted from (Malovichko et al., 2012)

499 2.1.5.2.2 GEOLOGIC DISCONTINUITY RELATED SEISMIC EVENTS

500 These seismic events are likewise caused by stress redistribution caused by mining, but
 501 on a much greater scale. The stress redistribution affects a broader area surrounding a
 502 mine as it grows (Gibowicz and Kijko, 1994). This can result in the reactivation of
 503 localized faults or the violent development of new cracks in otherwise unbroken rock.
 504 These occurrences can cause a lot of harm, and they can influence a broad area and

505 even be felt on the surface. These are known as mining- induced earthquakes, and
506 they can cause harm on the surface as well.

507 **2.1.5.2.2.1 FAULT SLIP**

508 Mining activities can lessen the clamping force along the fault, resulting in reduced
509 resistance in shear or increased shear force along the fault, leading to slip. The energy
510 released when slip happens causes harm to the excavations (Hudyma, 2010). When
511 the released energy strikes an opening in the rock, there is release of chunks of rock
512 defined by existing joints, a tensile stress close to mine openings, which leads in a
513 tensile failure, and a huge compressional stress, which results in a failure that is
514 followed by rock ejection.

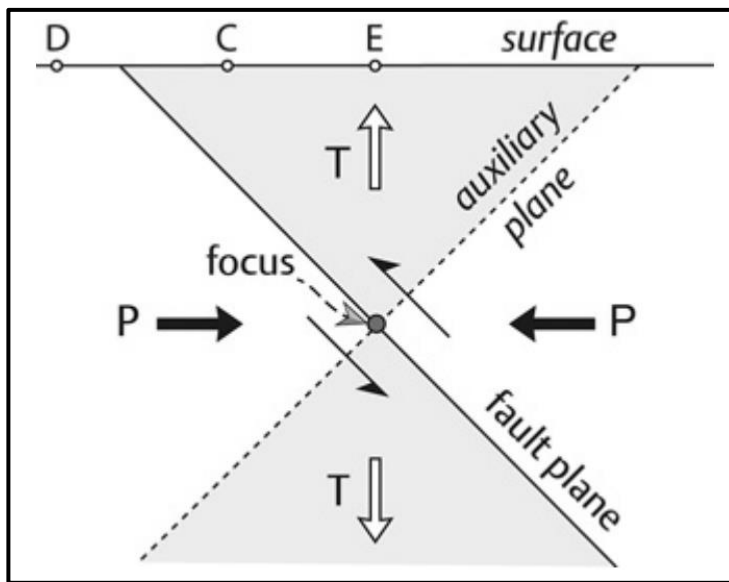
515 **2.1.5.2.2.2 SHEAR FAILURE**

516 Shear rupture is an abrupt shear failure through intact rock that causes seismic waves
517 to be released and damage to neighboring excavations. It happens when the
518 compressive pressures ahead of a mining face surpass the rock's shear strength, which
519 necessitates a triaxial state of stress (Gibowicz and Kijko, 1994). Shear rupture results
520 in the same type of damage as a fault slip occurrence.

521 **2.1.5.2.3 FOCAL MECHANISMS**

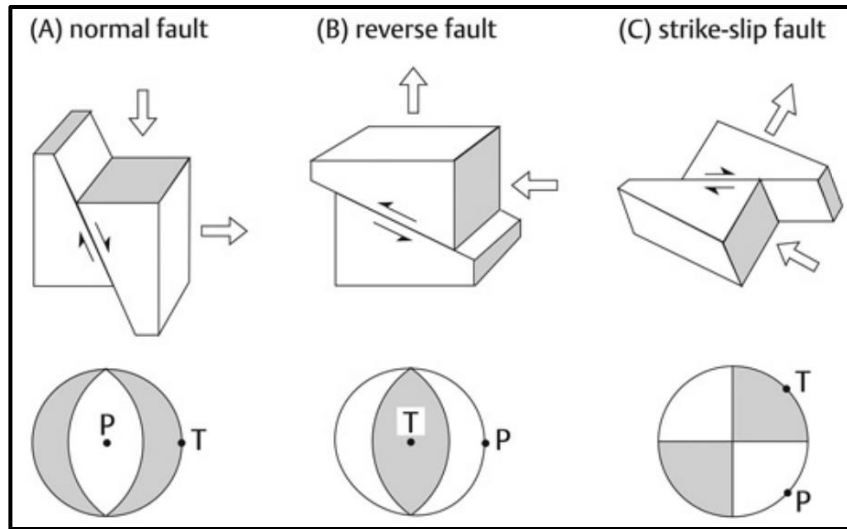
522 Where a seismic station is located in relation to the focus and the type of fault
523 influences the initial appearance of a P-wave on a seismogram. The motion of the P
524 wave may be upward or downward. A vertical cross-section across the focal point of an

525 earthquake on an inclined fault plane is depicted in Figure 2.13, the T-axis, which runs
 526 through the center of the (shaded) compressional quadrant, is the direction in which
 527 the largest P-wave initial motion is away from the source. The P- axis, which is placed
 528 in the center of the (unshaded) dilatational quadrant, is the direction in which the
 529 maximal initial motion is towards the source.



530
 531 Figure 2.13: A vertical cross-section across the focal point of an earthquake on an
 532 inclined fault plane (Adapted from Lowrie, 2018).

533 A geometric method of transforming a spherical distribution to a two-dimensional
 534 circular plot is employed in conjunction with first motions to offer information about
 535 the displacement on the fault plane. A focal mechanism projection, also known as a
 536 fault plane solution, is the graph used. The auxiliary plane and fault plane orientations
 537 are represented as arcs that are 90 degrees apart and the compressional first motion
 538 zones are shaded. The focal mechanism diagrams provide an inference of the type of
 539 faulting that occurred (Figure 2.14).



540

541 Figure 2.14: Tectonic faults with focal mechanisms and P and T axes (Adapted from
542 Lowrie, 2018).

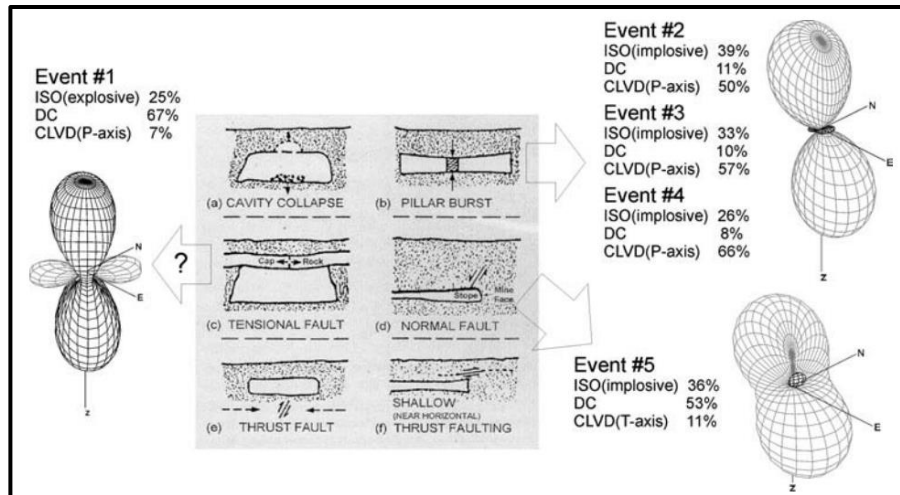
543 Moment tensor inversion is commonly used to characterize and understand the
544 faulting process (Guilhem et al., 2014). The body forces acting at a seismic point source
545 are characterized by the moment tensor (Vavryčuk, 2014). Due to poor signal-to-noise
546 ratios over extended periods, geometry and quality of seismic networks, the need for
547 precise velocity models at shorter wavelengths, and nonunique decompositions at the
548 source, source mechanisms for small-magnitude earthquakes (i.e., >1.5) are generally
549 difficult to establish (Guilhem et al., 2014).

550 Seismic wave amplitudes, amplitude ratios, or full waveforms are used to derive the
551 moment tensor (Vavryčuk & Kühn, 2012). The waveform inversion is a data-intensive
552 procedure that requires an accurate source location, a thorough understanding of the
553 velocity model, and strong focal sphere azimuthal coverage. The solution is distorted

554 by mistakes caused by a lack of data, an incorrect location, or an erroneous velocity
555 model (Vavryčuk & Kühn, 2012).

556 For the majority of source processes, seismic moment tensors have the property of
557 symmetry of components, hence they will only have two parts; deviatoric and isotropic
558 components (Mendecki et al., 2010). The isotropic component describes the change in
559 material volume in the seismic event source. The inelastic change of shape of material
560 in the source is described by the deviatoric component (Mendecki et al., 2010).

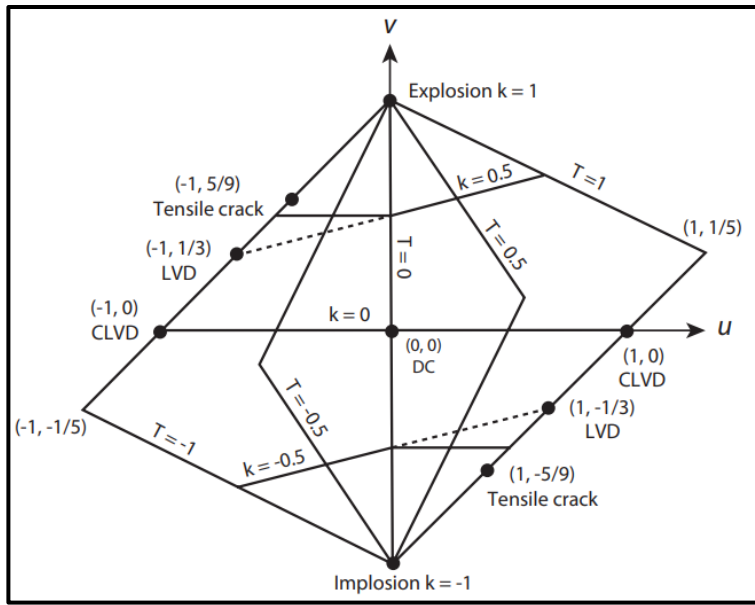
561 Decomposing moment tensors into isotropic (ISO), double-couple (DC), and
562 compensated linear vector dipole (CLVD) components is a technique for categorizing
563 and physically analyzing seismic sources. The DC and CLVD together comprise the
564 deviatoric component of the moment tensor. Figure 2.15 shows seismic source
565 mechanisms with their typical moment tensor components. Because the quantity and
566 quality of seismic data is improving, an efficient and physically sensible decomposition
567 of the moment tensors is required to invert for accurate moment tensors and interpret
568 aspects of the source process. (Vavryčuk, 2014; Vavryčuk & Kühn, 2012).



569

570 Figure 2.15: Six different source mechanisms of mine-induced tremors, with 3-
 571 dimensions display of the radiation patterns of the P-wave for a corresponding
 572 moment tensor (Adapted from Šílený & Milev, 2006).

573 The most frequent type of moment tensor in the world is the double-couple (DC),
 574 representing the force equivalent of shear faulting on a planar fault in isotropic
 575 material. Decomposition of the moment and source tensors must be efficient and
 576 physically justifiable. Hudson et al. (1989) proposed graphical representations of the
 577 DC and non-DC (Figure 2.16) components so that the most appropriate physical source
 578 matching to the retrieved moment tensor could be identified visually (Vavryčuk, 2014).
 579 K and T describe the Compensated Linear Vector Dipole (CLVD) and Isotropic
 580 components of the motion; they both range from -1 to 1 . $T=k=0$ is at the center which
 581 represents a double-couple (DC), an event resulting from slip. $K=1$ represents explosive
 582 while $k=-1$ represents implosive deformation. $K=0$ and $T=\pm 1$ is a pure CLVD mechanism
 583 characterized by compensation of strain by two axis from strain along one.



584

585 Figure 2.16: Hudson Plot (Adapted from Hudson et al., 1989). LVD, Linear Vector
586 Dipole; DC, Double Couple; CLVD, Compensated Linear Vector Dipole.

587 2.1.5.3 SEISMIC HAZARD

588 Seismic hazard is a measure of the potential for the greatest event to occur, which
589 changes in time and space. It is important because it shows the degree of strong
590 ground motion that could be affected by a seismic event, and hence the risk of rock
591 mass damage (Hudyma, 2010). In mines, seismic hazard estimations are often confined
592 to probabilities of occurrence, of seismic events of a specific magnitude, in order to
593 quantify relative exposure to seismicity and seismic risk (Mendecki et al., 2010).

594 2.1.5.3.1 ENERGY INDEX

595 Amount of energy released for a population of seismic events compared to the amount
596 of energy expected. Defined by:

$$EI = \frac{E}{E(P)} = \frac{E}{10^{d \log P + c}} = 10^{-c} \frac{E}{pd} \dots\dots\dots \text{Equation 2.6}$$

Where; E is the radiated seismic energy, E (P) is the average energy radiated by events, P is the observed seismic potency (integral of transformational strain over the source volume) and d = 1.0 and is proportional to the apparent stress.

While the EI is not considered a predictor for damaging seismic events, it may be used to identify potential areas of rock mass instability (Mendecki et al., 2010). A logarithmic relation of seismic energy and seismic moment can be graphed to provide visual identification of atypical events and assist in identifying regions experiencing potential instability (Hudyma, 2010). When areas are accumulating stresses, such as pillar and stope abutments, the EI will indicate a value greater than one; as the stresses increase and the structure begins to yield, the value will decrease to less than one (Smith, 2018).

2.1.5.3.2 CUMULATIVE APPARENT VOLUME (CAV)

CAV estimates the volume of rock mass deformation for a given seismic event. The slope of the CAV curve reflects differences in strain rate. Accelerating deformation over a period of time indicates unstable rock mass deformation (Smith, 2018).

Instability analyses can be conducted by plotting the CAV in relation to the Log EI in a time history chart; the resulting changes in the CAV indicate where significant changes in energy and associated stress increase and decrease are occurring related to a seismic event.

617 2.1.5.3.3 FREQUENCY-MAGNITUDE RELATION

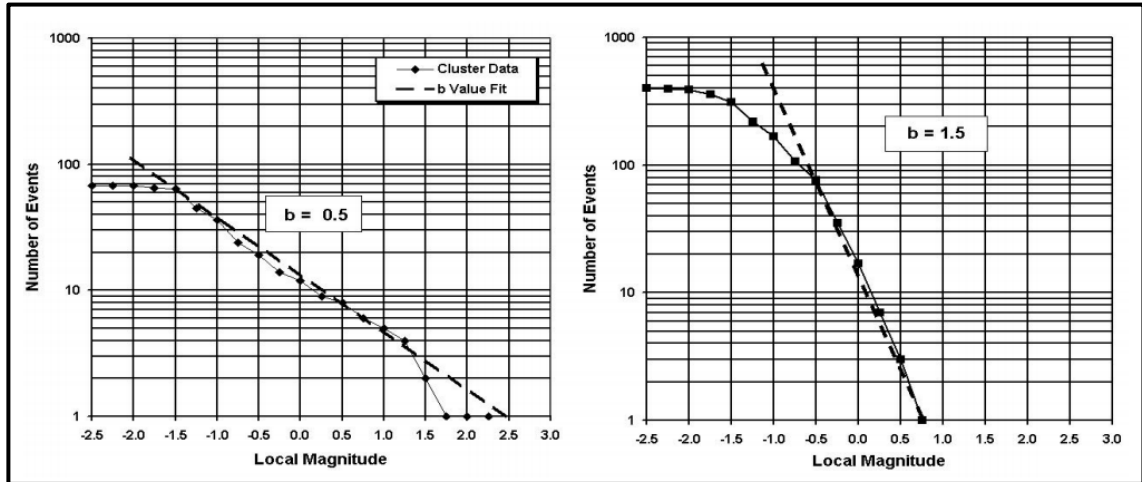
618 One of the most commonly accepted indicators for seismic hazard is frequency
619 magnitude analysis, which was developed in earthquake seismology. The magnitude of
620 earthquake occurrences is known to follow a power law relationship. This suggests
621 that for every 1000 occurrences with a magnitude of -2 or above, we should expect
622 around 100 events with a magnitude of -1. We also anticipate 10 events with
623 magnitudes equal to or greater than 0, and 1 event with magnitudes equal to or
624 greater than +1. The magnitude distribution of Gutenberg-Richter (1944) is sometimes
625 referred to as the Gutenberg-Richter magnitude distribution, and it can be stated as:

$$626 \quad \text{Log}N = a - bm \text{ Equation 2.7}$$

627 m is the event magnitude, N is the number of events with magnitudes equal to or
628 greater than m, b is the power law exponent and a is the number of events in the data.
629 Seismic hazard is related to the power law exponent, often known as b or b-value. A
630 high b-value indicates that there are few large events in a population of events. A low
631 b-value indicates that there are more larger events than small events. The b-value
632 accurately depicts the frequency of large vs small events in the dataset. As a result, the
633 b-value can be a useful indicator of seismic hazard.

634 The linear region in a frequency-magnitude relation shows that the frequency of
635 occurrence of seismic data follows a power law. Figure 2.16 indicates that recorded
636 seismicity follows a hypothesized linear trend (dashed line) to around local magnitude

637 -1.5 in the chart on the left. The reported seismicity follows a hypothesized linear
638 trend to roughly local magnitude -0.5, as shown in Figure 2.17 on the right.



639

640 Figure 2.17: Frequency Magnitude graphs from two different Seismic sources (Adapted
641 from Hudyma et al., 2003)

642 Although both clusters have almost the same number of Local Magnitude = 0 events,
643 the left cluster has a higher fraction of huge events (Figure 2.17). The cluster on the
644 right features a lot of small events but nearly no large ones. The relative seismic hazard
645 for the cluster on the left is substantially higher.

646

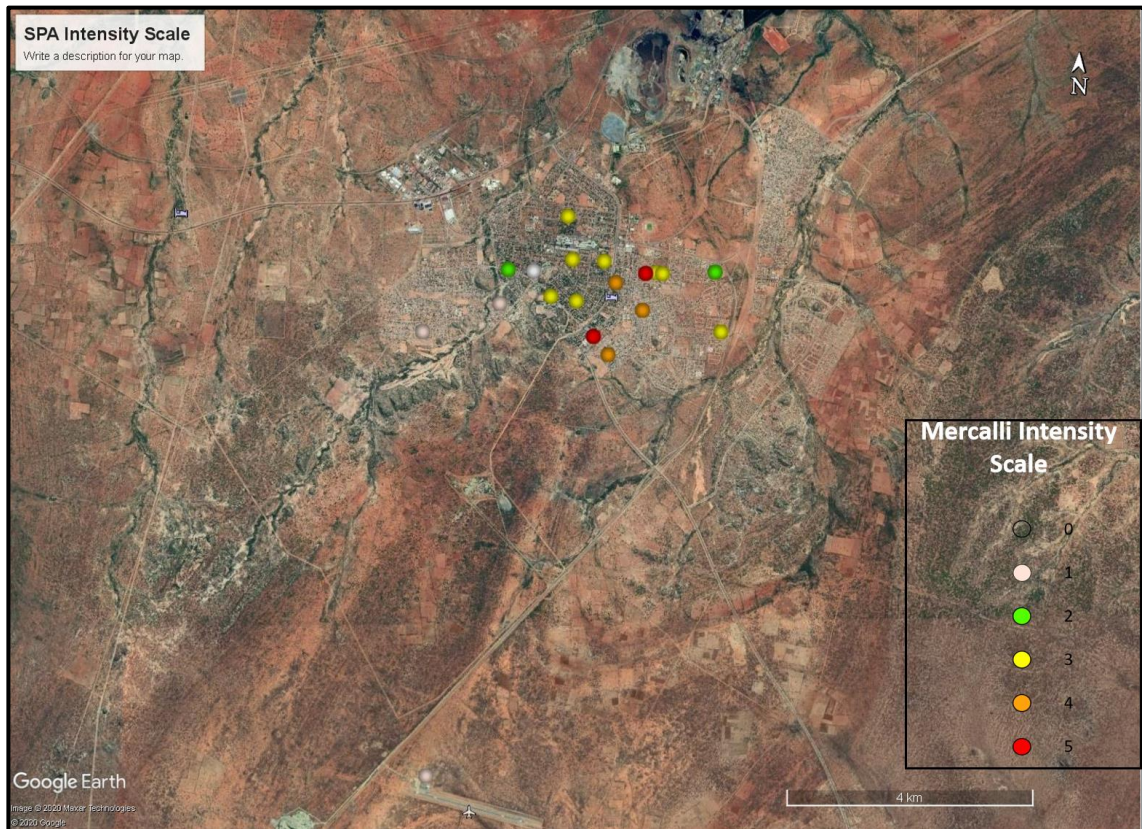
3.0 CHAPTER THREE

647

3.1 METHODOLOGY

648

3.1.1 DATA ACQUISITION STATIONS



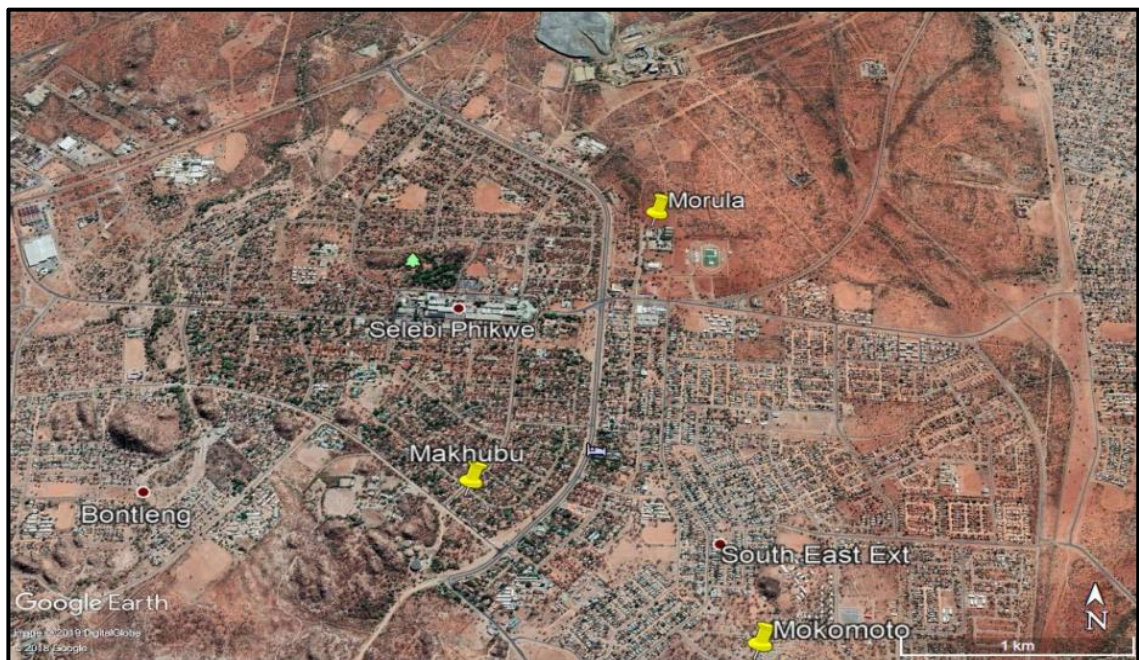
649

650 Figure 3.1: Map showing microseismicity survey (Adapted from Botepe et. al. 2020).

651 In order to determine the suitable location for microseismic sensors BGI conducted a
652 microseismicity survey. Results of the survey showed the intensity of seismicity over
653 the study area as shown in Figure 3.1. The south east extension of the BCL mine was
654 characterized by high microseismic intensity therefore it was enclosed by sensors.
655 From there, to avoid vandalism and to secure the equipment, places like schools and

656 secure households of residents were chosen to mount the sensors for the temporary
657 seismic monitoring system.

