APPENDIX B

UPDATED KENT COUNTY GEOLOGIC STABILITY STUDY FOR THE JOHN BALL ZOOLOGICAL GARDEN EXPANSION WEST OF I-196

BY
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FINAL REPORT

SUBMITTED TO

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Investigation of the Surface Stability Above the Former Domtar Industries, Inc. Gypsum Mine Located in Grand Rapids, Michigan

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APPENDIX C (Formally Appendix A in the original report) – Report of Investigation of Water Problems at the Grand Rapids Gypsum Mine, E. Burt, 1965

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INTRODUCTION

"...miners should leave numerous arches under the mountains which need support..."
Georgius Agricola, 1550

Purpose and Scope

The John Ball Zoological Gardens (Zoo) located in Grand Rapids, Michigan, is considering expanding its operations to property adjacent to the existing Zoo property. The potential expansion site lies west of the current zoo location across Interstate I-196 and lays directly over a portion of the former Domtar Industries, Inc. (Domtar) gypsum mine. As with most underground mines, the stability of the remaining mine structure is important for surface development. Consequently, a request was made by Kent County officials to provide an evaluation of the stability of the general area to determine the suitability of the site for surface development activities. The purpose of this report, therefore, is to provide an evaluation of the stability of the underground gypsum located under the property being considered for the Zoo expansion. The following three issues outline the scope of the evaluation:

1. Characterization of the geologic stability of the site - now and in the future.
2. Describe measures taken by others (e.g. MDOT and CMS) to characterize stability and what measures were taken, if any, to address this issue.
3. Is the site, as it currently exists, or a portion of it, suitable (geotechnically) for construction of a Zoo?

Location

The proposed Zoo expansion site is located in the south half of Section 27 of Township 7 North, Range 12 West. Excluded from this area is the NE 1/4 of the SW 1/4 of Section 27 and to the western boundary of the former Domtar mine properties, which is approximately the west 250 feet of the SW 1/4 of Section 27. Geographically, the proposed site is bordered to the east by Interstate I-196, to the south by O'Brien Street and to the west by Portfliet Creek. A CMS Energy (Consumers Energy Company) high voltage power line also transects the site, roughly separating the site into northern and southern sections. Figure 1 shows the location of the proposed site along with the outline of the Domtar mine as well as an adjacent Georgia Pacific (GP) Company mine (Butterworth Mine), immediately west of the Domtar mine.

Area Geology

The bedrock in the Grand Rapids area is the Michigan Formation, a Mississippian age sedimentary rock formation well known in the Michigan Basin for its evaporite layers consisting of salt, anhydrite and gypsum. The gypsum evaporites are mined in various locations in the Lower Peninsula of Michigan. However, shale is the dominant rock type in the Michigan Formation with interlayers of sandstone and to a lesser degree carbonates and evaporites. The formation is overlain by unconsolidated glacial overburden consisting of gravel, sand and clay. Directly below the Michigan Formation is the Marshall Sandstone. Figure 2, adapted from a Williams and Works report of 1984 for Domtar on water infiltration to the mine shows the average thickness, elevation and characteristics of the subsurface formations. Significant geologic features of this site are as follows:

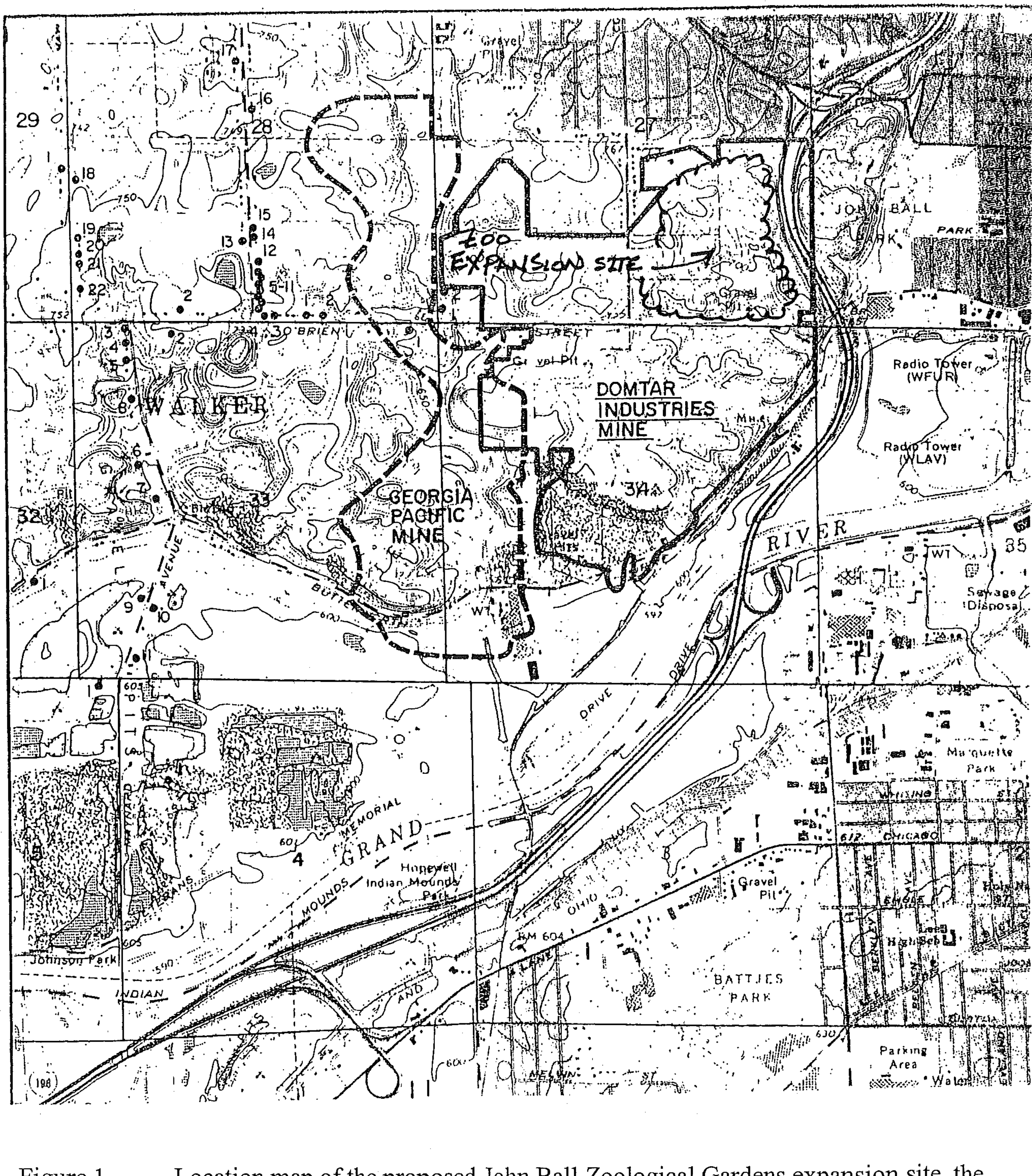

Figure 1. Location map of the proposed John Ball Zoological Gardens expansion site, the Domtar Mine, and the Georgia Pacific (Butterworth Mine).