658 According to Aqualogic and OHMS (2019) seismic equipment installation was from 24-
659 28 June 2019 where a total of six geophones were installed (5 triaxial and 1 uniaxial).
660 Three triaxial geophones were installed at the surface (Figure 3.2) and the remaining
661 three underground (Figure 3.3). The surface stations were installed at Morula school
662 and at the Mokomoto and Makhubu residence while the underground stations were
663 mounted 980m below the ground.



664
665 Figure 3.2: Location of surface data acquisition stations, marked with yellow pins
666 (Adapted from Aqualogic & OHMS, 2019)

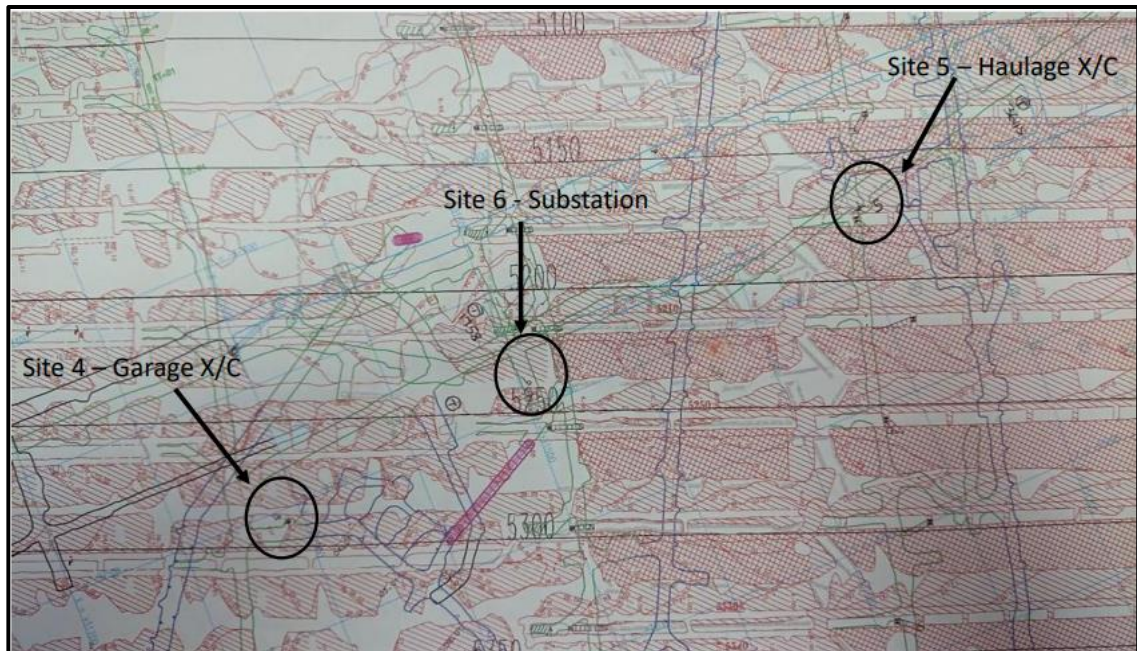


Figure 3.3: Location of underground data acquisition stations, 980m below the ground
(Adapted from Aqualogic & OHMS, 2019)

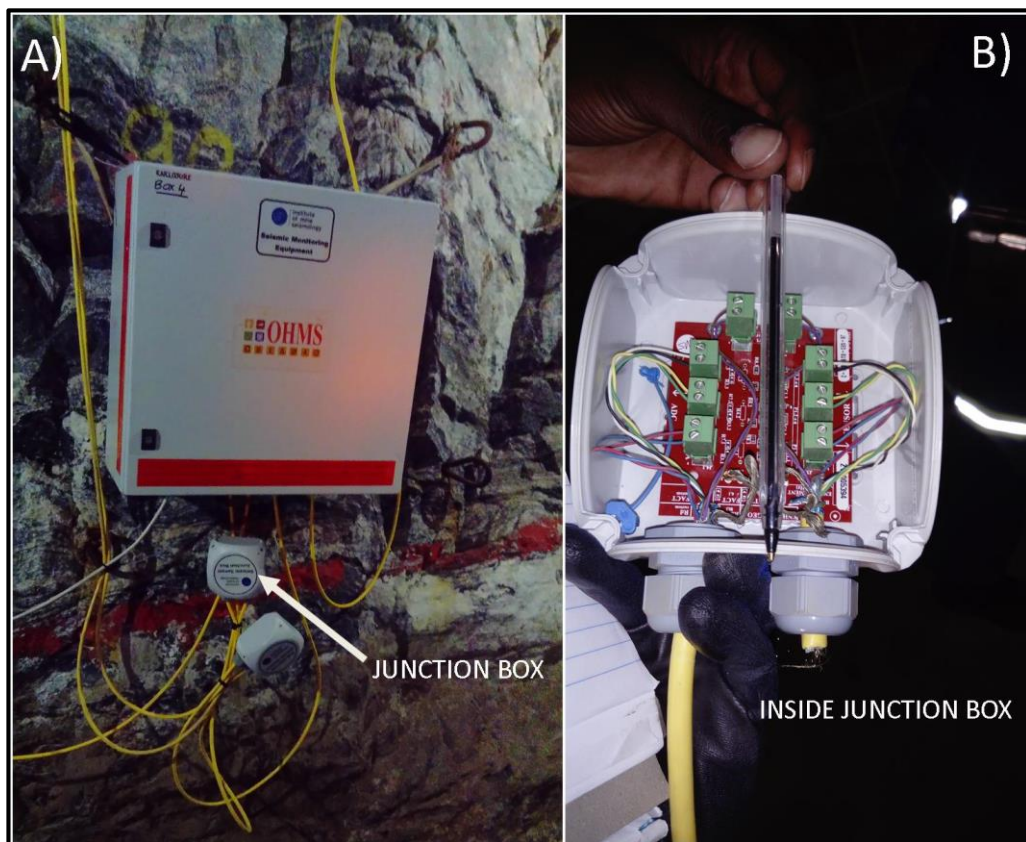
3.1.2 SENSORS

The type of sensor used for data collection is the surface mount sensor. For sensors at the surface, excavation was carried out up to bedrock followed by laying a concrete slab, in order to couple the sensor with the bedrock. After all the installations the sensor was covered with a white cushioning plastic material Figure 3.4B and buried with soil. Underground there was no excavations done; the sensor was mounted on an already existing concrete slab as in Figure 3.4A. The sensors were all placed facing north, so that the orientation can be properly determined, that is, if an event occurs it is known where it occurs from. The sensor was connected to a junction box through a cable. The junction box, Figure 3.5 connects the sensor to the seismological monitoring equipment and it also filters noise.



681

682 Figure 3.4: Surface mount sensor.



683

684 Figure 3.5: Junction Box.

685 **3.1.3 SEISMOLOGICAL MONITORING EQUIPMENT**

686 All the seismological monitoring equipment was protected with a steel box, Figure 3.6
687 and 3.7. The box was connected to the sensor and the power source. Cables from the
688 sensor are yellow and the ones from the power source are white. These go in through
689 the steel box to the seismic monitoring equipment. The equipment is grouped into
690 three; namely data acquisition units, communications and other devices.



691
692 Figure 3.6: Underground seismological monitoring equipment set up.



693

694 Figure 3.7: Surface seismological monitoring equipment setup.

695 The data acquisition units are the Seismological Digitizer (netADC) and the
 696 Seismological Processor (netSP). The netADC converts analogue data from the sensor
 697 into a digital format and timestamps the analogue signals. The netSP performs several
 698 signal processing tasks such as filtering and triggering then buffers the data before
 699 transferring it to the server.

700 For communications there is the Digital Subscriber Line (DSL) modem, Time distributor
 701 and GPS timer. The DSL modem converts Ethernet to DSL so that digital data can be
 702 transmitted over telephone lines while the time distributor has a GPS antenna that
 703 gets time from the satellite and synchronizes it with the underground station. The GPS
 704 timer then distributes time throughout the system.

705 Other devices include the Uninterruptable Power Supply (UPS+) and Surge protector.
706 The UPS+ distributes power to other devices and it can last for four to six hours after
707 power cut. The surge or overload protector protects the seismic monitoring equipment
708 from lighting damage.

709 The seismic monitoring equipment is connected to a telephone wire which connects it
710 with the WI-FI radio or antenna. This is so that data from the box is sent through the
711 wire to the antenna so as to be accessed remotely.

712 **3.1.4 DATA PROCESSING SOFTWARE**

713 **3.1.4.1 IMS TRACE**

714 Raw data from the IMS seismic monitoring equipment was post associated prior to
715 being transferred into the BCL database server for processing. The IMS system was
716 connected to the database server located at the BCL mine to enable data to be stored
717 remotely in the database so that it is accessed from anywhere. The first step when
718 processing with trace after logging in was to download data from the seismic server to
719 a local database so that any alterations made do not permanently affect the data in
720 the server.

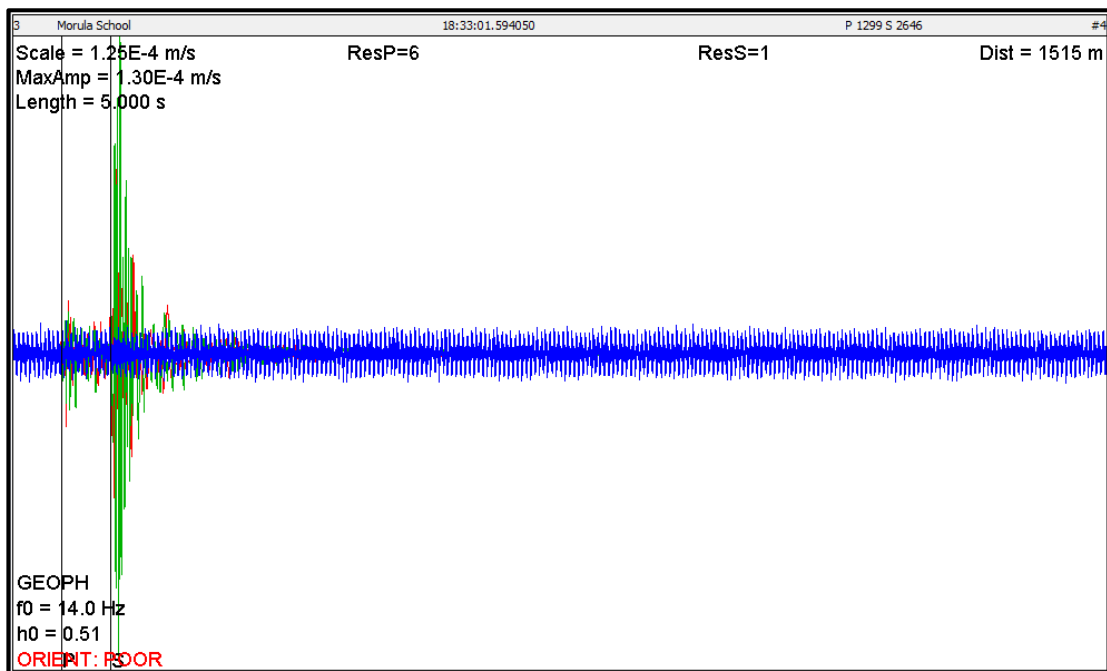
721 **3.1.4.1.1 Distinguishing from blasts**

722 When processing in IMS Trace™ the main thing is to distinguish between blasts and
723 normal seismic events. This is done by considering whether the event occurred during
724 normal blasting times, whether there was blasting delays, weak S wave, high frequency

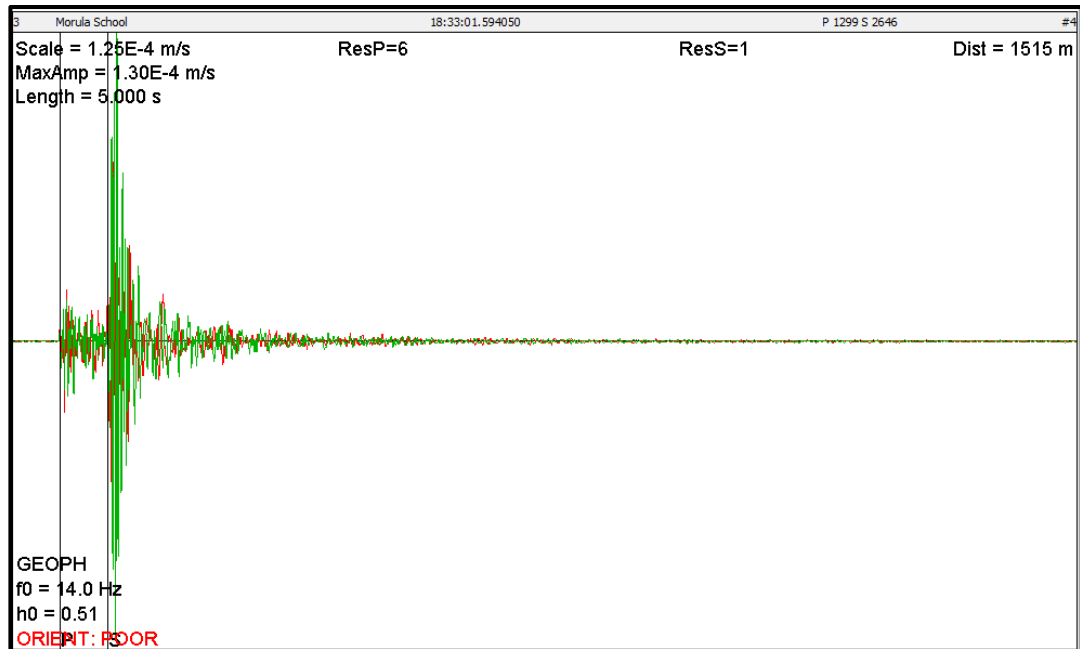
725 and a spectrum that was not smooth. Events deemed as blasts were saved as blasts
726 and processing for normal events continued.

727 3.1.4.1.2 Determining the quality of seismogram data

728 Some sensor components or axes (red is X axis, green is the Y axis, blue is the Z axis) in
729 the seismogram appeared as a flat line while some were distorted, Figure 3.8. This may
730 negatively affect the picking of the P and S waves arrival times. To ensure that phase
731 picking was done precisely non- contributing sensor axes were disabled, Figure 3.9.



732
733 Figure 3.8: Sensor component distorted (appeared as a thick flat line).

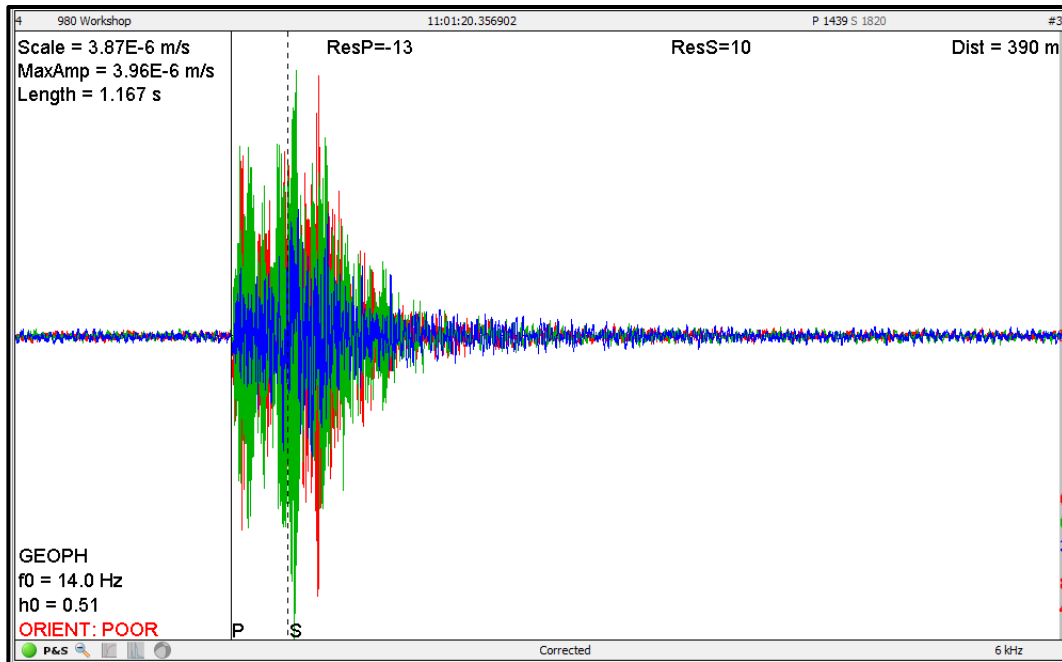


734

735 Figure 3.9: Distorted sensor component disabled.

736 3.1.4.1.3 Identification and Picking of phase arrivals

737 Taking into consideration that phase picking was key in determining accurate seismic
 738 event location. P and S wave picks were placed at the base of the largest pick
 739 representing the arrival of the individual waves. This was done one seismogram at a
 740 time. Sometimes due to data capturing and the configuration of IMS seismic system
 741 one or both of the first arrivals of P and S waves may not be clear making it nearly
 742 impossible to pick. In this case picks that were not clear were disabled therefore they
 743 were not used in the estimation of the seismic source location, Figure 3.10.



744

745 Figure 3.10: Disabled S wave.

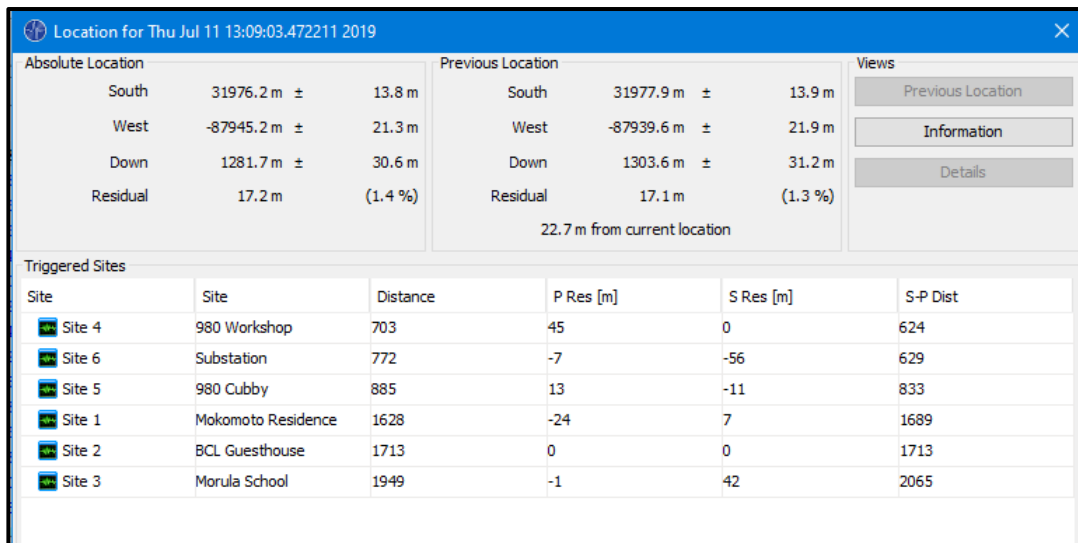
746 Another tool used to aid phase picking is the seismogram rotator which only works on
 747 triaxial seismograms. It rotates the seismogram to a coordinate system related to the
 748 direction of ground motion making the P wave visible on a rotated red component and
 749 the S wave observable only on the rotated blue and green components. This made it
 750 easier to distinguish the two waves as the P wave would be dominated by red and S
 751 wave dominated by blue and green and the transition between the two was
 752 noticeable.

753 When processing seismic data, more seismograms are better in estimating event
 754 location therefore rejecting seismograms was a last resort. Seismograms were rejected
 755 when they were erroneously biasing event location determination and when both

756 picks could not be made. This can happen when some noise interruptions happened at
 757 the very same time the event is taking place for example when a truck is passing by.

758 3.1.4.1.4 Estimating Source Location

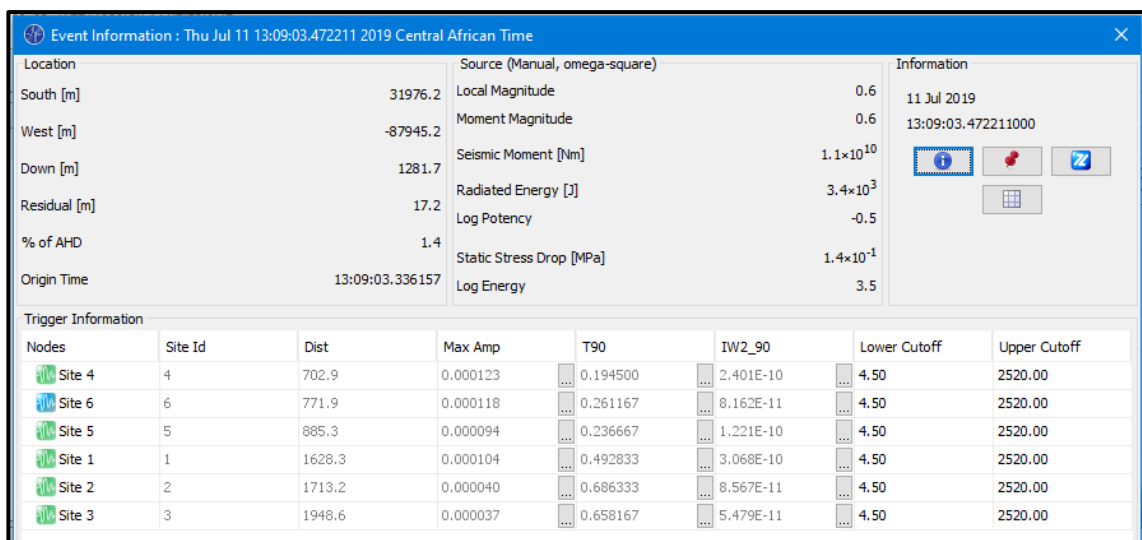
759 The source location was analyzed by determining whether it is sensible, whether it is
 760 stable and is of low residual error. This is to say events should not be occurring where
 761 there is no mining activity, the first sensor displayed should be the closest to the
 762 source and sites nearest to the source should have greater amplitudes. To determine
 763 stability one wave was disabled at a time, recalculating the source location each time
 764 to observe the change in residual error and source location. The residual error was
 765 minimized (below 5%) while maintaining a balance of number of seismograms and
 766 wave picks for accurate source location. Another way of reducing residual error is by
 767 comparing arrival times of P and S waves. This was achieved through the travel time
 768 processing mode.



769

770 Figure 3.11: Screen capture of Source Location parameters

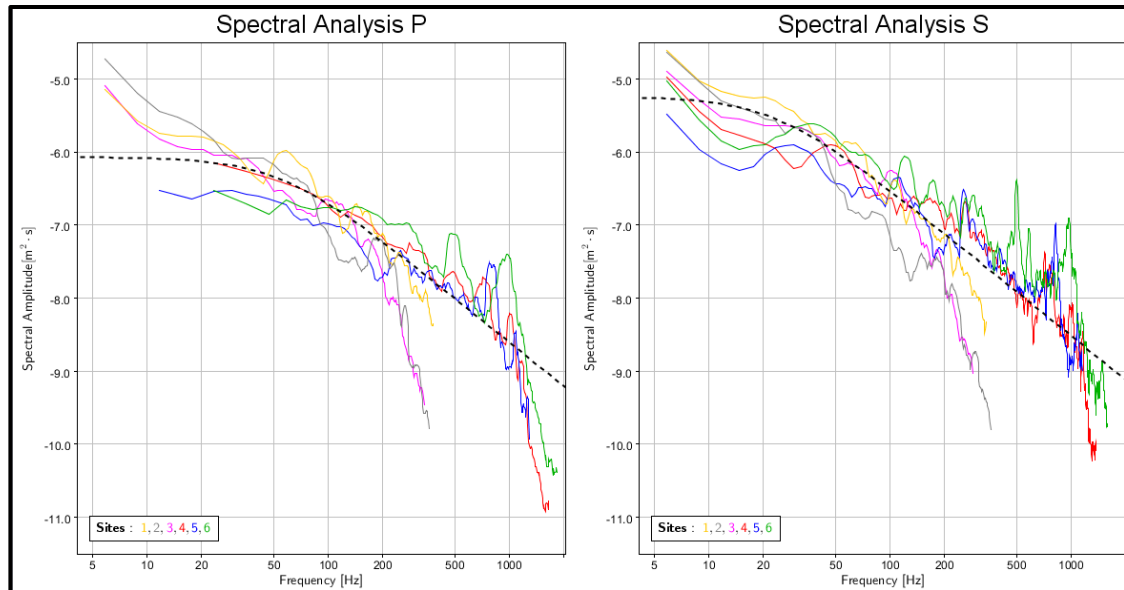
771 Figure 3.11 shows an absolute source location. This is determined after all
 772 seismograms of an event has undergone phase picking as well as the process of
 773 accepting or rejecting seismograms or certain components within them. This was
 774 performed several times to reduce residual error for more precise location. A residual
 775 error of 1.4% is very reasonable therefore the location was accepted. This is the
 776 location of an event that occurred on the 11th July 2019.



777

778 Figure 3.12: Event Information.

779 An example in Figure 3.12 shows source information of an event that occurred on the
 780 11th July 2019. It shows several source parameters of the event such as the magnitude,
 781 moment energy and static stress drop. It also shows the number of sites triggered and
 782 their order of trigger.



783

784 Figure 3.13: Spectral Analysis.

785 Figure 3.13 is the spectrum of the event mentioned above that comes up when
 786 performing source location. The different colors represent individual sensors triggered
 787 by the event. It is quite evident that the sites are in line with each other as well as the
 788 black averaged line therefore the event is a normal event not a blast.

789 3.1.4.1.5 Moment tensor Decomposition

790 Moment Tensor decomposition was only performed for large events due to their high
 791 signal to noise ratio. The first thing done was to check whether the orientation settings
 792 are correct and whether the sensor sites are in good orientation. A poor orientated
 793 sensor was not used for the mechanism calculation. There were two options to
 794 calculate the moment tensor using the amplitude and polarities and using the full
 795 waveform. Amplitude and Polarities depends on the P and S picks therefore their
 796 decomposition should show the selected wave where a pick is present. Visual filters

797 were applied and inversion was performed to reveal the decomposition menu which
798 indicates the total mechanism, volumetric component and the deviatoric component.
799 A statistic menu was revealed as well to show the Hudson plot, PTB axes and the nodal
800 planes.

801 **3.1.4.2 IMS VANTAGE**

802 Vantage is basically a visualization tool kit where events processed in trace were
803 viewed in a 3D space. On the 3D window where visualization took place mine plans
804 were integrated with surface plans to observe their orientation. The later were also
805 integrated with events of different magnitudes and event time. Filtering was also
806 applied.

807

4.0 CHAPTER FOUR

808

4.1 RESULTS

809

4.1.1 SEISMOGRAMS

810

Of all the six sensors that were mounted in this project, only one sensor was a uniaxial

811

type of sensor. This is the Substation sensor placed 980m below ground level. Figure

812

4.1 is the seismogram signature of the uniaxial sensor that was acquired when a

813

particular event triggered the sensor. Figure 4.1 shows a signature of only one

814

component or axis, this is the Z component of the sensor, sensitive to depth variations.

815

Figure 4.1 also shows manually picked P and S wave's arrival times. The seismogram is

816

for an event that occurred on the 11th of July 2019 13:09. The seismogram indicates

817

that the event occurred 781m away from the sensor.

818

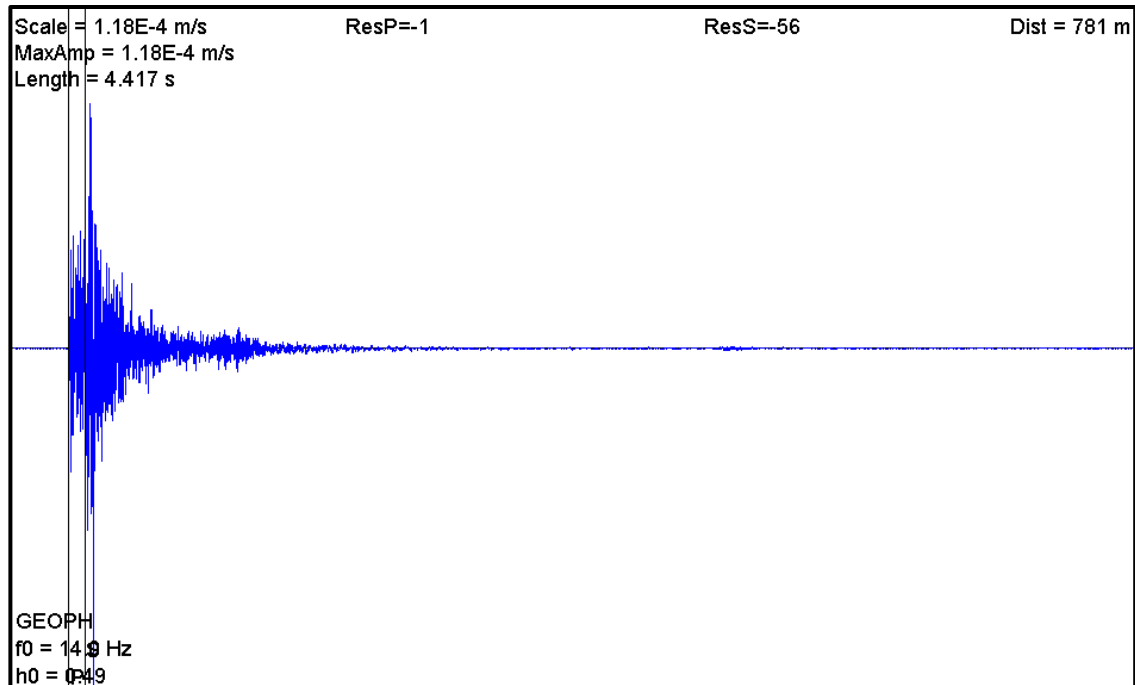
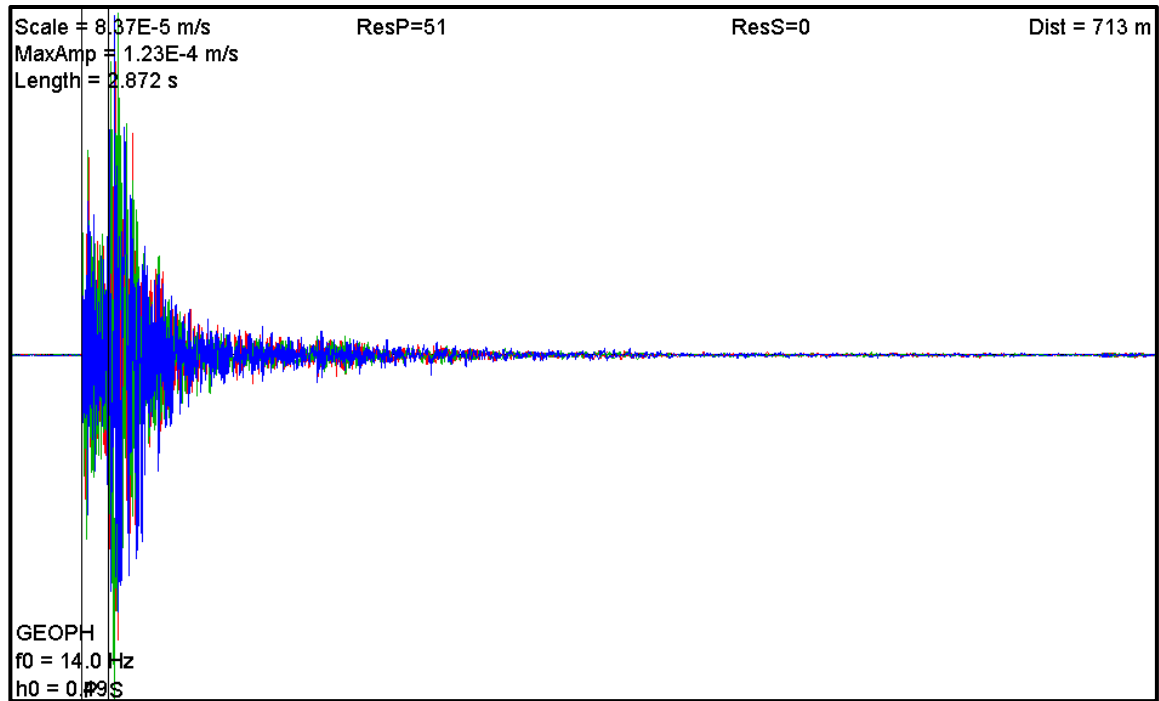


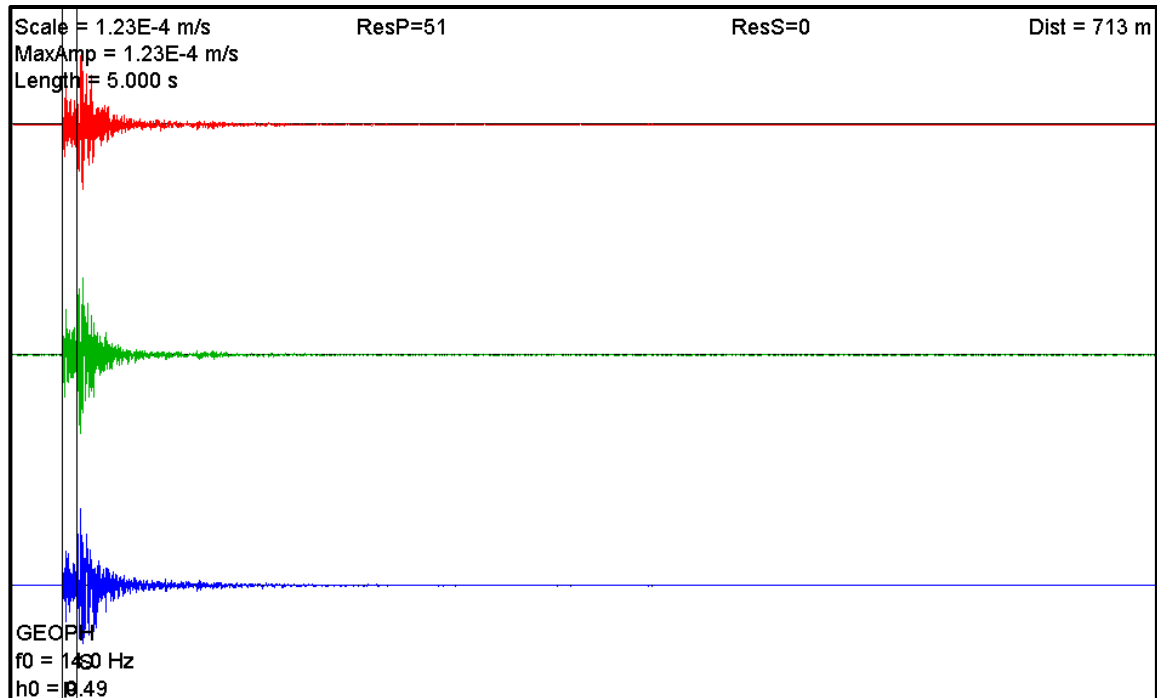
Figure 4.1: Uniaxial Seismogram.

Five of the six sensors mounted for this project were triaxial sensors with three on the surface and two underground. This signature (Figure 4.2) is from the 980 workshop sensor located 980m below ground level and it was acquired when the sensor was triggered by a particular event. Figure 4.2 shows signatures of all the three components (X, Y, Z) displayed together. The X component is red in colour, the Y component is green and the Z component is blue. This display shows how all the three components overlay when intertwined.



829 Figure 4.2: Triaxial Seismogram.

830 Figure 4.3 shows the exact same triaxial seismogram to Figure 4.2 above. On this
 831 diagram components are split so as to observe their individual characteristics. Figure
 832 4.3 also shows manually picked P and S wave's arrival times. The seismogram is for an
 833 event that occurred on the 11th of July 2019 13:09. The seismogram shows that the
 834 event occurred 713m away from the 980 workshop sensor.

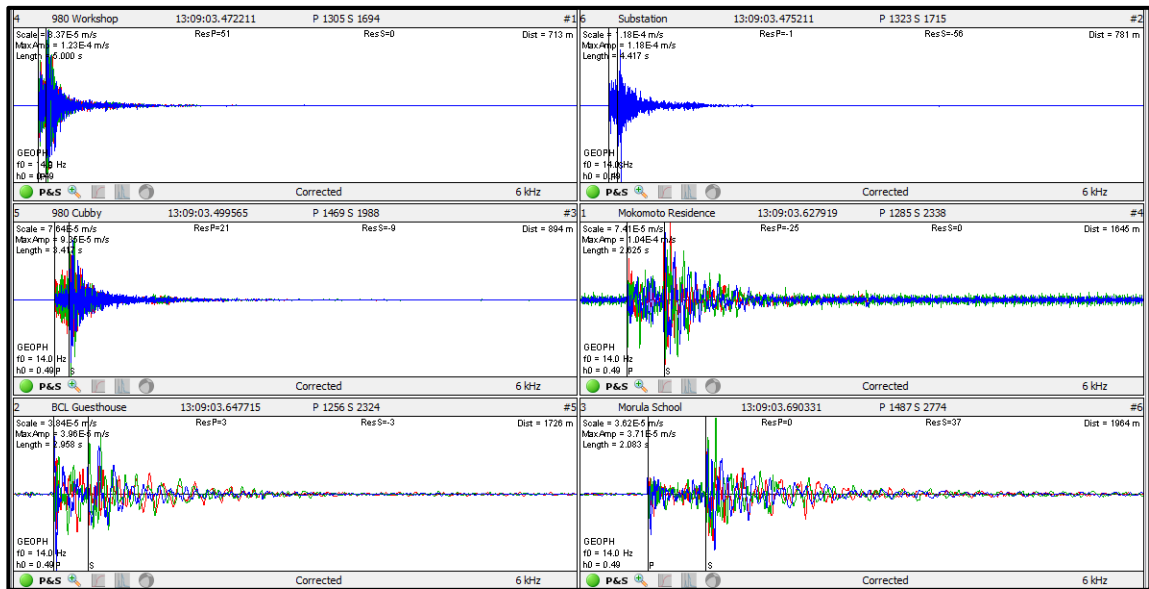


835

836 Figure 4.3: Triaxial seismogram split into its components.

837 For a certain ground motion to be accepted as an event it has to have triggered at least
 838 three sensors for proper source location estimates. For this project a certain ground
 839 motion is accepted as an event when it has triggered at least four sensors because
 840 more sensors enable better source location estimates. Figure 4.4 shows seismograms
 841 of an event that triggered all 6 geophones clearly indicating 5 triaxials and 1 uniaxial.
 842 This particular event provides precise source location estimates and it is usually of a
 843 positive local and moment magnitude. The seismograms show their individual
 844 distances from the source. Manual picking of P and S wave arrivals is depicted on each
 845 seismogram. Figure 4.4 shows all the six stations in order of trigger starting with the
 846 first to be triggered to the last; this is indicated by the increase in the distance
 847 between the P and S wave observed from the first seismogram to the last. The more

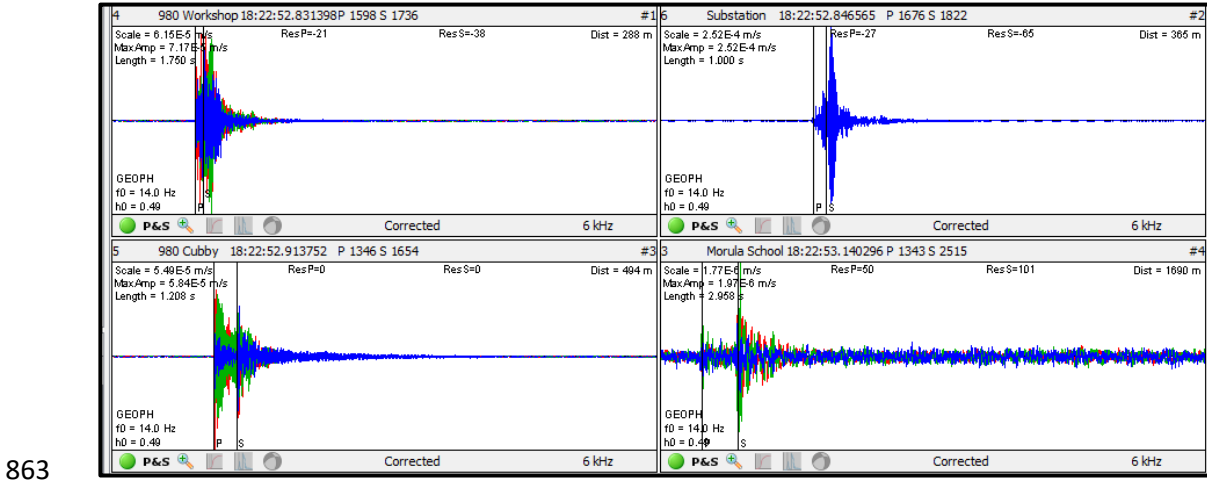
848 the distance between the P and S wave the further from the source and vice versa. The
 849 event has a local and moment magnitude of 0.6, corner frequency of 23.2Hz, static
 850 stress drop of 140.0 KPa and apparent stress of 10.1 KPa. The event occurred on 11th of
 851 July 2019 13:09:03.



852
 853 Figure 4.4: Seismic event that triggered six sensors.

854 Figure 4.5 shows seismograms of an event that triggered a total of 4 stations. The
 855 seismograms clearly show their individual distances from the source. P and S wave's
 856 arrival times have been manually picked and since the seismograms are arranged from
 857 first to be triggered to the last we can notice that the distance between the P and S
 858 waves increases in that order as well. This indicates that the distance to source
 859 increases from the first trigger to the last. Events of this calibre usually have a lower or
 860 negative local and moment magnitude. The event has a local and moment magnitude

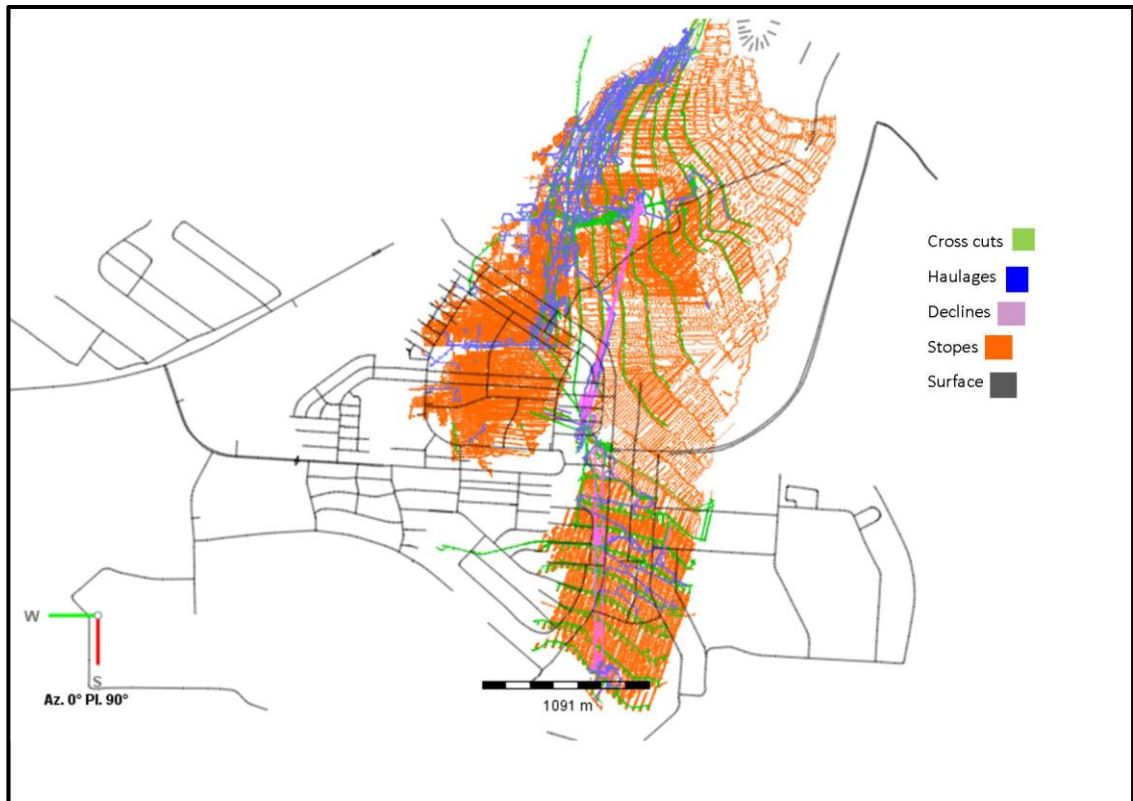
861 of -0.5, corner frequency of 294.4Hz, static stress drop of 1320.2 KPa and apparent
 862 stress of 458.1 KPa. The event occurred on 11th of July 2019 18:22:52.