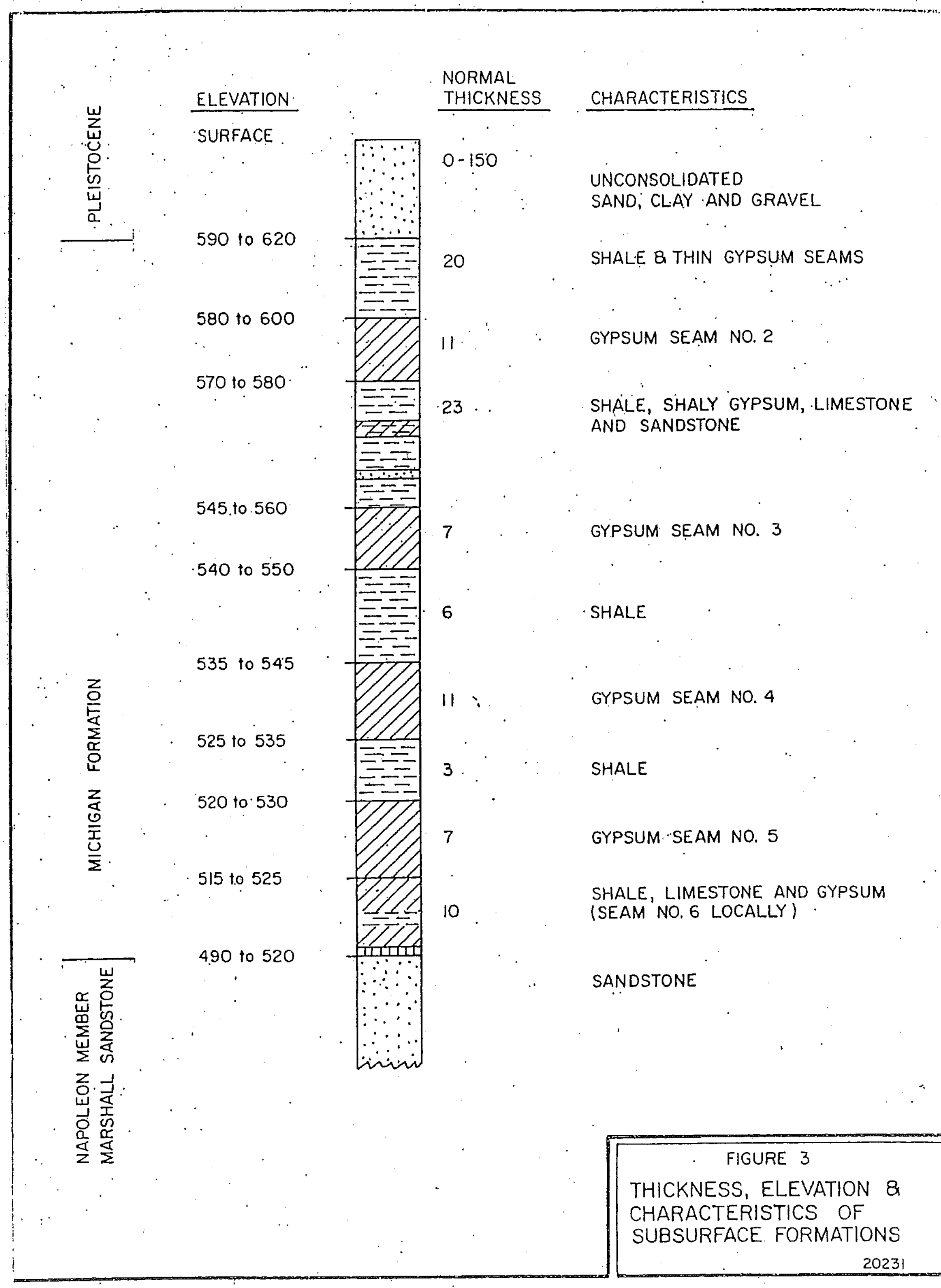

Figure 2 Thickness, elevation and characteristics of the subsurface formations at the Domtar Mine.

Feature 1: The glacial overburden varies from zero to 150 feet in thickness over the Domtar mine. While the unconsolidated soil consists of some clays and silts, the glacial overburden provides the main source of water that infiltrates the mine. Due to the unconsolidated nature of the overburden, it can be assumed that its full weight or pressure is applied to the roof rock of the mine and that its effective pressure will vary with the rise and fall of the water table level, which is located within the overburden. By most mining standards, this is a relatively shallow mine and the pressures will probably not exceed 140 pounds per square inch (psi), assuming a fully saturated overburden at 135 lbs/ft^3.