864 Figure 4.5: Seismic event that triggered four sensors.

865 4.1.2 EVENT DISTRIBUTION

866 Mine plans sourced from BCL were only two dimensional and are displayed on Figure
 867 4.6. Figure 4.6 shows a plan view of an integration of the surface and the underground
 868 layouts. The surface is shown by an outline of the streets in grey and underground is
 869 outlined by cross cuts in green, haulages in blue, declines in purple and stopes in
 870 orange. Figure 4.6 simply depicts the relationship in space between the surface and
 871 underground structures.



872

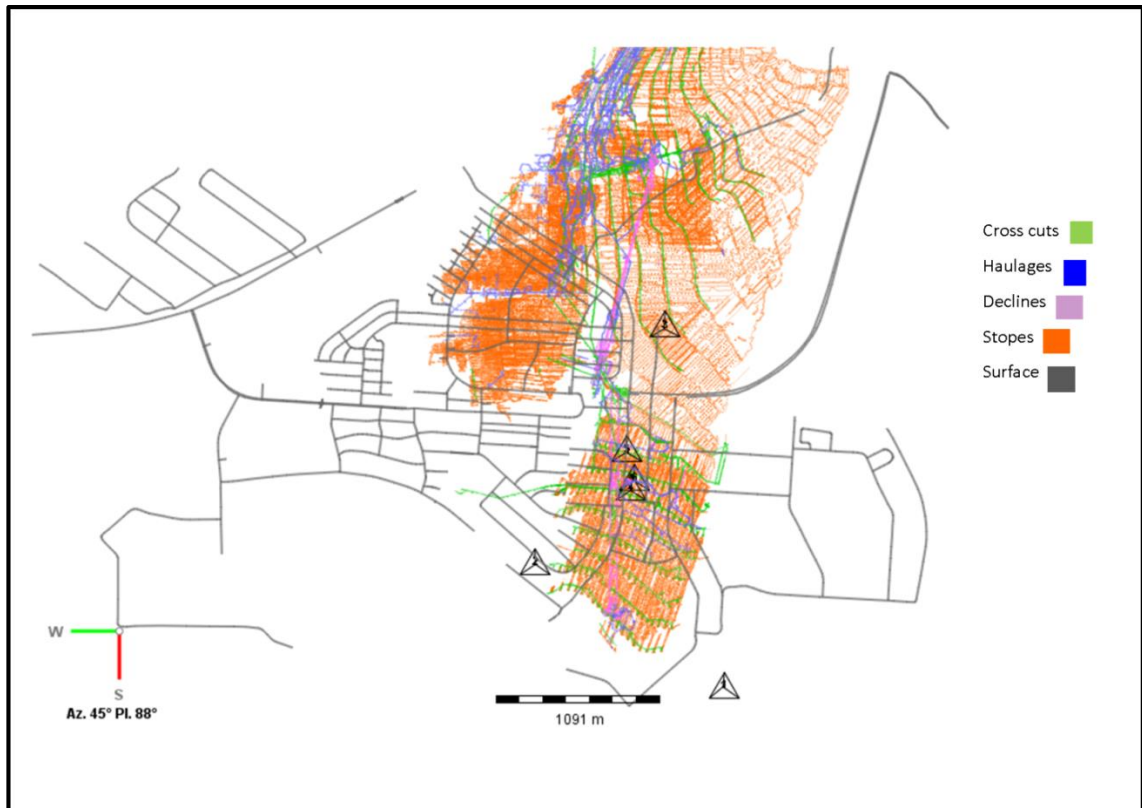
873 Figure 4.6: Mine plans.

874 Mine plans have been integrated with sensor sites to show their spacial relationship.

875 Figure 4.7 shows the spaced out surface sensors, with the underground ones not so

876 spaced out. As shown in the diagram, the sensors have been deployed towards the

877 lower parts of Figure 4.7; this is the south east extension of the mine.

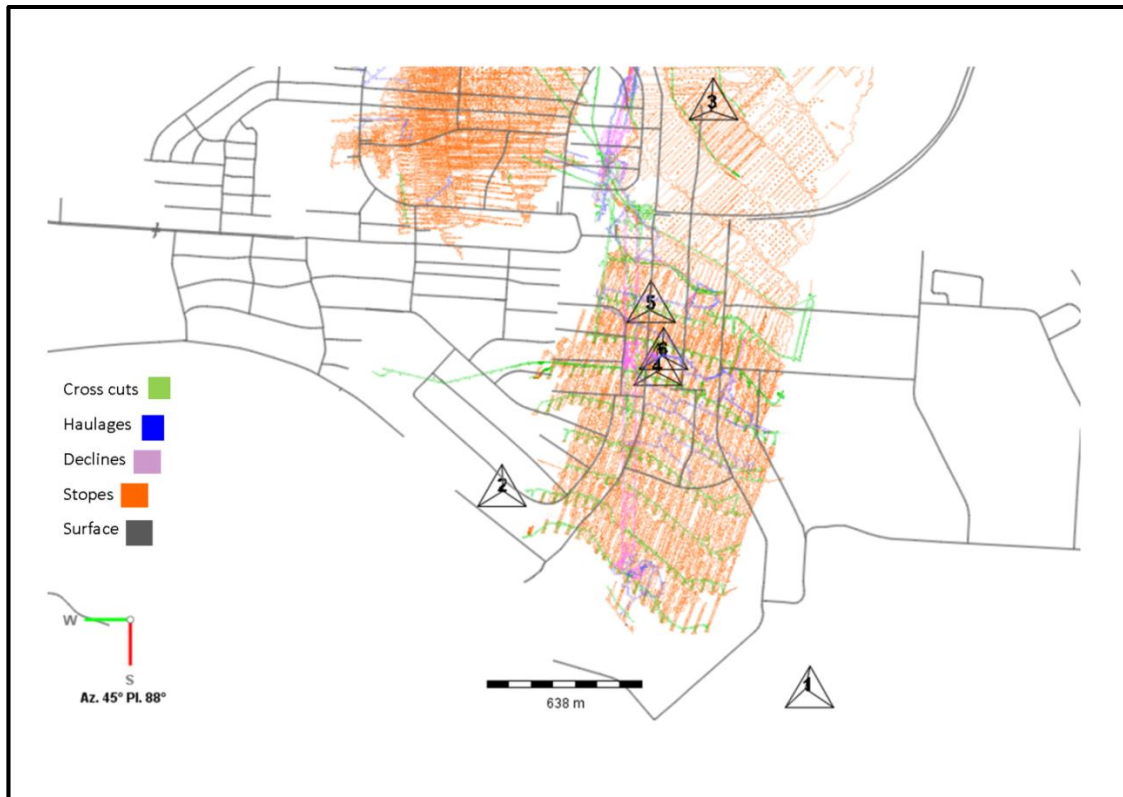


878

879 Figure 4.7: Mine plans and sensor sites

880 Figure 4.8 shows only the south east extension of the mine where seismic events are

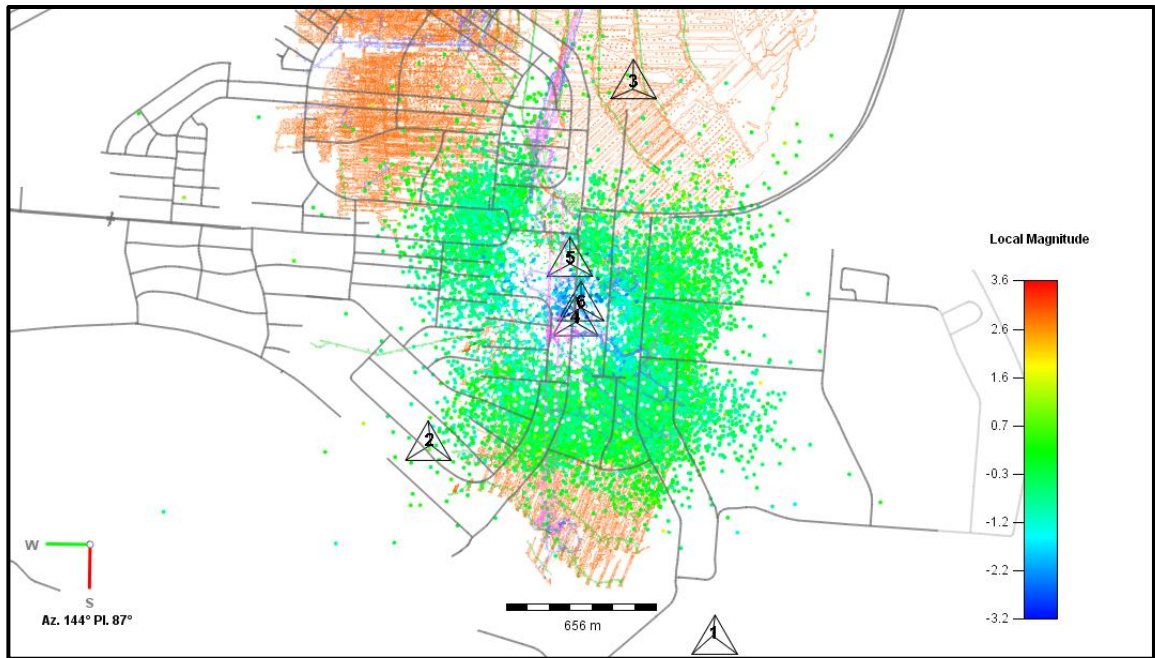
881 prone. This is a plan view of the area that is mostly the focus of this research.



882

883 Figure 4.8: South east extension with mine plans and sensor sites.

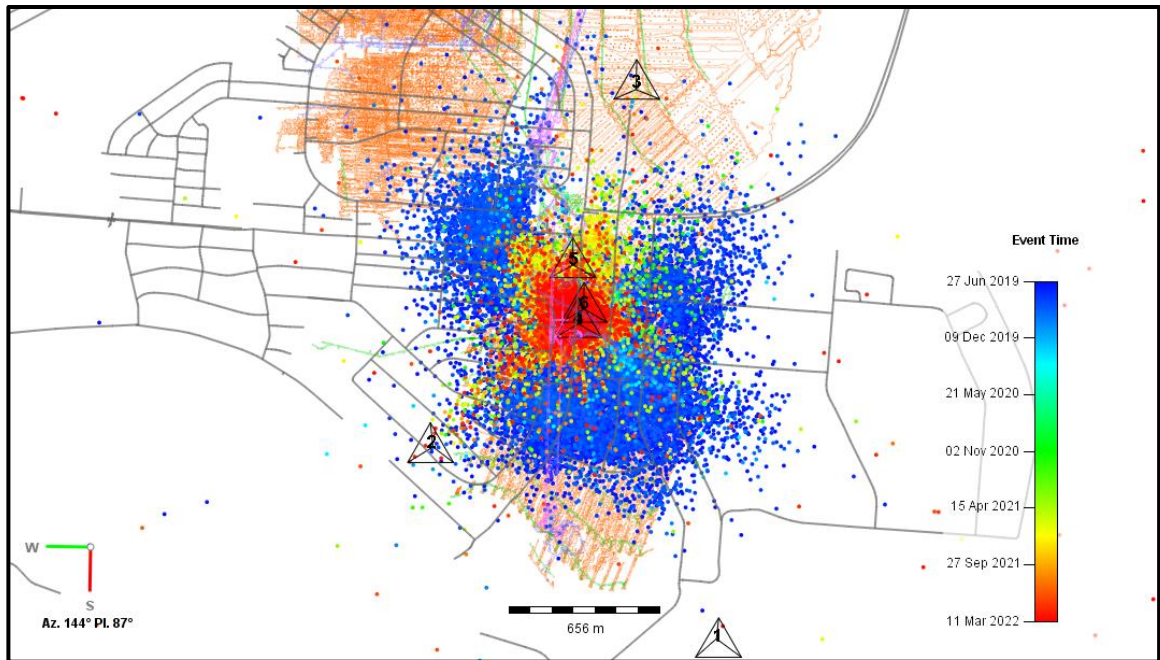
884 Figure 4.9 shows a general overview of the plan view distribution of all events
 885 recorded differentiated by their individual local magnitudes. It clearly shows that the
 886 sensor sites have enclosed the events therefore location calculations are acceptable
 887 and are of good quality. A total of **266,931** events have been processed, time ranges
 888 from 27 June 2019 to 11March 2022. The local and moment magnitude of all the
 889 events ranges from -3.2 to 3.6. According to Figure 4.9 most frequent events are of
 890 magnitude ranges from -1.2 to 1.4, followed by those of lower magnitudes of around -
 891 3.2 to -2.6 and very few events are of higher magnitudes.



892

893 Figure 4.9: Mine plans with sensor sites and events (Local magnitude).

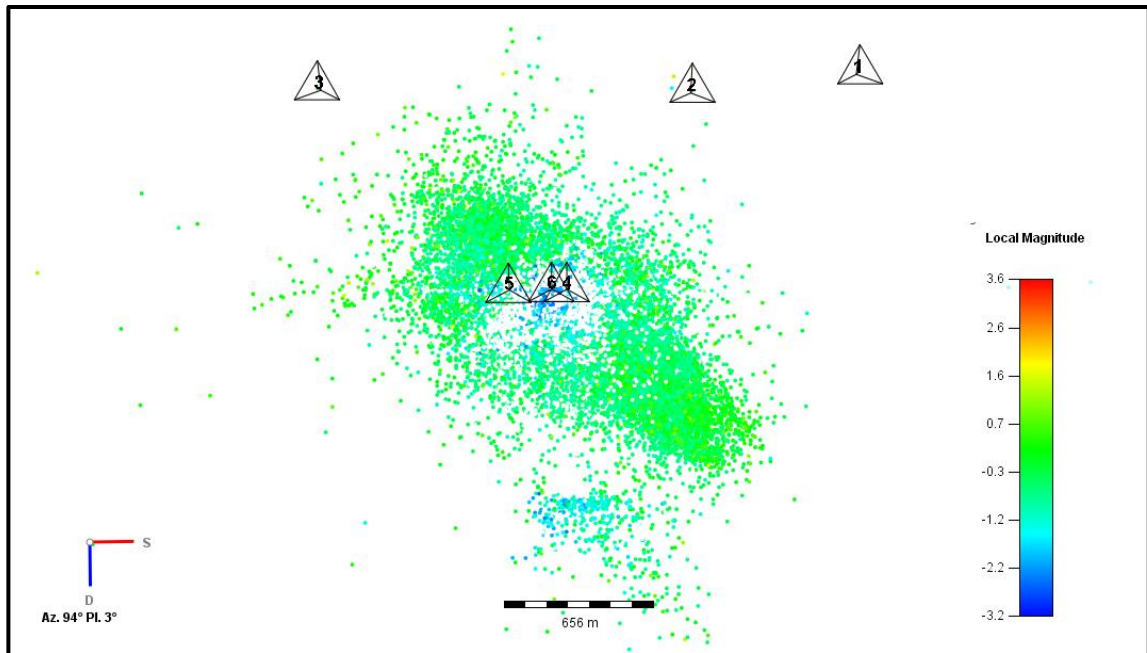
894 Figure 4.10 shows a general overview of the plan view distribution of all events
 895 recorded differentiated by their individual trigger times. A total of **266,931** events have
 896 been processed with event time ranging from 27June 2019 to 11 March 2021. Figure
 897 4.10 shows that most events recorded occurred in 2019 followed by those in 2021.
 898 Events in 2020 are not clearly visible because the seismic monitoring equipment was
 899 disconnected for a period of approximately 4 months while switching from a
 900 temporary to a permanent seismic monitoring system.



901

902 Figure 4.10: Mine plans with sensor sites and events (Event time).

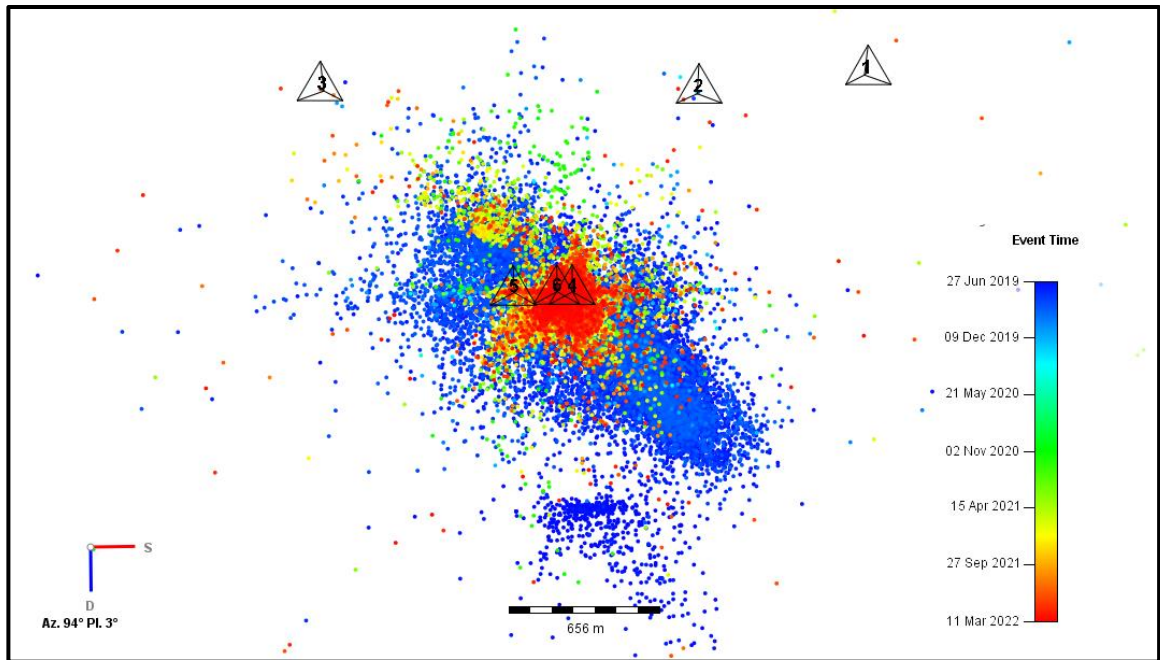
903 Figure 4.11 shows a general overview of the side view distribution of all events
 904 recorded differentiated by their individual local magnitudes. This shows the different
 905 local magnitudes of events with respect to depth as well as their distribution in
 906 relation with the sensor sites in a 3D space. From Figure 4.11 it can be observed that
 907 there are events present even below the 980m level of the underground sensors and
 908 generally most events occur there. The events occur in an interesting slanting manner;
 909 this is along the decline in the south east extension of the mine.



910

911 Figure 4.11: Side view of sensor sites with events (local magnitude).

912 Figure 4.12 shows a general overview of the side view distribution of all events
 913 recorded differentiated by their individual trigger times. This depicts the different
 914 timeframes of events with respect to depth as well as their distribution in relation with
 915 the sensor sites in a 3D space. Events in 2019 are generally dominant whether below
 916 980m level or above. Majority of both 2020 and 2021 events also occur more around
 917 the 980m level and above.



918

919 Figure 4.12: Side view of sensor sites with events (Event time).

920 4.1.3 SOURCE PARAMETERS OF LARGE EVENTS

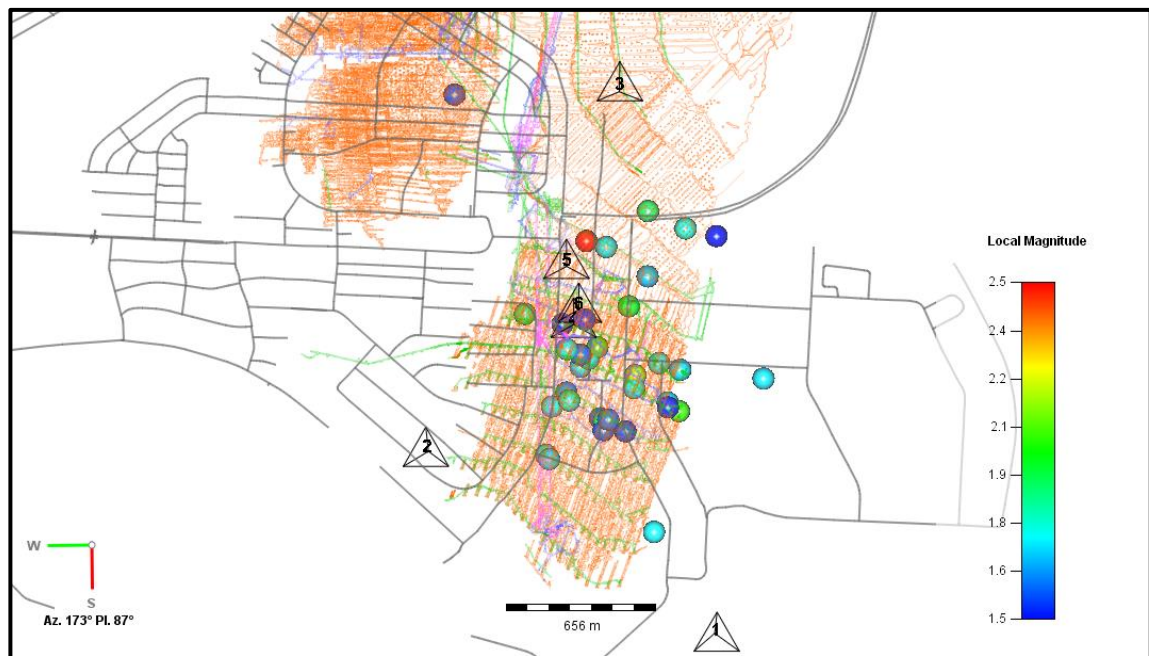
921 The table shows seismic source parameters of a few events at BCL mine. The events
 922 are large events with local magnitude greater than 1.5. Large events are vital in making
 923 location and source parameter calculations as well as computing source mechanisms
 924 and making seismic hazard analysis as they yield more accurate results. Most of the
 925 events triggered all the six sensors and majority of them occurred in 2019 with two of
 926 the thirty-four occurring in 2020 and three in 2021. Time of day of occurrence is very
 927 random for the large events; they are not of a specific time frame. The dominant large
 928 magnitude is 1.7 and the highest normal large event is 2.5 local magnitude. A filter has
 929 been applied to this data (the normal events filter), where events are manually
 930 processed and accepted; blasts and test events are excluded.

931 **Table 4.1: Seismic source parameters**

No.	Date	Time	X[m]	Y[m]	Z[m]	Mag	Energy [J]	App Stress [Nm]	Sites Triggered
1	2019/06/27	17:21:54	31885.2	-88338.8	1590.1	1.7	1.94 ³	1.35 ²	3
2	2019/06/29	10:12:17	31790.3	-87877.4	1115.9	1.7	2.20 ⁵	1.40 ⁴	6
3	2019/06/29	20:48:40	32219.8	-87390.7	1413.1	1.7	2.87 ⁶	2.04 ⁵	5
4	2019/07/04	01:21:00	32044.7	-87617.4	1455.8	1.6	1.19 ⁶	1.37 ⁵	6
5	2019/07/04	03:56:22	32053.7	-87633.9	1402.5	1.9	5.49 ⁶	1.86 ⁵	6
6	2019/07/04	06:04:02	31607.7	-87454.6	1003.9	1.5	1.35 ⁵	1.95 ⁴	6
7	2019/07/06	08:15:34	31929.7	-87470.1	1444.5	1.6	2.55 ⁶	2.42 ⁵	6
8	2019/07/07	06:13:56	31537.3	-87747.4	1094.1	2.0	4.15 ⁵	1.26 ⁴	6
9	2019/07/07	07:40:33	31565.5	-87290.1	1100.3	1.9	4.01 ⁵	1.46 ⁴	5
10	2019/07/09	01:20:18	32101.2	-87727.7	1399.8	1.6	7.04 ⁵	8.81 ⁴	6
11	2019/07/11	12:56:46	32013.1	-87963.9	1343.5	2.1	7.60 ⁵	1.66 ⁴	6
12	2019/07/11	18:47:42	32094.3	-87631.5	1383.0	1.6	5.00 ⁵	5.82 ⁴	6
13	2019/07/12	21:23:07	31955.6	-87481.2	1253.0	1.8	1.74 ⁶	8.98 ⁴	6
14	2019/07/13	00:02:22	31746.7	-87532.8	1066.7	1.6	4.32 ⁵	4.88 ⁴	6
15	2019/07/17	01:00:40	31717.6	-87607.7	1125.1	2.0	1.95 ⁶	4.54 ⁴	6
16	2019/07/19	02:40:05	31223.2	-88135.5	857.1	1.5	2.66 ⁵	3.98 ⁴	6

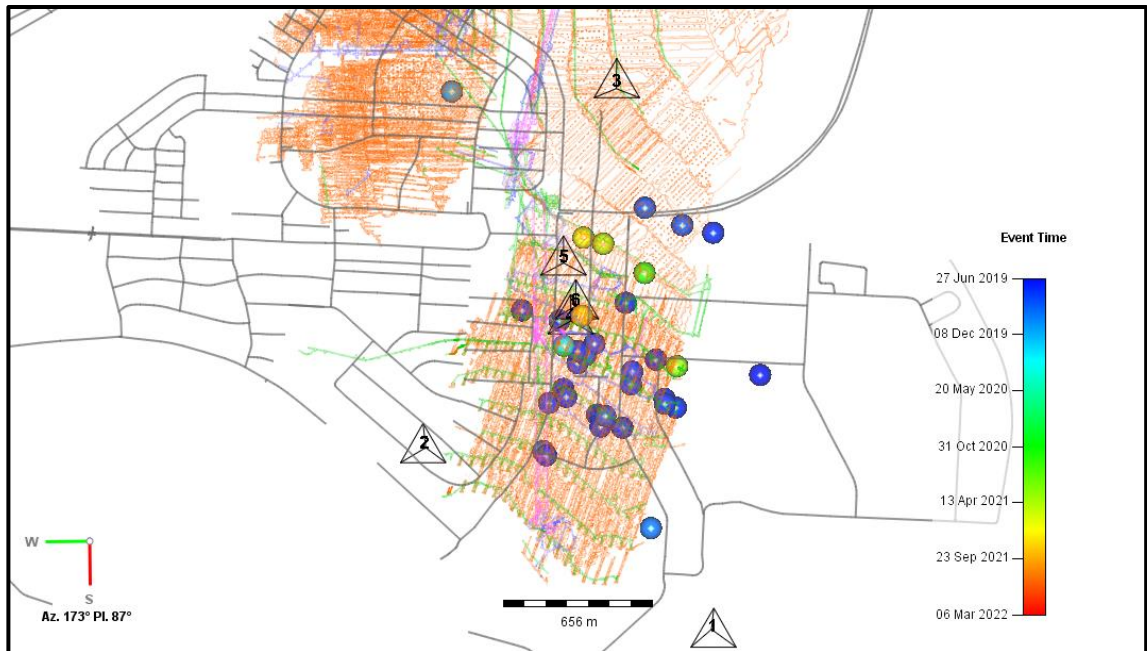
17	2019/07/19	13:09:22	31903.0	-87767.5	1224.5	1.8	4.51 ⁵	2.61 ⁴	5
18	2019/07/20	12:17:45	31988.7	-87915.2	1192.4	1.5	2.09 ⁵	3.03 ⁴	5
19	2019/07/20	19:12:19	31847.6	-87773.5	1239.8	2.2	3.39 ⁶	5.25 ⁴	6
20	2019/07/23	22:02:53	31973.0	-87914.4	1307.6	1.7	1.23 ⁵	8.89 ³	4
21	2019/07/25	08:15:23	31992.2	-87406.6	1487.7	1.7	5.11 ⁵	3.23 ⁴	5
22	2019/07/26	04:07:58	31808.4	-87533.3	1270.7	1.7	1.66 ⁶	1.14 ⁵	6
23	2019/08/14	12:37:09	32045.0	-87652.4	1313.9	1.6	1.36 ⁶	1.45 ⁵	5
24	2019/08/22	19:23:35	31118.2	-87837.0	1054.4	1.9	2.59 ⁶	9.14 ⁴	5
25	2019/08/23	21:46:00	31768.3	-87567.8	1134.5	1.7	1.29 ⁶	8.92 ⁴	6
26	2019/08/24	07:41:45	31194.4	-88000.7	999.2	1.8	8.78 ⁵	4.96 ⁴	6
27	2019/09/09	18:36:50	32212.0	-87379.0	1656.0	1.8	2.61 ⁶	1.26 ⁵	6
28	2019/09/29	17:52:55	32410.7	-87830.7	1564.7	1.7	2.41 ⁵	1.55 ⁴	4
29	2019/11/06	07:09:00	30586.6	-86991.1	860.2	1.6	5.19 ⁵	6.38 ⁴	4
30	2020/01/23	23:07:08	31720.7	-87473.1	1038.1	1.7	3.82 ⁴	2.48 ³	4
31	2020/12/04	14:53:12	31355.1	-87825.2	53.5	1.7	2.35 ⁵	1.96 ⁴	4
32	2021/03/20	12:36:01	31819.8	-87970.2	1094.4	1.7	4.59 ⁵	3.37 ⁴	4
33	2021/04/10	23:39:25	31246.3	-87647.8	437.1	1.7	7.16 ⁵	5.00 ⁴	4
34	2021/05/28	05:27:15	31226.4	-87561.8	613.1	2.5	4.48 ⁶	1.92 ⁴	4

933 Figure 4.13 shows the plan view of the large events displayed on Table 4.1. The events
934 are differentiated by their individual local magnitudes and are much concentrated in
935 the center of the sites around the underground sensors. Majority of events are of
936 magnitude 1.7 followed by those between 1.9 and 2.1. Figure 4.13 displays a total of
937 34 events with magnitude ranges from 1.5 to 2.5.



938
939 Figure 4.13: Plan View of large events (Local Magnitude).

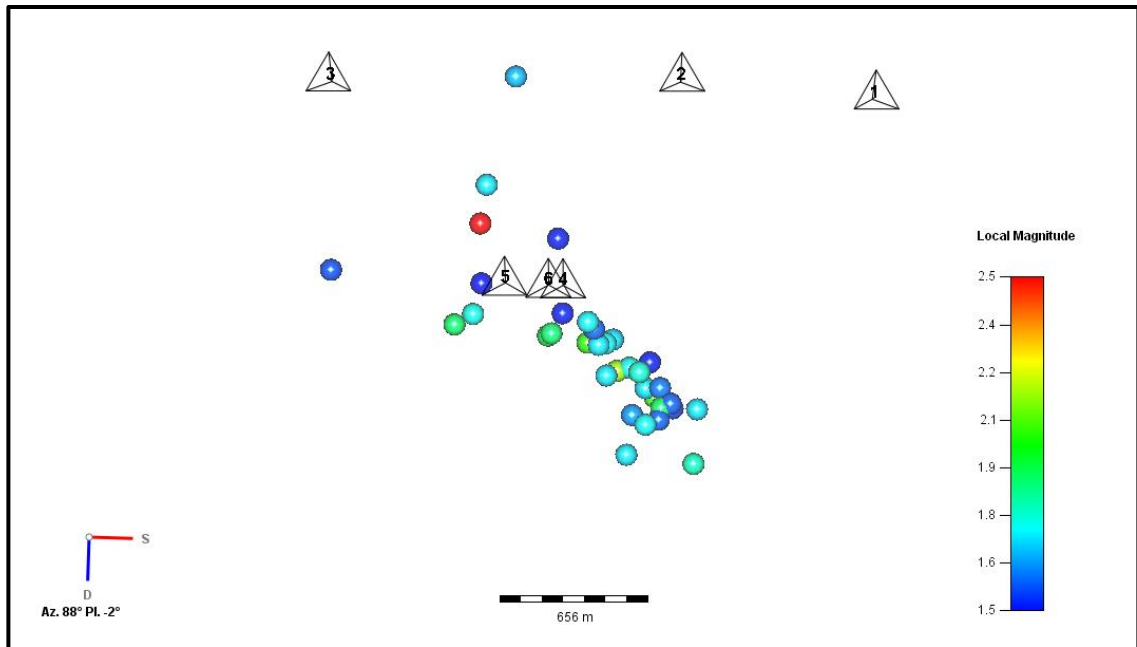
940 Figure 4.14 shows the plan view of large events coloured with their individual times of
941 occurrence. Time ranges from 27 June 2019 to 06 March 2022. It shows that most
942 events occurred in 2019 with only a few in 2020 and 2021. When correlating Figure
943 4.14 to Figure 4.13, it shows that the largest event ever recorded occurred on the 28th
944 of May 2021.



945

946 Figure 4.14: Plan View of large events (Event time).

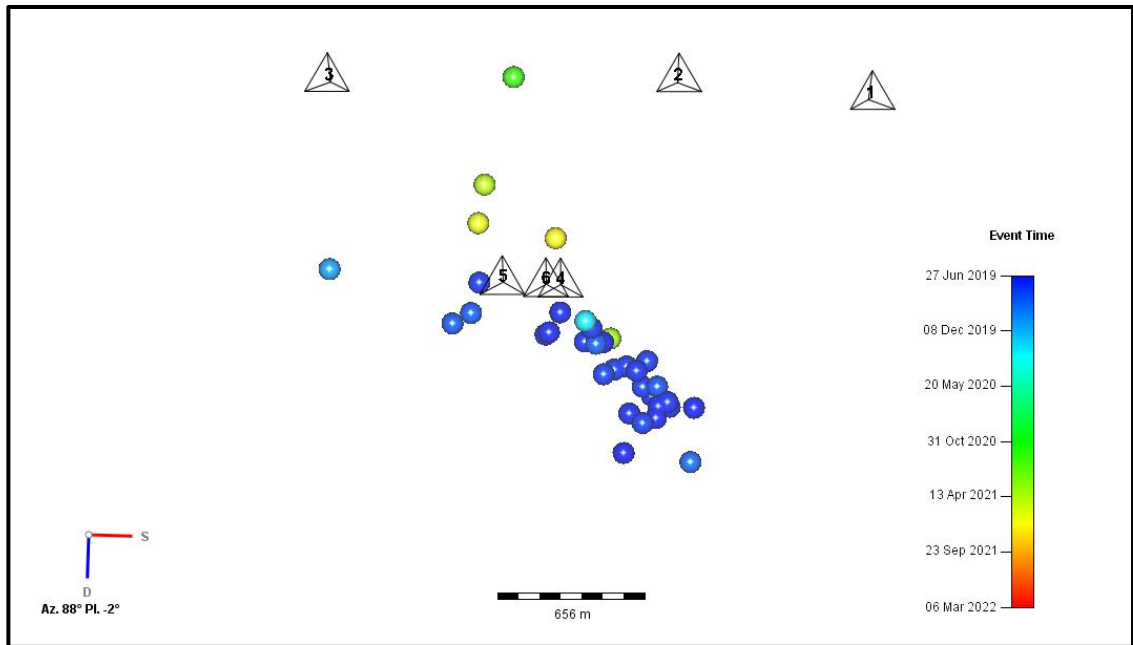
947 Figure 4.15 shows a side view distribution of large events coloured with their individual
 948 local magnitudes. Majority of events occur below the 980m level while the largest
 949 event occurs in between the sensors, more towards the underground sensors. There's
 950 an interesting occurrence of these events in a slanting manner especially on the ones
 951 below the 980m level. They are occurring along a decline in the south east extension of
 952 the mine.



953

954 Figure 4.15: Side View of large events (Local Magnitude).

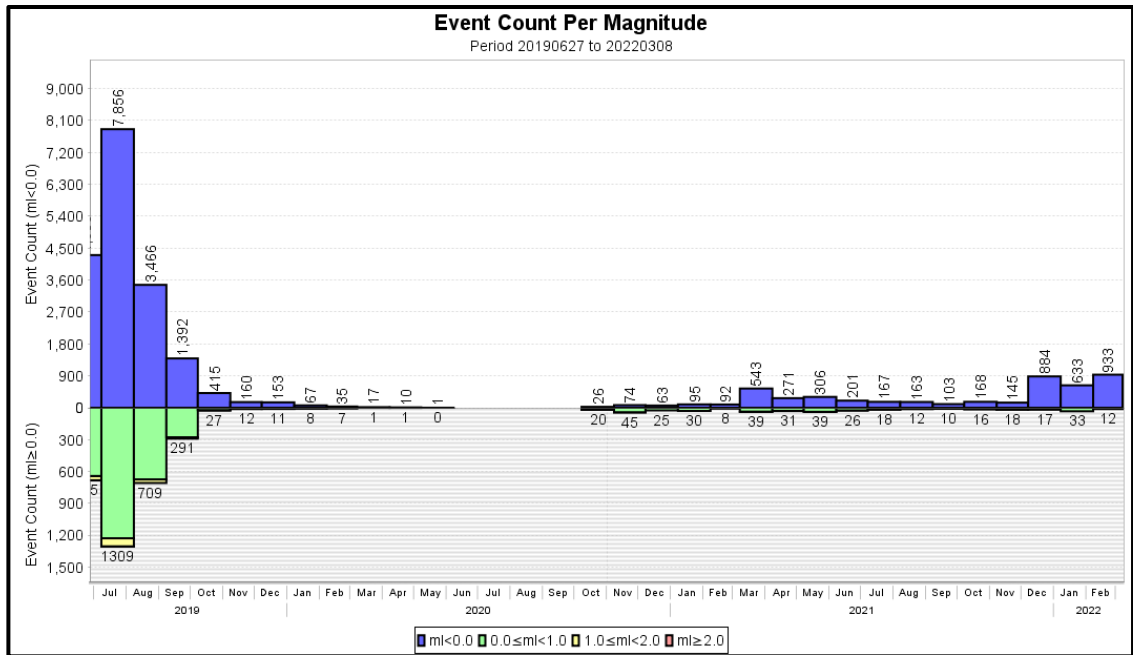
955 Figure 4.16 shows a side view distribution of large events coloured with their time of
 956 occurrence. Generally large events occur beneath the underground sensors 980m
 957 level. Majority of the events below the 980m level occurred in 2019 while majority of
 958 those that occurred above the 980m level are much more recent occurring in 2020 and
 959 2021.



960

961 Figure 4.16: Side View of large events (Event time).

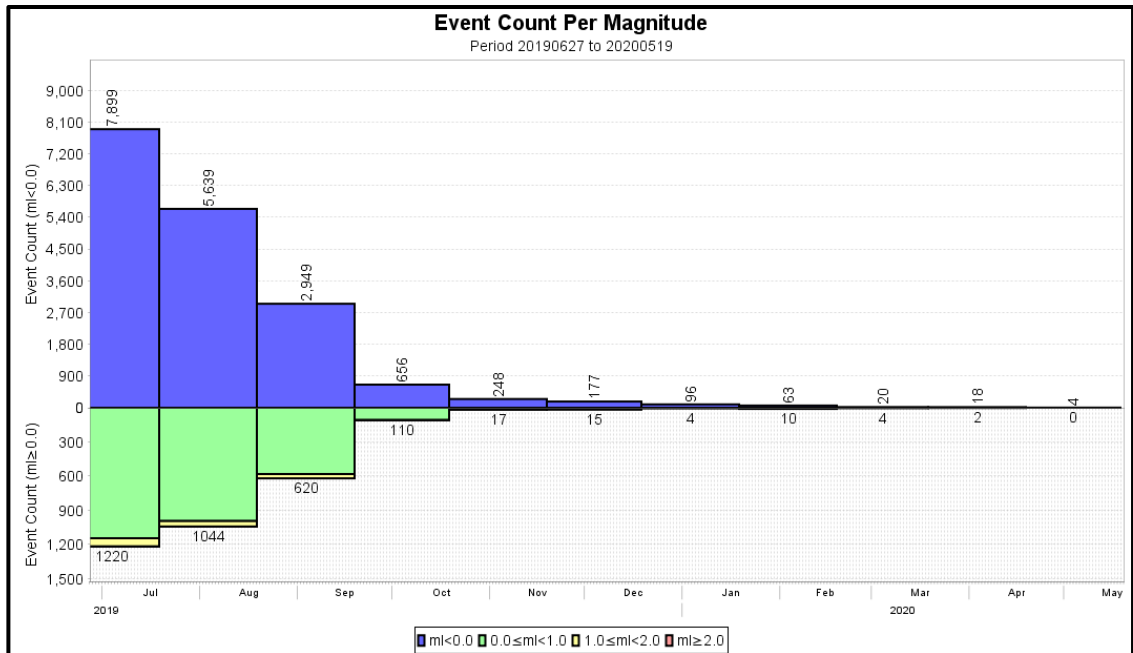
962 Figure 4.17 shows number of events per month with events less than zero at the top in
 963 blue and events more than zero at the bottom in green and yellow respectively. The
 964 data presented is for all the data acquired (including both the temporary and
 965 permanent acquisition periods). The data clearly separates the two time periods
 966 indicating a time of no recording of the events for approximately four months. From
 967 the diagram the BCL mine experiences more events less than zero than those more
 968 than zero and the temporary monitoring system period recorded more events in both
 969 small and large events than the permanent monitoring system period.



970

971 Figure 4.17: Number of events per month, All monitoring.

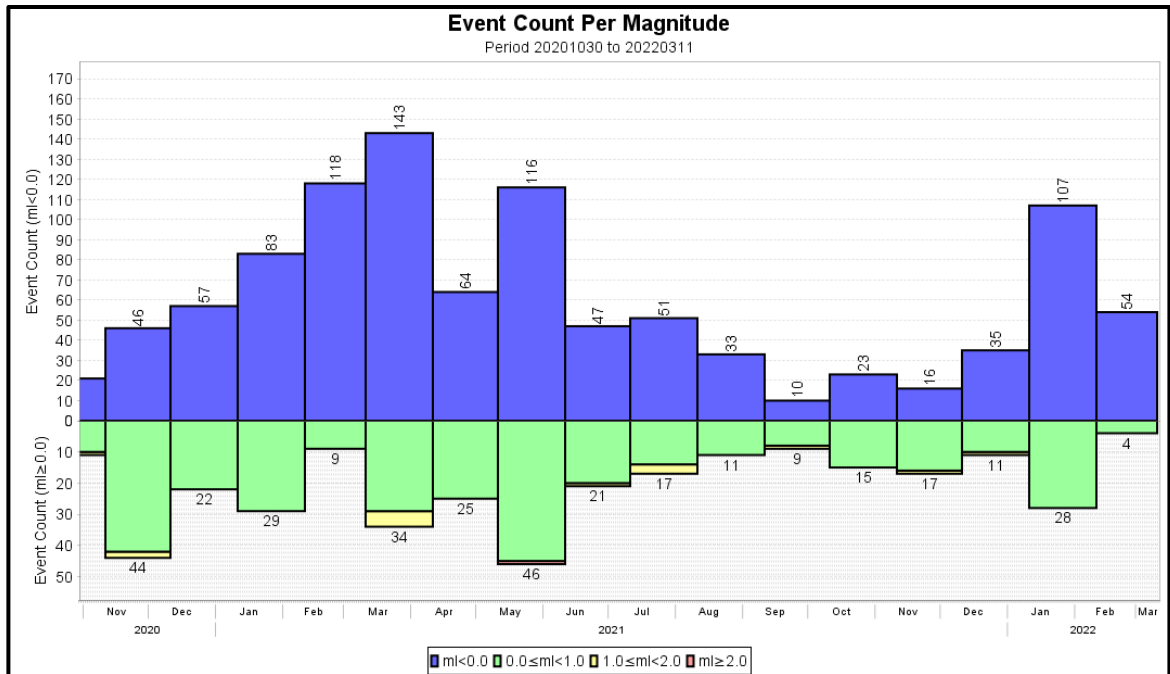
972 Figure 4.18 shows number of events per month for the period of the temporary
 973 seismic monitoring system. There was a decrease in the number of events per month
 974 from as high as 7899 for small events and 1220 for large events in July 2019, to 18 and
 975 2 respectively in April 2019. This decrease in events has been correlated with water
 976 pumping activities at the mine. Towards the end of 2018 pumping activities were
 977 ceased at the BCL Limited mine, therefore the southeast extension of the mine filled
 978 with water such that the water head increased at a rate of 2.25m per day on average.
 979 Pumping activities were resumed on the 2nd of August 2019 hence the decrease in the
 980 number of events since then.



981

982 Figure 4.18: Number of events per month, Temporary seismic monitoring.

983 Figure 4.19 shows the number of events per month for the period of the permanent
 984 seismic monitoring system. Smaller events have a clear domination over the large
 985 events. There isn't a clear increase or decrease of the number of events with time
 986 especially with large events as compared to the previous temporary monitoring
 987 system. For small events there's an increase followed by a sharp decrease then an
 988 increase followed by a decrease of the number of events with time. Large events are
 989 characterized by a decrease then increase followed by a decrease with time. The spike
 990 in March just shows that there were more events occurring that month rather than
 991 anything significant. This is because when compared to the time frame of the
 992 temporary monitoring system, the increase is minute.