Feature 2: There are six gypsum layers associated with the mine with the upper layer identified as # 1 down to lowest layer # 6. Figure 2 does not show the # 1 seam, but labels it as shale and thin gypsum seams, with the remaining seams numbered.

Feature 3: The majority of the gypsum was mined from the #2 seam, Later the # 4 seam and limited amounts of the #5 seam were mined. According to the 1984 Williams and Works report the #3 gypsum seam was not mined. Also, mine records indicate that the recoverable #2 seam was mined out by 1980 when the mine temporarily closed down. The #2 seam had the highest quality of gypsum of all of the gypsum seams.

Feature 4: The bedrock between the unconsolidated overburden and the #2 seam forms the roof rock over the #2 seam. As shown in Figure 2, the average thickness of the roof rock is about 20 feet. However, five drill holes from a 1963 drilling program indicate that the roof rock thickness varies from a high of 35 feet in the north to seven feet at the northeast corner of the mine. Mine maps show that in the southern part of the mine the roof rock was very thin to absent, which precluded mining the #2 seam in portions of the south. A major sinkhole in the southern part of the mine can be correlated with the absence of the roof rock over the #2 seam. There was an additional drilling program in 1966, but this data was not available for inspection. In general, the roof rock tends to be thicker in the north center portion of the mine while thinning to the east, west and south. The primary control on the thickness of the roof rock is the amount of erosion that occurred during the advance and retreat of the glaciers and the action of the Grand River. The stability of the roof of the #2 seam is an important factor in the formation of sinkholes.

Feature 5: In some locations the roof rock consists of interbedded shales and gypsum. However, the drill hole data shows that in some areas the roof rock consists entirely of shale, while in another location it consists entirely of gypsum.

Feature 6: The average thickness of the #2 seam is about 11 feet; with a roof elevation between 580 and 600 feet mean sea level (msl) and a floor elevation between 570 and 580 feet. Drill hole data and elevation data in the mine shows that the #2 seam, while relatively flat dips to the east from an elevation 578 in the west to about 568 in the east. Thus, water inflow to the mined out #2 seam would flow from the west to east and then south through outlets created by the mining operation. There are two locations in the #2 seam where topographic low spots developed after being mined. These topographic lows were referred to as lakes and were used as pumping locations for the infiltrating water. The largest of the two lakes was the Portfliet Lake located in the northwest corner of the mine. The mine water from this pumping location was discharged into the Portfliet Creek directly above this lake. The second lake, called the Scranton Lake, was located in the west central part of the mine. The water from this station was discharged directly south of the mine through the mine portal.

Feature 7: There is an average 36 feet between the #2 seam and the #4 seam. A conservative estimate of the maximum ground pressure on the #4 roof rock (assuming 1 psi/foot) would be approximately 200 psi (maximum before mining).

Feature 8: A portion of the Domtar mine had both the #4 and #5 seam mined together along with a three-foot shale parting. When both the #4 and #5 seams were mined the room height averaged approximately 18 feet (Parker, 1983).

Feature 9: The Marshall Sandstone is approximately ten feet below the #5 seam. One of the concerns discussed in the mining documents is the potential inflow of water from the Marshall into the mine under artesian conditions. This would present significant stability problems for the gypsum pillars due to the high solubility of gypsum.

Feature 10: At the close of mining operations in late 1990's, the Domtar mine was allowed to fill with water. The Butterworth Mine, which closed in the mid-1970's, was also allowed to fill with water. Based on observations of the ground water table level observed in the existing Domtar Mine portal, the ground water table has reestablished itself within the overburden and therefore all of the gypsum seams are flooded.