993

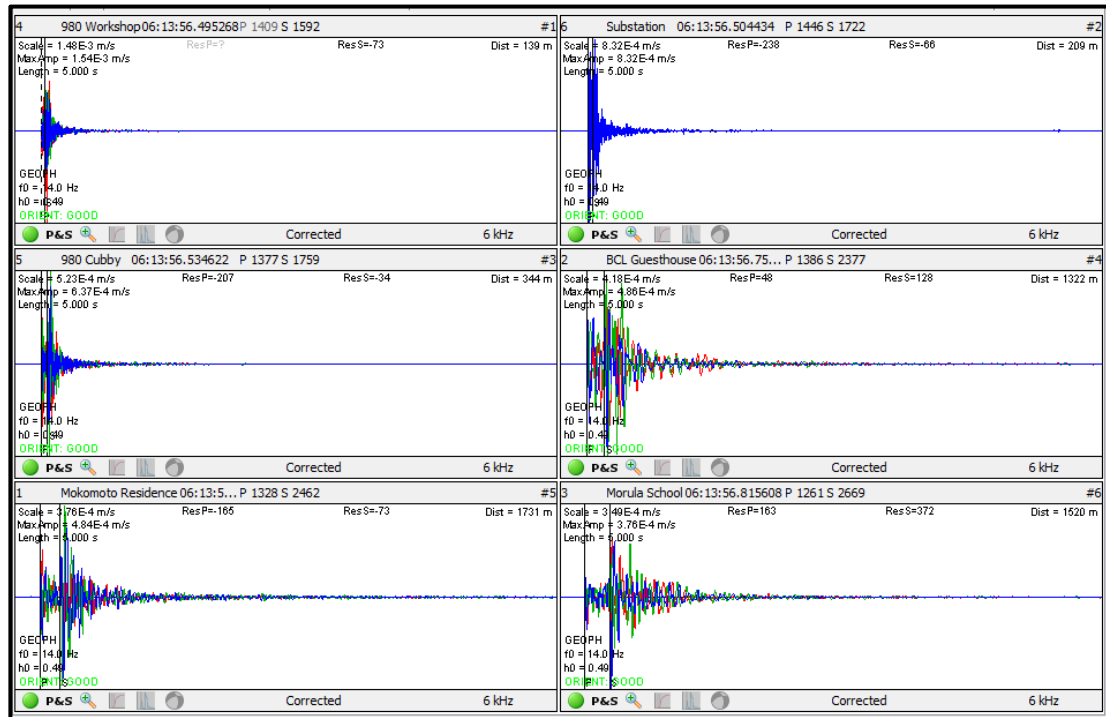
994 Figure 4.19: Number of events per month, Permanent seismic monitoring.

995 4.1.4 SEISMIC SOURCE MECHANISM

996 Large events (local magnitude greater than 1.5) were used for the decomposition of
 997 the moment tensor since they yield more accurate results compared to the smaller
 998 ones. This is due to their low signal to noise ratio. A total of 34 events were used for
 999 the moment tensor inversion but, only the decomposition process of one is shown
 1000 because the process is the same for all the 34 events. The first inversion will be for the
 1001 amplitude and polarities followed by the full waveform inversion. This is so that the
 1002 two results are compared. The solutions involve both the volumetric and deviatoric
 1003 components.

1004 Figure 4.20 shows the waveform of a 1.9 magnitude event that occurred on the 7th July
 1005 2019, this will be used to show the process of the moment tensor decomposition. All

1006 the six sensors were triggered by the event. Sensor orientation is good as indicated in
 1007 the diagram and the P and S waves has been manually and correctly picked.

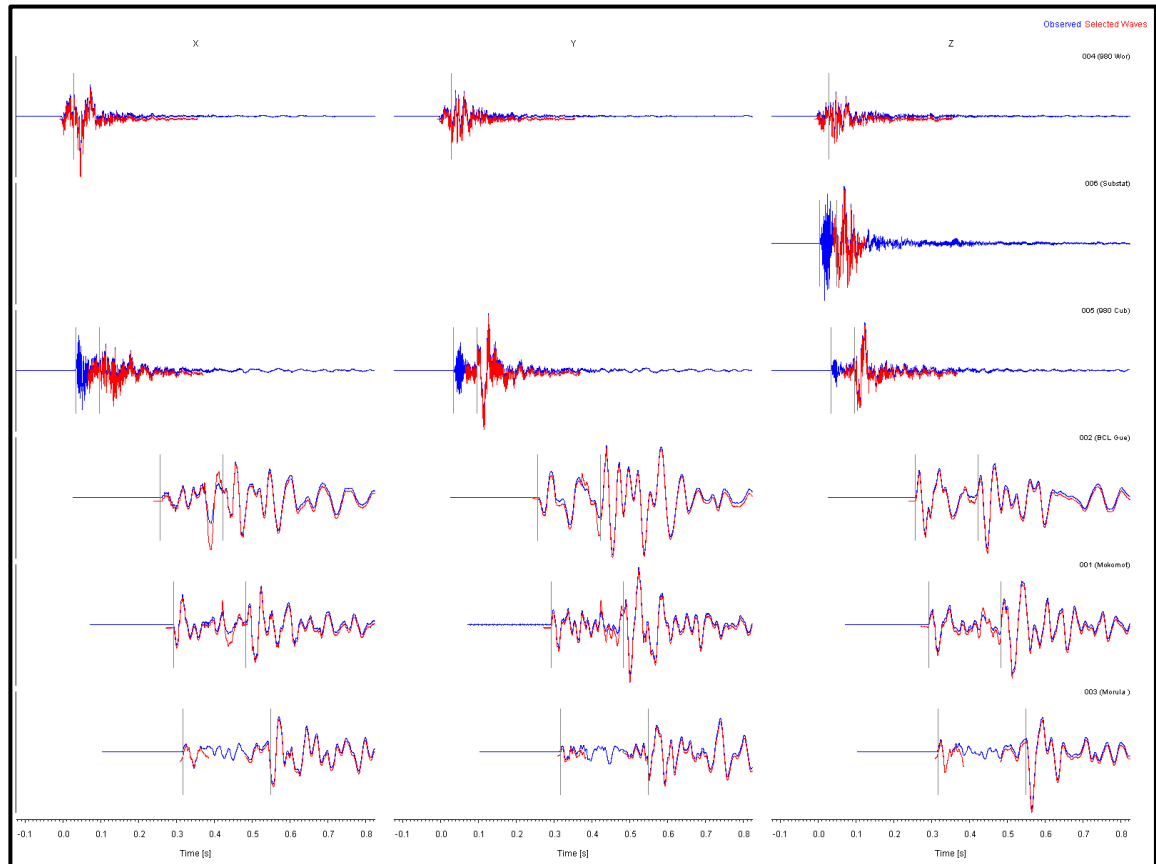


1008
 1009 Figure 4.20: Waveform of a 1.9 magnitude event that occurred on the 7th July 2019.

1010 4.1.4.1 AMPLITUDES AND POLARITIES

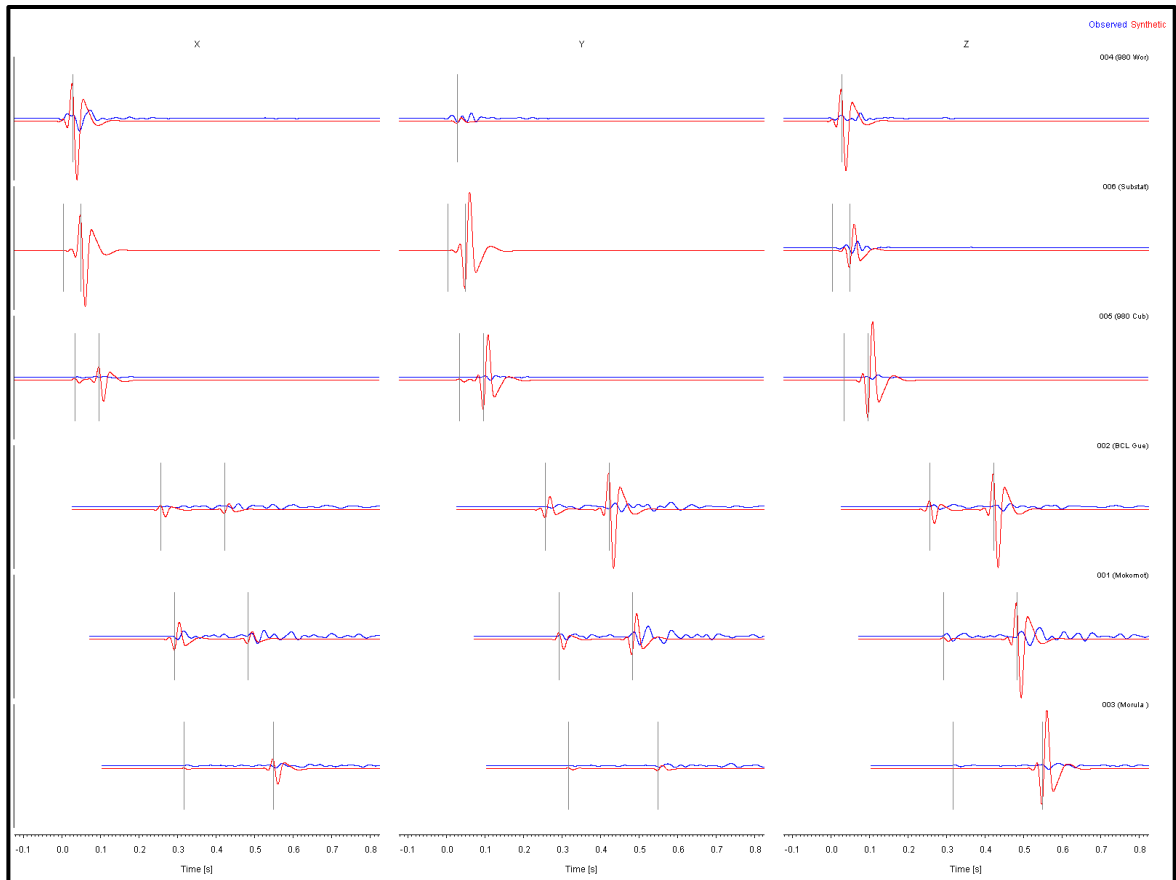
1011 Figure 4.21 shows the observed waveform in blue and the waveform selected for the
 1012 inversion in red. The waveforms are divided into their individual X, Y, Z components.
 1013 Figure 4.21 shows the waveform of all the six sensors starting with the first triggered at
 1014 the top and the last triggered at the bottom. The grey vertical marks indicate the P and
 1015 S picks. The P pick for the first triggered sensor was not clear as shown on Figure 4.21
 1016 above therefore it will not be used for the inversion and it is not marked on the
 1017 diagram. Amplitudes and polarities depends on the P and S picks therefore ideally the

1018 selected waves should be around the P and S picks as shown in the last sensor
1019 triggered.



1020
1021 Figure 4.21: Selected parts of the waveform used for moment tensor inversion,
1022 Amplitude and polarities.

1023 Figure 4.22 shows the waveform after inversion has been carried out. The red line is
1024 the best calculated mechanism (modelled seismogram). The fit is not necessarily great
1025 even though the event is of a higher magnitude; ideally a certain degree of correlation
1026 should be seen between the observed (blue) and synthetic (red) waveforms.



1027

1028 Figure 4.22: Moment tensor Inversion waveform result, Amplitude and Polarities.

1029 Figure 4.23 shows the decomposition results of the amplitude and polarities inversion.

1030 Numbers 1, 2, 3, 4, 5, and 6 represents the sensors triggered positioned on whether

1031 the first P wave motion is away from the source or towards the source. The shaded

1032 area represents the dilatational quadrant where the first motions are moving away

1033 from the source and T is the axis of tension located in the middle of the dilatational

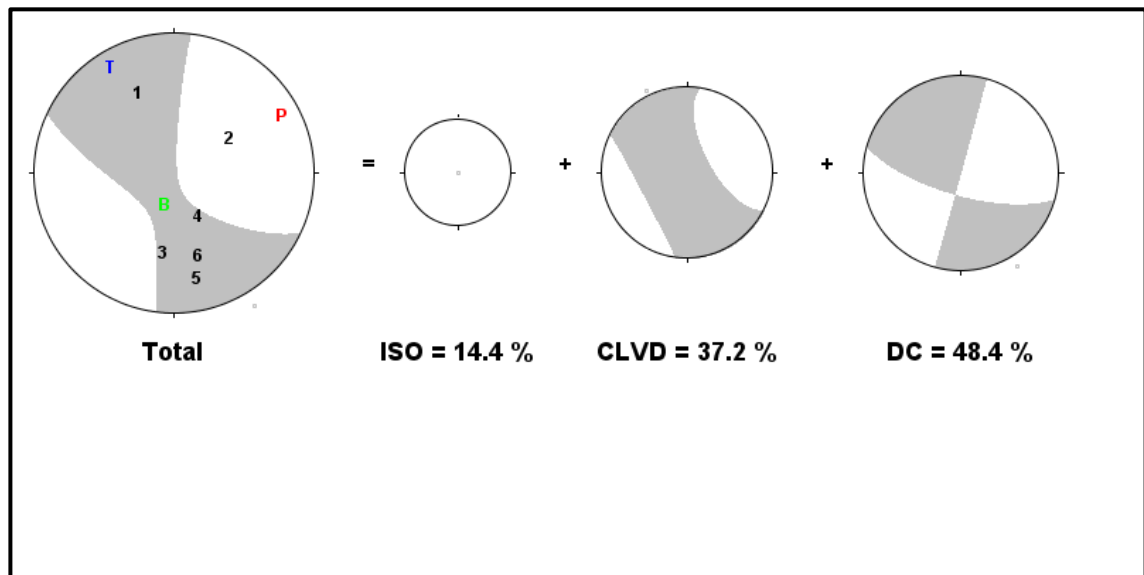
1034 quadrant. The unshaded area represents the compressional quadrant where the first

1035 motions are moving towards the source and P is the axis of compression located in the

1036 middle of the compressional quadrant. B is the null or intermediate axis. Sensor 2 is

1037 the only sensor with first motions moving toward the source while other sensors

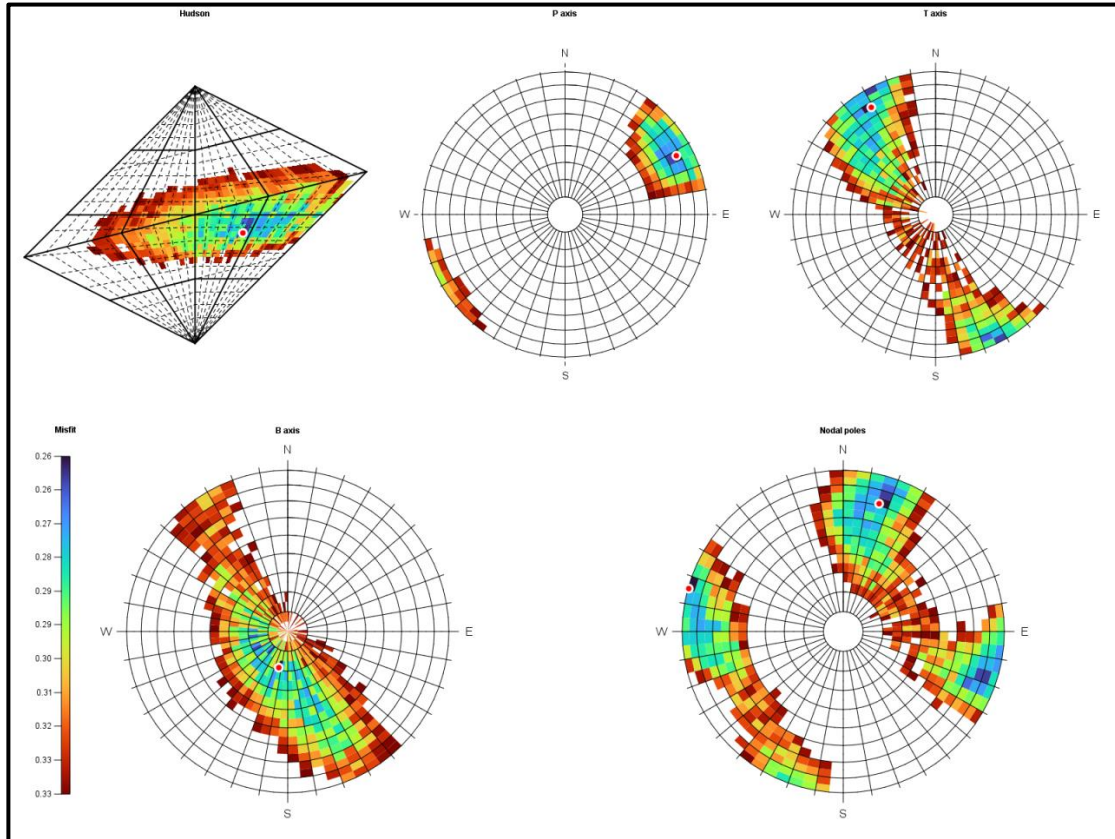
1038 received first motions moving away from the source. Moment tensors are
 1039 characterized by two components, the volumetric (ISO) and the deviatoric (CLVD and
 1040 DC) components. The moment tensor inversion yielded a solution with a 37.2% slightly
 1041 vertically oriented CLVD, a 48.4% double couple component and a 14.4% volumetric
 1042 contraction. This shows a higher deviatoric component than the volumetric
 1043 component, which is interpreted that the event could be a result of deformation at the
 1044 source due to stress on the rock mass. It is also interpreted that the event may not
 1045 have been characterized by excessive amounts of rock shedding.



1047 Figure 4.23: Moment tensor decomposition result Amplitudes and Polarities.

1048 Figure 4.24 shows the Hudson plot together with four stereo nets showing the nodal
 1049 planes, and the P T and B axis. The top of the Hudson plot represents explosion, the
 1050 bottom represents implosion, the middle represents DC component, and the two
 1051 extreme left and right sides represents the CLVD component. The Hudson plot is well
 1052 constrained and it indicates the event to be neither implosive nor explosive but more

1053 to the implosive side. The P axis has a north east orientation while the nodal planes, T
1054 axis and B axis are poorly constrained.

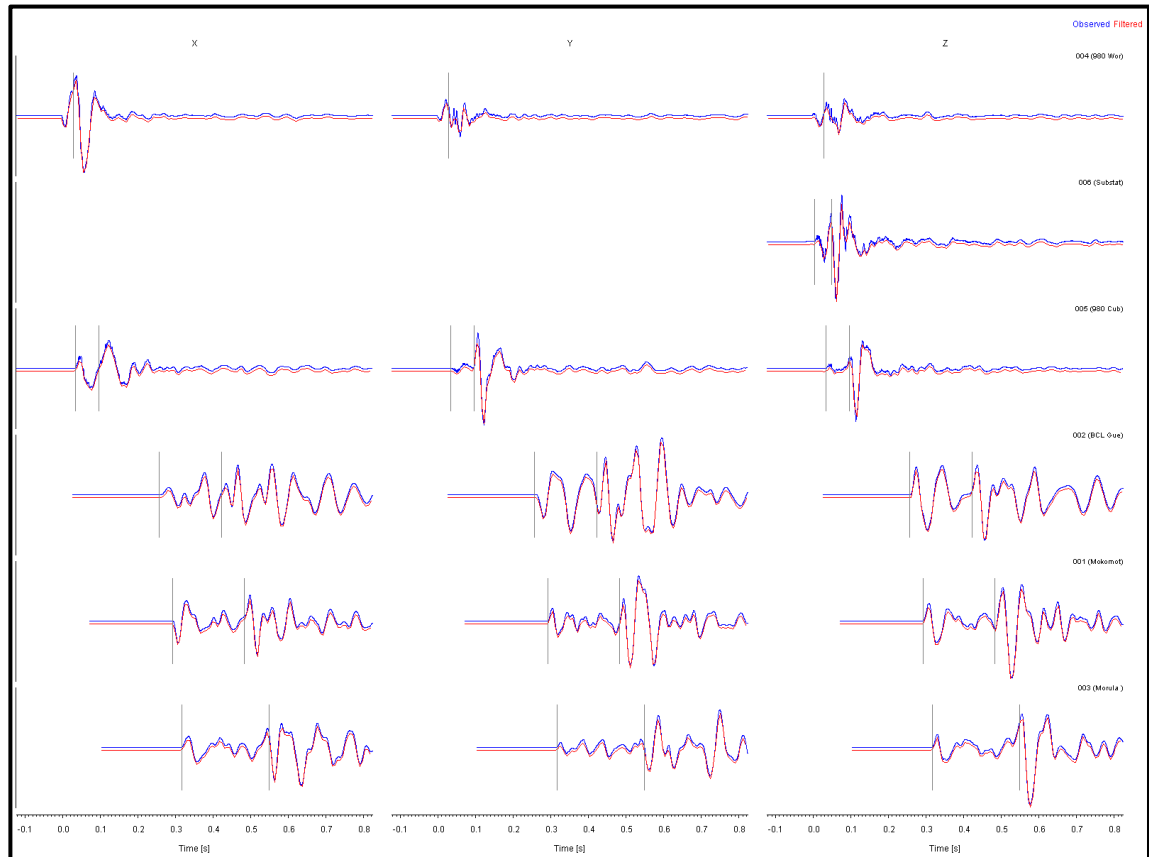


1055
1056 Figure 4.24: Hudson plot, nodal planes and the P, T, B axis of the Amplitude and
1057 Polarities Inversion

1058 4.1.4.2 FULL WAVEFORM

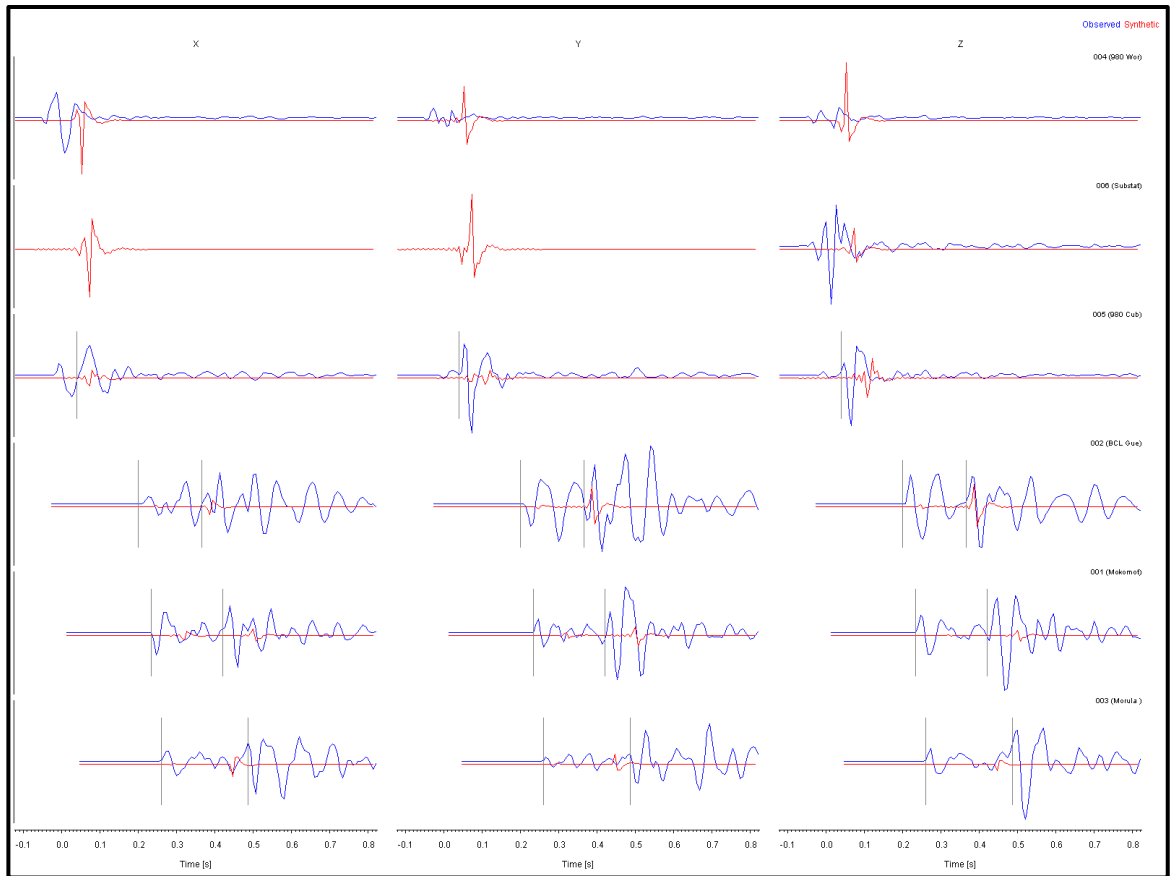
1059 Figure 4.25 shows the waveform selected for the full waveform inversion. The
1060 observed waveform in blue and the waveform selected for the inversion in red. The
1061 waveforms are divided into their individual X, Y, Z components. The diagram shows the
1062 waveform of all the six sensors starting with the first triggered at the top and the last
1063 triggered at the bottom. The grey vertical marks indicate the P and S picks. For the full

1064 waveform inversion, the whole waveform is selected unlike for amplitude and
1065 polarities where certain areas of the waveform are selected for inversion.



1066
1067 Figure 4.25: Selected parts of the waveform used for moment tensor inversion, Full
1068 waveform

1069 Figure 4.26 shows the waveform after inversion, the red line represents the best
1070 calculated mechanism. Generally compared to the amplitude and polarities waveform
1071 the fit of the full waveform inversion is not a great fit especially on the surface sensors.

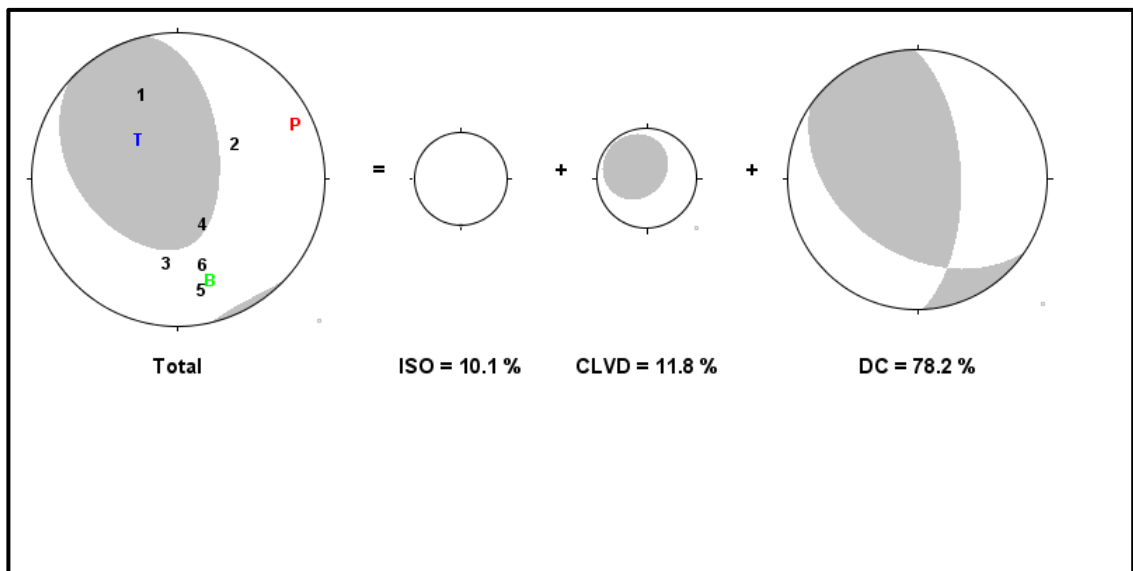


1072

1073 Figure 4.26: Moment tensor Inversion waveform result, Full waveform.

1074 Figure 4.27 shows the decomposition results of the full waveform inversion. Sensors 1
 1075 and 4 are in the compressional quadrant while sensors 2, 3, 6 and 5 are in the
 1076 dilatational quadrant. There are more sensors in the dilatational quadrant than those
 1077 of the amplitude and polarities inversion. The P, T, B axis are clearly shown, they are
 1078 almost the same orientation compared to the ones in the amplitude and polarities. The
 1079 decomposition produced a total deviatoric component of 90% with 11.8% CLVD and
 1080 78.2% DC and an isotropic component of 10%. This varies with the amplitude and
 1081 polarities decomposition in that the CLVD component is more rounded than slightly
 1082 vertical and its value is lesser. On the other hand, the difference between the

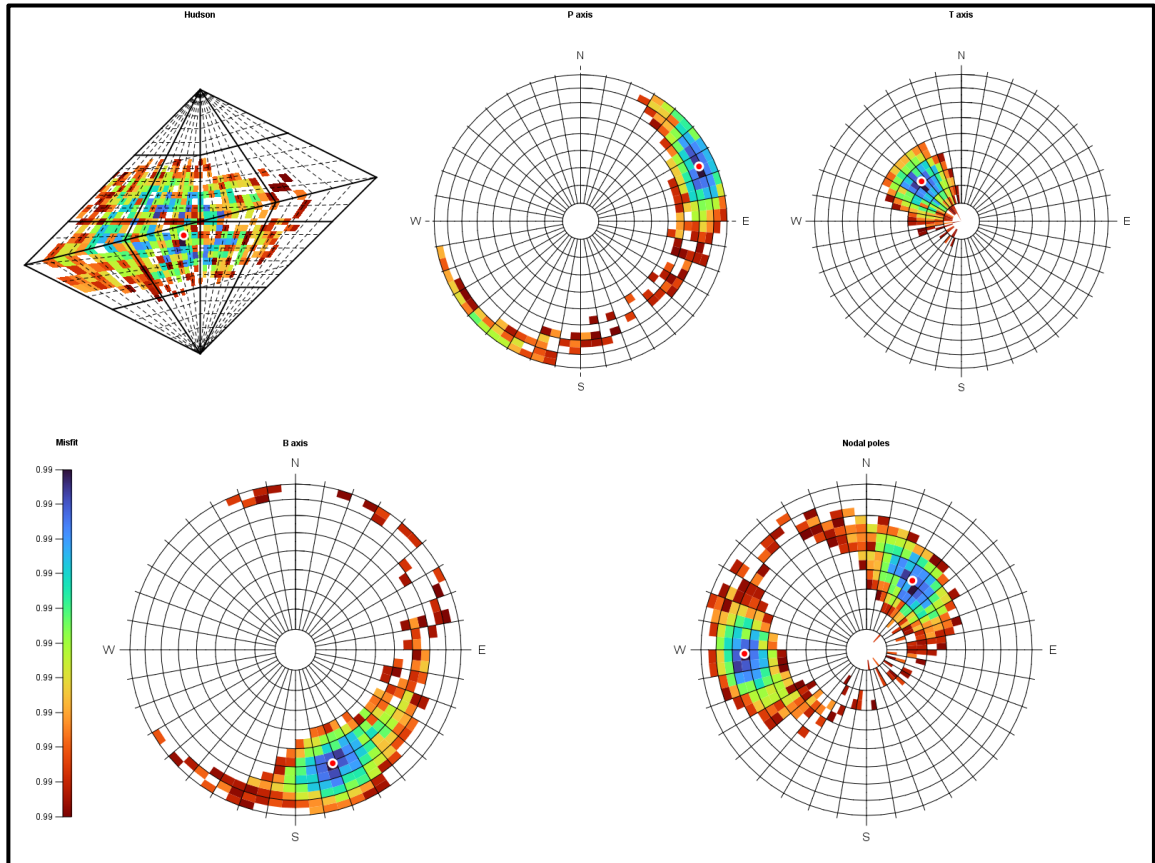
1083 deviatoric components is quite significant. There is still a much more deviatoric
 1084 component than volumetric in both, which still suggests that the rock mass might have
 1085 undergone deformation, but more shearing in the rock mass in this case. This still
 1086 shows that the rock mass has been subjected to stress therefore deforming in
 1087 response to the stress.



1088
 1089 Figure 4.27: Moment tensor decomposition result, Full waveform

1090 The event orientations (Figure 4.28) are much constrained compared to the amplitude
 1091 and polarities ones. The Hudson plots are similar with a very clear DC component
 1092 correlating with the high percentage in the moment tensor decomposition result. The
 1093 event is neither implosive nor explosive. All the axis and nodal planes are quite well
 1094 constrained. The P axis just as in the Amplitudes and polarities are in the northeast
 1095 quadrant, the T axis are in the Northwest while the B axis are in the southeast

1096 quadrant. One of the two nodal planes is in the southwest while the other is in the
1097 northwest direction.



1098
1099 Figure 4.28: Hudson plot, nodal planes and the P, T, B axis of the Full Waveform
1100 Inversion.

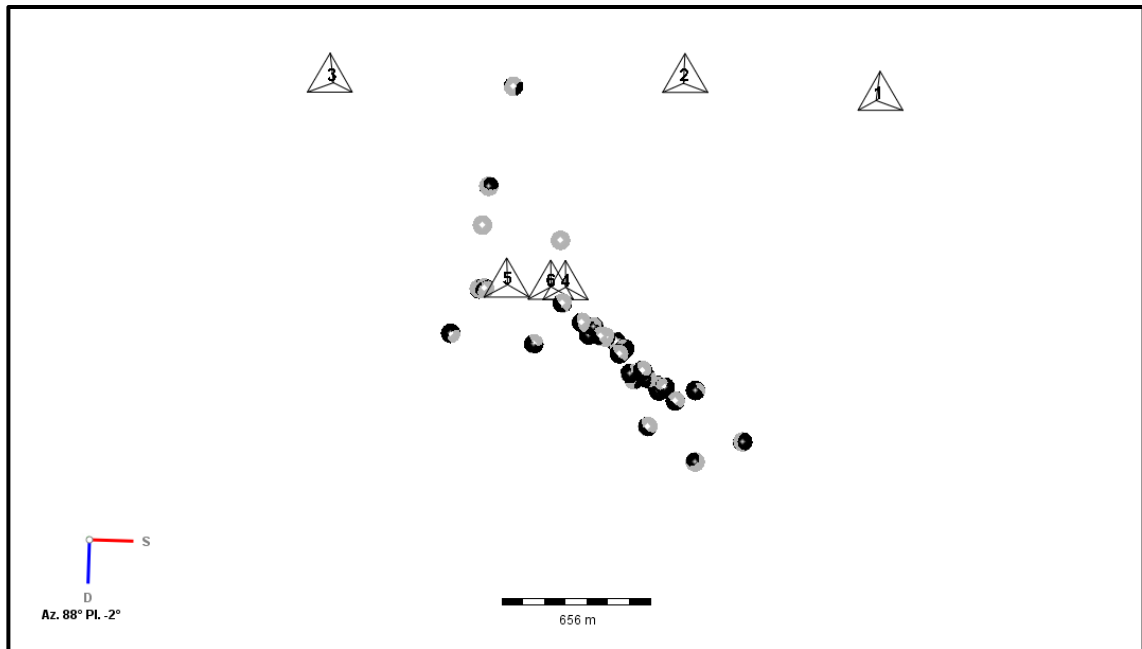
1101 Figure 4.29 shows plan view of moment tensor decomposition of large events
1102 integrated with mine plans. It shows a total of 34 mechanisms majority of which have a
1103 more deviatoric component. Similar mechanisms occur around the same areas.



1104

1105 Figure 4.29: Plan view, moment tensor decomposition, large events.

1106 Figure 4.30 shows side view distribution of moment tensor decomposition of large
 1107 events. From Figure 4.30 it can be seen clearly that the two events just above the
 1108 underground sensors with no shaded area indicate that all first motion detected by the
 1109 sensors were all compressional (towards the source) as a result of an event dominated
 1110 by implosion, a pillar crush would look like an implosion I presume.



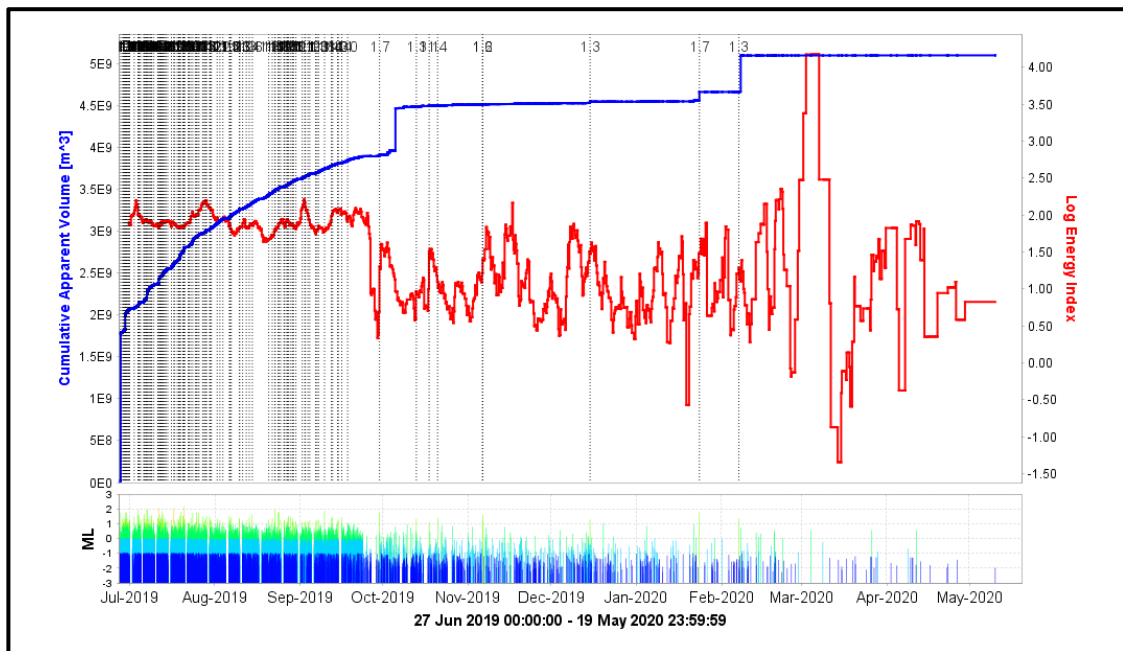
1111

1112 Figure 4.30: Side view, moment tensor decomposition, large events.

1113 **4.1.5 SEISMIC HAZARD ASSESSMENT**

1114 The graph (Figure 4.31) shows the relationship between CAV and Log EI with regards to
 1115 the time period when the temporary seismic monitoring system was in operation. This
 1116 shows certain periods characterized by a relatively significant increase in CAV
 1117 associated with rapid energy drops, while other periods are characterized by a
 1118 relatively static CAV with rapid energy drops. From the start of acquisition in June 2019
 1119 to late September 2019 Log EI remained at a small range while CAV was increasing
 1120 steadily. This indicated deformation at a rather constant rate. Thereafter there was a
 1121 drop in Log EI which was followed by Log EI fluctuations with ranges slightly more than
 1122 the previous time period, this indicated a general drop in energy released since the
 1123 fluctuations do not go beyond zero. Subsequently, when the drop in log EI (Figure 4.31)
 1124 occurred there was a significant change in the magnitude series where there is a

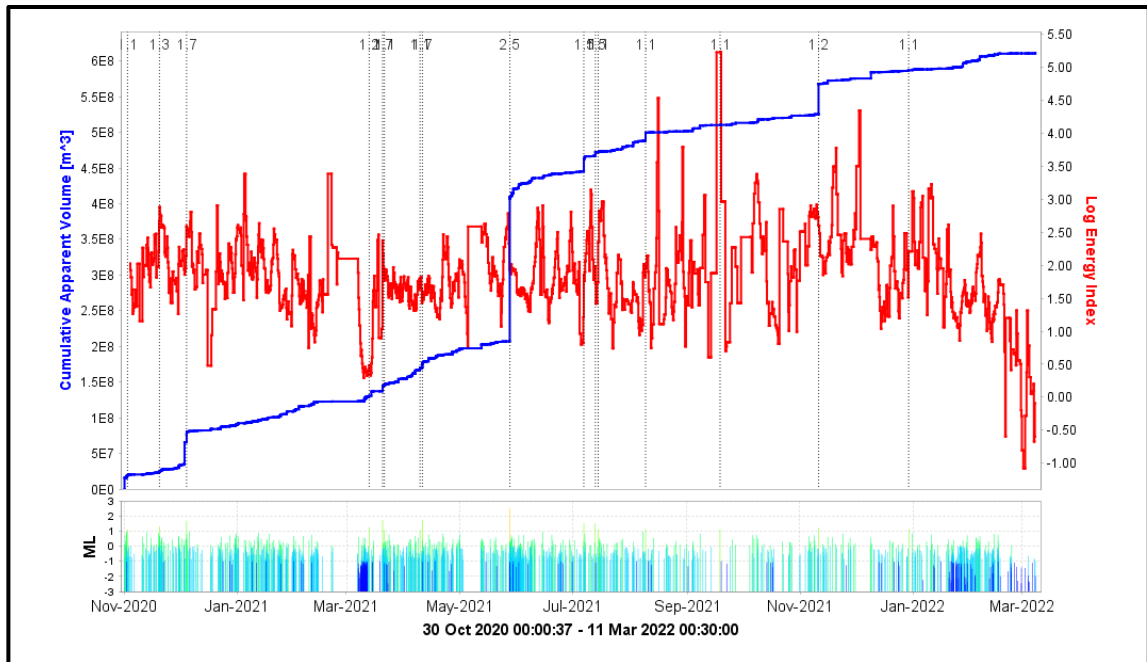
1125 reduction in density of events, this is correlated to the resumption of water pumping
 1126 activities that were carried out around the same period of time. CAV changes which
 1127 are significant associated with large scale failure are not typical. The significant CAV
 1128 increases around October 2019 and the other around February 2020 together with an
 1129 increase in Log EI may reflect an artefact of seismic system updates rather than actual
 1130 rock mass failure events. The general trend shows a decrease in Log EI and an increase
 1131 in CAV which becomes constant towards the end.



1132
 1133 Figure 4.31: Plot of CAV vs Log EI for the Temporary monitoring system

1134 The graph (Figure 4.32) shows the relationship between CAV and Log EI with regards to
 1135 the time period when the permanent seismic monitoring system was in operation. This
 1136 shows periods where a significant increase in CAV does not correlate with rapid energy
 1137 drops, like the significant increase in CAV observed mid November 2020 (that can be
 1138 attributed to an artefact of system updates rather than events that caused rock mass

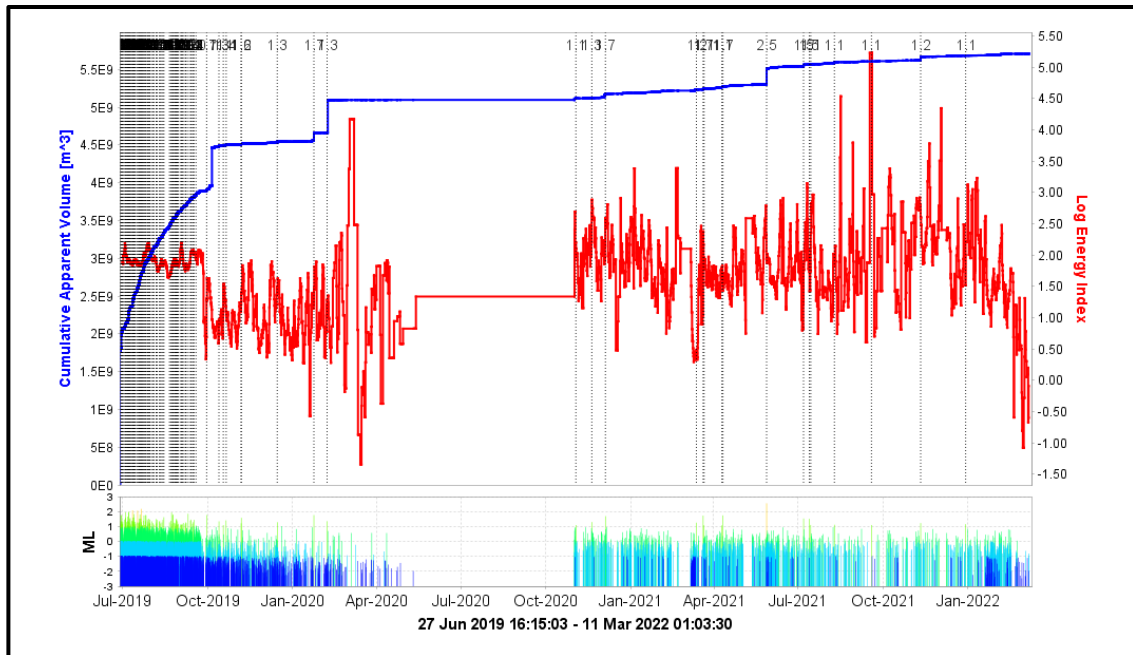
1139 failure). Around the beginning of March 2020 (Figure 4.32) there is a significant energy
1140 drop though not below zero which correlates with a slight increase in CAV. This is a
1141 sign of parts of rock mass becoming unsteady within the monitoring area and large
1142 scale rock mass deformation might occur. This drop is followed by suitable high energy
1143 releases which are several higher magnitude events within the same month greater
1144 than 1.0 as indicated by the magnitude series (Figure 4.32), the largest occurring on
1145 the 20th of March 2021 with a magnitude of 1.7. Events of a similar magnitude
1146 occurred in the month of April 2021 as well, this is shown by continued high energy
1147 releases all the way to the month of May 2021 where the highest normal event ever
1148 was recorded on the 28th of May 2021. The drop could also be due to the fact that Log
1149 EI is more sensitive to all events as compared to apparent stress that is only sensitive
1150 to large events. Towards the end of February 2022 and beginning of March 2022 Log EI
1151 is seen to decrease sharply to the extend where it goes below zero. The period where
1152 log EI decreases sharply might be seen as a strain softening stage, that was a
1153 commencement of potential damage and could be regarded as a caution indicator. At
1154 the time Log EI is decreasing sharply CAV is increasing steadily, this shows that as the
1155 rock mass was yielding or releasing stress there was an increase of deformation in the
1156 rock mass.



1157

1158 Figure 4.32: CAV vs Log EI for the Permanent Seismic Monitoring System

1159 The straight line in Figure 4.33 represents the time between the deployment of the
 1160 temporary and permanent systems where there was no recording of data. The
 1161 magnitude series has no record of events during that time as well. Figure 4.33 shows
 1162 that CAV is increasing at a constant rate across all monitoring periods and for the most
 1163 part Log EI is centered around 1. The magnitude series shows a difference in density
 1164 between the two monitoring periods which indicates more events occurred during the
 1165 temporary monitoring.