Glacial History

As noted in Feature 4, the thickness of the roof rock over the #2 seam is controlled by the glaciation in the area and the action of the Grand River. In 1965 by Edward Burt, a Grand Rapids geologist, estimated ground water infiltration to the Domtar mine was made as well as the topography of the bedrock surface, which is shown in Figure 3. The topography provides an indication of the magnitude of erosion as well as an indication of the thickness of the remaining roof rock above the #2 seam. It can be seen that erosion has taken place on the east, south, and west sides of the mine. As noted above the #2 seam dips to the east and therefore rises to the west intersecting the bedrock surface. Due to this erosion, the #2 seam does not exist over the Georgia-Pacific Butterworth Mine to the west of the Domtar mine. The bedrock map also provides an indication of the #2 roof rock thickness on the west side of the mine. The bedrock elevation on the west side of the mine is approximately 610 feet, while the base of the #2 seam is 578 feet. The base of #2 seam at elevation 578 plus approximately 11 feet of seam thickness yields an approximate roof elevation of 590 feet, providing approximately 20 feet of roof rock. A general overview of the bedrock topography indicates that the roof thickness of the #2 seam is greatest in the north central part of the mine, followed by the west side, while the east side thins to as low as 7 feet (based on drill hole data), to approximately zero thickness in the south end. The Burt 1965 report is provided in Appendix C.

While this study is not involved with the Butterworth Mine, the mine does provide information to help assess the stability of the proposed Zoo site. The Butterworth mine opened in the early 1900's. As noted above, erosion has eliminated the #2 seam in Butterworth Mine so only the #4 and #5 seams were mined. The mine closed in 1971 and was allowed to fill with water. Since that time, numerous sinkholes have developed above the mine, particularly at the south end of the mine. At least one large collapse of underground pillars also occurred in which a subsidence depression formed north of O'Brien Street as well as a crack along O'Brien Street (Mroczkowski, 2002). However, more dramatic was the flow of mine water from the mine that flooded the Georgia-Pacific processing plant facility (West Plant) as pressurized water poured out of the abandoned mine shaft. A dike had to be placed around the plant to divert the water flow since it took a number of days for the water to stop flowing as the mine de-pressurized from the roof collapse. A report by Williams and Works (1984) concerning water infiltration to the Domtar Mine notes that the Georgia-Pacific mine officials estimated a pumping rate of approximately 1,500 gallons per minute to maintain the water level in the Butterworth mine. This provides an estimate of the amount of water flowing through the Butterworth Mine.

Gypsum Mineralogy and Dissolution Potential

Salt, anhydrite and gypsum are all evaporite rocks. According to White et al, (1995) evaporite rocks underlie about 35 to 40 percent of the United States and are found in 32 of the 48 contiguous United States, Canada and Mexico, and on other continents, especially Europe and Asia (China). Figure 4 is from a recent US Geological Survey proceeding (2001) concerning karst (topography characterized by sinkholes, caves and enlarged fractures formed by dissolution of carbonate or evaporite deposits) development in the United States showing that the Grand Rapids area has been identified as having both evaporites and karst development.

A recent article in American Scientist by Martinez et al. (1998) on sinkholes in evaporite rocks makes the following statement:

> "Evaporite deposits form when various salts precipitate from evaporating water, mainly seawater. The principal evaporite rocks include gypsum (or anhydrite, the anhydrous form) and salt (halite), although potash (sylvite) and other rarer salts also are locally important. Evaporites have the highest solubility of common