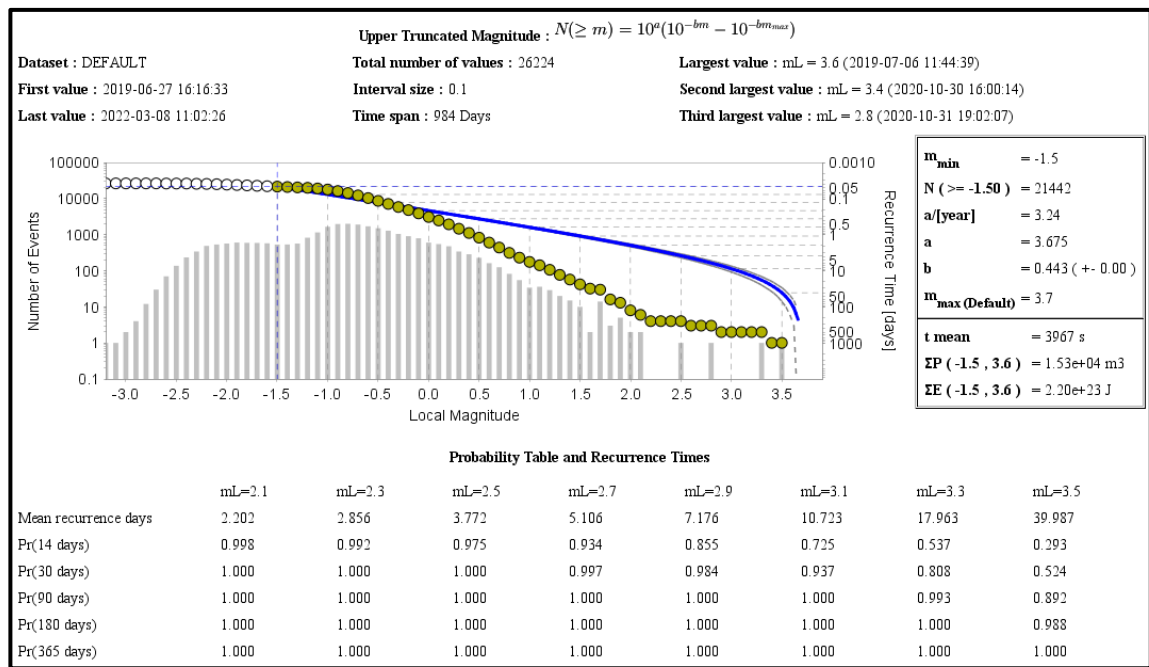


1166

1167 Figure 4.33: Plot of CAV vs Log EI for All Monitoring

1168 Figure 4.34 shows the upper truncated version of the Gutenberg Richter relation which
 1169 expresses the relationship between the event magnitude and total number of similar
 1170 sized events in a given time period. This is also referred to as the frequency magnitude
 1171 analysis. Bars represent non-cumulative and the circles represent cumulative
 1172 distributions of events. Frequency magnitude analysis of the events shows that the
 1173 events are a relatively well constrained data set with the graph showing a linear
 1174 relationship on more than two magnitudes. The graph (Figure 4.34) shows the top 3
 1175 largest magnitudes ever experienced in the study area with their occurrence times
 1176 respectively. No data filter has been employed for this graph therefore all microseismic
 1177 activity that took place at the BCL Limited mine was integrated. The graph shows
 1178 dominance in events ranging from magnitudes of -1.5 to 0.5, this correlates with the
 1179 Probability Table and Recurrence Times to show that larger events are less frequent.

1180 The maximum event size expected to occur at the mine is 3.7 slightly bigger than the
1181 highest magnitude recorded. The probability of an event of magnitude 3.5 to occur in a
1182 month is 52.4%. The b value of the frequency magnitude relation of the events is
1183 0.443; this is a generally low b value which shows that there is a high proportion of
1184 large events at the area, suggesting a higher proportion of seismic hazard.



1186 Figure 4.34: Frequency-Magnitude distribution

1187

5.0 CHAPTER FIVE

1188

5.1 DISCUSSION

1189 Optimal placement of seismic sensors ensures good quality location estimations as in
1190 the case of this research project. The microseismicity survey conducted using Mercalli
1191 Intensity Scale adequately served its purpose in providing the degree of intensity to
1192 determine suitable locations for microseismic sensors. The intensity scale showed high
1193 intensity in the south east extension of the mine and the results are in correlation with
1194 this, as this is where majority of the project was focused. The results indicated that
1195 events are distributed at the south east extension of the BCL mine where they were
1196 well enclosed within the surface sensors ensuring good quality location calculations.
1197 Majority of events that occur in the south east extension of the BCL mine range
1198 between magnitudes of -1.0 to 0.6 local magnitude. Smaller events mostly occur in the
1199 middle of the surface sensors where underground sensors are located. The results
1200 indicated that the period of the deployment of the Temporary seismic monitoring
1201 system in 2019 recorded the most events. During that time most events occur below
1202 the 980m level of the underground sensors and this is where most high magnitude
1203 events occurred as well. During the deployment of the permanent seismic monitoring
1204 system there were high magnitude events occurring in the areas between the
1205 underground and surface sensors but more towards the surface sensors. Lack of three-
1206 dimensional mine plans inhibits the correlation of these events with structures in the
1207 mine.

1208 Generally, the BCL mine recorded more events less than zero local magnitude
1209 compared to events more than zero in both the temporary and permanent seismic
1210 monitoring data acquisition times, according to Hudyma (2008) events more than zero
1211 are macroevents and events less than zero are microevents. The results showed that
1212 the number of events per month declined significantly from the period of temporary
1213 deployment to the period of permanent deployment. This decrease correlated with
1214 pumping activities at the mine. Towards the end of 2018 pumping activities were
1215 ceased. This is very common as well in South African mines (Du Plessis et al., 2015;
1216 Reimer & Durrheim, 2012). The flooding of mines is highly correlated with seismic
1217 activity due to acid mine drainage, a process where chemical and geochemical
1218 processes cause water to be highly acidic (Goldbach, 2010). This acidic water coupled
1219 with pressure and its corrosive nature speeds up the process of weakening cracks and
1220 joints reducing the clamping forces and therefore altering the stress state and stability
1221 of rock mass. Water flooding or infiltration could be the primary cause of seismic
1222 events in the BCL Limited mine this is in agreement with the literature, especially cases
1223 of South African mines. From this project a correlation between the pumping activities
1224 and seismic events was established and with this information future research can use
1225 integration of the hydrology data with seismic events. BCL is a very extensive mine,
1226 having started operation sixty-six years ago indicates that there are huge mine voids to
1227 flood.

1228 There is a significant degree of uncertainty associated with producing seismic source
1229 mechanisms by carrying out the moment tensor decomposition. The main one is that

1230 there was no sensor orientation inversion carried out, therefore the orientation of the
1231 sensors was accepted as they were. There was no good coverage on the underground
1232 sensors; they are basically one point since they are so close to each other. There are
1233 only two triaxials and one uniaxial underground therefore more triaxial sensors are
1234 needed. These could be the main reasons why the moment tensor inversion produced
1235 graphs with a not so good fit and some axis and nodal planes not being so well
1236 constrained. Baring in mind the degree of uncertainty, moment tensor decomposition
1237 was carried out to provide an understanding of the failure mode that led to the seismic
1238 activity taking place at the BCL Limited mine. The results produced majority of
1239 mechanisms having decomposition results with a higher deviatoric component than
1240 volumetric component. Amongst them there were few significant ones which had a
1241 high volumetric component these were interpreted to be pillar failures. When
1242 providing a general interpretation of what could really be happening at the BCL Limited
1243 mine, (since there are mechanisms interpreted to be pillar failures), the bursting of
1244 those pillars redistributed stress in the rock mass at the mining area. These lead to
1245 subsequent events with a higher deviatoric component because the rock mass is under
1246 high stress, therefore deforming inelastically with noticeable amounts of shearing
1247 (Double Couple, DC). The most common mechanisms are of this calibre which shows
1248 the extent of pressure in the study area. According to Gibowicz and Kijko (1994) pillar
1249 failures might cause conchoidal events or failures leading to the collapse of the whole
1250 or part of the mining area.

1251 Hudyma (2008) has indicated that the main objective of instability analysis is to pin
1252 point unstable rock mass conditions susceptible to large seismic events that cause
1253 damage. CAV and Log EI are useful tools in understanding energy changes pertaining to
1254 seismic events recorded at the BCL mine and can be used to indicate potential
1255 instability. A decrease in log EI shows periods of rock mass failure whereas a large
1256 failure is signified by sudden change in CAV at the same time (Smith, 2018). Smith
1257 (2018) continues to explain that periods where Log EI is greater than zero are periods
1258 where stresses are accumulating in the rock mass and as Log EI decreases beyond zero
1259 the rock mass is undergoing fracturing. On the other hand, Abolfazlzadeh (2013) and
1260 Hudyma (2010) indicate that EI drops coincide with an increase in CAV because this
1261 shows that at the same time as stress is being shed away from a structure,
1262 deformation is increasing rapidly. The combination of the latter has shown to serve as
1263 a predecessor to major events. According to Hudyma (2010) past studies have shown
1264 that an area with a pillar fault or dyke is accumulating stress when the EI for that event
1265 is greater than 1 and failure occurs when Log EI drops below 1. The increase in CAV in
1266 the BCL mine that is accompanied by a decrease below zero of Log EI is an indication of
1267 an increase in fracturing of parts of the rock mass within the monitoring area as they
1268 become unstable and there might occur large scale rock mass deformation. Log EI
1269 generally being greater than zero indicates accumulation of stress. Areas where Log EI
1270 decreases sharply may be viewed as a stage of strain softening, which represented the
1271 start of potential damage and could be viewed as a prior warning indicator. Periods

1272 with a significant increase in CAV with a consequent decrease in Log EI indicate rock
1273 mass destressing and could potentially lead to instability.

1274 Mendecki et al. (2010) says that in mines, seismic hazard estimations are usually
1275 confined to probabilities of occurrence or recurrence times of seismic events of
1276 specified magnitudes in order to quantify relative exposure to seismicity and seismic
1277 risk. This is true for the frequency magnitude relation. The data from BCL mine is
1278 generally stable and well constrained with it being linear in over 2 magnitudes.

1279 Hudyma (2008) explains that the b-value simply describes the frequency of major
1280 occurrences vs minor events in the data collection. Large events are substantially more
1281 common in datasets with b-values of 0.5 than in datasets with b-values of 1.5. As a
1282 result, the b-value is a measure of relative seismic hazard. He continues to compare
1283 two frequency magnitude graphs with one having a much gentler cumulation and the
1284 other having a much steeper cumulation. The gentler one had a higher proportion of
1285 large events and a lower b-value compared to the steeper one. The BCL data is similar
1286 to the gentler one with a b-value of 0.443 therefore there is a high proportion of large
1287 events. A probability of 52.4% indicates that there is a slightly higher likelihood of a
1288 magnitude 3.5 seismic event occurring in a month at the BCL mine. A magnitude 3.5
1289 seismic event is considered significant and can result in moderate to strong shaking.

1290 These events have the potential to cause damage to mine structures over prolonged
1291 periods of time, pose a risk to personnel safety, and may require extensive safety
1292 measures to be implemented. Therefore, there is a significantly noticeable degree of
1293 seismic hazard in the BCL area.

1294

6.0 CHAPTER SIX

1295

6.1 CONCLUSION

1296 This study aimed to identify the seismic source parameters; in conclusion, events
1297 occurred in the south eastern extension of the mine, most of them occurred below the
1298 980m level of the underground sensors in 2019 during the time when pumping
1299 activities were ceased.

1300 The failure mechanism that causes seismic activities has been interpreted to be pillar
1301 bursts causing stress redistribution in the south east extension of the mine. This leads
1302 to the mechanism of the most occurring large events to be shear dislocations on
1303 relatively planar faults but there is little to no information to completely rule out slip in
1304 structures to be the main cause, especially due to the uncertainty regarding moment
1305 tensor decomposition.

1306 It has been concluded based on the results that the south east extension of the BCL
1307 Limited mine could be highly unstable with a significantly noticeable degree of seismic
1308 hazard and there is potential for rock mass deformation.

1309

6.2 RECOMMENDATIONS

1310 It is recommended that three dimensional BCL Limited mine plans be constructed.

1311 It is recommended that additional seismic sensors deployed at the mine with good
1312 coverage around the seismically active areas to constrain the event locations and
1313 moment tensor inversion.

1314 It is recommended that sensor orientation inversion be carried out by seismic
1315 monitoring equipment providers for higher quality moment tensor inversion results.

1316 For further studies seismic data can be integrated with hydrological, geological and
1317 geophysical data to correlate different structures with the events.

1318

REFERENCES

- 1319 Abolfazlzadeh, Y. (2013). *Application of Seismic Monitoring in Caving Mines - Case*
1320 *Study of Telfer Gold Mine* (Thesis). Retrieved from
1321 [www.researchgate.net/publication/325531529_Application_of_Seismic_Monitoring_i](http://www.researchgate.net/publication/325531529_Application_of_Seismic_Monitoring_in_Caving_Mines_-_Case_Study_of_Telfer_Gold_Mine)
1322 [n_Caving_Mines - Case Study of Telfer Gold Mine](http://www.researchgate.net/publication/325531529_Application_of_Seismic_Monitoring_in_Caving_Mines_-_Case_Study_of_Telfer_Gold_Mine)
- 1323 Agnew, D. C. (1989). Seismology: History. *Encyclopedia of Earth Science*, 1198– 1202.
1324 https://doi.org/10.1007/0-387-30752-4_143
- 1325 Alaneme, K. K., & Okotete, E. A. (2018). Critical evaluation of seismic activities in Africa
1326 and curtailment policies – a review. *Geoenvironmental Disasters*, 5(1).
1327 <https://doi.org/10.1186/s40677-018-0116-2>
- 1328 Andersen, L., 2001, A relative moment tensor inversion technique applied to seismicity
1329 induced by mining. Ph.D. Thesis, University of Witwatersrand, Johannesburg, South
1330 Africa
- 1331 Aqualogic & OHMS. (2019). Selibe Phikwe Microseismic study for BGI (No. 3).
1332 Botswana Geoscience Institute.
- 1333 Båth, M. (1979). Scope and History of Seismology. *Introduction to Seismology*, 13–28.
1334 https://doi.org/10.1007/978-3-0348-5283-8_1
- 1335 Botepe, K. G., Ntibinyane, O., Kwadiba, M. T., & Maritinkole, J. R. (2020). Report on
1336 Macroseismic Intensity Survey in the Selebi-Phikwe Area. Botswana Geoscience
1337 Institute.

1338 Du Plessis, I., Liebenberg, K., Smit, A., Coetzee, S., & Kijko, A. (2015). Preliminary
 1339 investigation into the cause of acid mine water induced seismicity in Johannesburg.
 1340 South African Journal of Geomatics, 4(3), 299. <https://doi.org/10.4314/sajg.v4i3.10>
 1341 Gibowicz, Sławomir J., and Andrzej Kijko. An Introduction to Mining Seismology.
 1342 Academic Press, 1994.
 1343 Glazer, S. N. (2018). Mine Seismology: Seismic Response to the Caving Process: A Case
 1344 Study from Four Mines (Softcover reprint of the original 1st ed. 2019 ed.). Springer.
 1345 Goldbach, O. (2010). What is the seismic risk of mine flooding? Science Real and
 1346 Relevant Conference. Center for Mining Innovation.
 1347 Guilhem, A., Hutchings, L., Dreger, D. S., & Johnson, L. R. (2014). Moment tensor
 1348 inversions of $M \sim 3$ earthquakes in the Geysers geothermal fields, California. *Journal of*
 1349 *Geophysical Research: Solid Earth*, 119(3), 2121–2137.
 1350 <https://doi.org/10.1002/2013jb010271>
 1351 Hudson, J. A., Pearce, R. G., & Rogers, R. M. (1989). Source type plot for inversion of
 1352 the moment tensor. *Journal of Geophysical Research*, 94(B1), 765.
 1353 <https://doi.org/10.1029/jb094ib01p00765>
 1354 Hudyma, M. (2008). Analysis and Interpretation of Clusters of Seismic Events in Mines.
 1355 <https://www.researchgate.net/publication/303541856>
 1356 Hudyma, M.R. (2010). Applied mine seismology concepts and techniques. Technical
 1357 notes, Laurentian University, Sudbury, Ontario, Canada.

- 1358 Hudyma, M., Heal, D., & Mikula, P. (2003). Seismic monitoring in mines—Old
1359 technology—New applications.Proc. in 1st Aus-tralasian ground control in mining
1360 conference(pp. 201–218).Sydney, Australia: UNSW School of Mining Engineering.
- 1361 Kearey, P., Brooks, M., & Hill, I. (2002). An Introduction to Geophysical Exploration.
1362 Wiley.
- 1363 Letshwenyo, M. (2016). Sulphur and heavy metals contents in soils and *Grewia bicolor*
1364 leaves around the Selibe Phikwe Cu-Ni mine (BCL), Botswana. *Journal of Environmental*
1365 *Chemistry and Ecotoxicology*. 8. 73-81. 10.5897/JECE2013.0306.
- 1366 Lowry, W. (2018). *Geophysics: A Very Short Introduction (Very Short*
1367 *Introductions)*(Illustrated ed.). Oxford University Press.
- 1368 Maier, W. D., Barnes, S.-J., Chinyepi, G., Barton, J. M., Eglington, B., & Setshedi, I.
1369 (2007). The composition of magmatic Ni–Cu–(PGE) sulfide deposits in the Tati and
1370 Selebi-Phikwe belts of eastern Botswana. *Mineralium Deposita*, 43(1), 37–60.
1371 <https://doi.org/10.1007/s00126-007-0143-5>
- 1372 Malovichko, D., van Aswegen, G., & Clark, R. (2012). Mechanisms of large seismic
1373 events in platinum mines of the Bushveld Complex (South Africa). *The Journal of the*
1374 *Southern African Institute of Mining and Metallurgy*, 419–429.
- 1375 McCourt, S., Kampunzu, A. B., Bagai, Z., & Armstrong, R. A. (2004). The Crustal
1376 Architecture of Archaean Terranes in Northeastern Botswana. *South African J. Geol.*,
1377 107,147-158. <https://doi.org/10.2113/107.1-2.147>

- 1378 Mendecki, A. J., Lynch, R., & Malovichko, D. (2010). *Routine Micro-Seismic Monitoring*
 1379 *in Mines*. Australian Earthquake Engineering Society, Perth, Australia.
 1380 <https://www.researchgate.net/publication/268439633>
- 1381 Mendecki, A. J., van Aswegen, G., & Mountfort, P. (1999). A guide to routine seismic
 1382 monitoring in mines. In *A Handbook on Rock Engineering Practice for Tabular Hard*
 1383 *Rock Mines* (Ch. 9). Creda Communications.
- 1384 Millonig, L. J. (2009). The Neoproterozoic and Palaeoproterozoic metamorphic evolution
 1385 of the Limpopo Belt's Central Zone in southern Africa. Retrieved from
 1386 [https://opus.bibliothek.uni-wuerzburg.de/opus4-](https://opus.bibliothek.uni-wuerzburg.de/opus4-wuerzburg/frontdoor/deliver/index/docId/4022/file/millonig.pdf)
 1387 [wuerzburg/frontdoor/deliver/index/docId/4022/file/millonig.pdf](https://opus.bibliothek.uni-wuerzburg.de/opus4-wuerzburg/frontdoor/deliver/index/docId/4022/file/millonig.pdf)
- 1388 Motswaiso, F. S., Nakamura, K., Watanabe, N., & Komai, T. (2019). Geochemical
 1389 Investigation of Metals and Trace Elements around the Abandoned Cu-Ni Mine Site in
 1390 Selibe Phikwe, Botswana. *Journal of Geoscience and Environment Protection*, 7, 275-
 1391 293. <https://doi.org/10.4236/gep.2019.75020>
- 1392 Nthaba, B., Simon, R. E., & Ogubazghi, G. M. (2018). Seismicity Study of Botswana from
 1393 1966 to 2012. *International Journal of Geosciences*, 09(12), 707–718.
 1394 <https://doi.org/10.4236/ijg.2018.912043>
- 1395 Riemer, K. L., & Durrheim, R. J. (2012). Mining seismicity in the Witwatersrand Basin:
 1396 monitoring, mechanisms and mitigation strategies in perspective. *Journal of Rock*
 1397 *Mechanics and Geotechnical Engineering*, 4(3), 228–249.
 1398 <https://doi.org/10.3724/sp.j.1235.2012.00228>

- 1399 Ryder, J. A., & Jager, A. J. (2002). A handbook on rock engineering practice for tubular
1400 hard rock mines [Book]. Safety in Mines Research Advisory Committee (SIMRAC).
- 1401 Shearer, P. (1999). Introduction to Seismology. Cambridge University Press; 0 edition
1402 (1999–09-28).
- 1403 Šílený, J., & Milev, A. (2006). Seismic Moment Tensor Resolution on a Local Scale:
1404 Simulated Rockburst and Mine-induced Seismic Events in the Kopanang Gold Mine,
1405 South Africa. *Pure and Applied Geophysics*, 163(8), 1495–1513.
1406 <https://doi.org/10.1007/s00024-006-0089-z>
- 1407 Smith, S. (2018). Retrospective Analysis of Mine Seismicity: Glencore, Kidd Mine
1408 (Thesis). <https://doi.org/10.13140/RG.2.2.15192.80640>
- 1409 Udías, A. “Editorial: Seismology a Multidisciplinary Science.” *Journal of Seismology*, vol.
1410 1, no. 1, 1997, pp. 103–103., doi:10.1023/a:1009772612700.
- 1411 Vavryčuk, V. (2014). Moment tensor decompositions revisited. *Journal of Seismology*,
1412 19(1), 231–252. <https://doi.org/10.1007/s10950-014-9463-y>
- 1413 Vavryčuk, V., & Kühn, D. (2012). Moment tensor inversion of waveforms: a two-step
1414 time-frequency approach. *Geophysical Journal International*, 190(3), 1761–1776.
1415 <https://doi.org/10.1111/j.1365-246x.2012.05592.x>
- 1416 Vurayai1, R., Nkoane, B., Moseki, B., & Chaturvedi, P. (2015). Assessment of heavy
1417 metal pollution/contamination in soils east and west of the Bamangwato Concessions

1418 Ltd (BCL) Cu/Ni mine smelter in Selebi-Phikwe, Botswana. *Journal of Biodiversity and*
1419 *Environmental Sciences (JBES)*, 7(6), 111–120.

1420 Wyss, M. and Brune, J.N. (1968) Seismic moment, stress and source dimensions for
1421 earthquakes in the California-Nevada region. *Journal of Geophysical Research*, Vol.73,
1422 pp. 4681-4694.