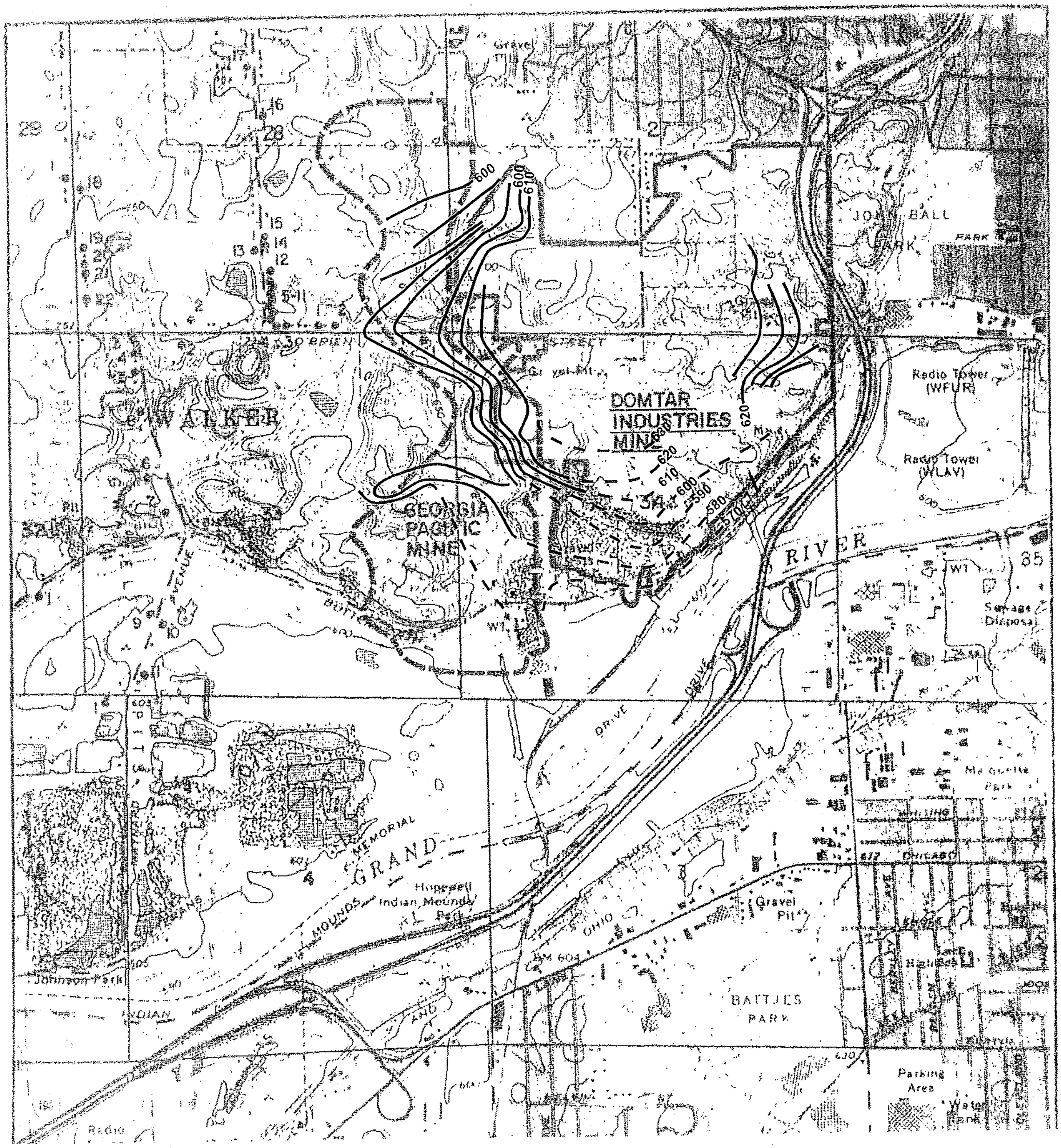

Figure 3. Bedrock topography of the Domtar Mine adapted from Burt (1965).
Georgia-Pacific Butterworth Mine

rocks; water that is unsaturated with respect to gypsum ($CaSO_4 * 2H_2O$) or salt ($NaCl$) rapidly dissolves them and carries them off in solution. Indeed, gypsum and salt are, respectively, about 150 and 7,500 times more soluble than limestone. Such high solubility enables subsurface dissolution channels and sinkholes to form in a matter of only days, weeks or years, and catastrophic collapse can result. Unlike sinkholes in carbonate rocks, evaporite sinkholes may result from either natural causes or from human activities."

The high solubilities of salt and gypsum permit cavities to form in days to years, whereas cavity formation in carbonate bedrock is a very slow process that generally occurs over centuries to millennia. Human activities can also expedite cavity formation in these susceptible materials and trigger their collapse, as well as the collapse of pre-existing subsurface cavities. A number of very well documented collapses have formed over salt solution mines. One of the most recent was the 1994 Retsof Salt Mine collapse in Genesee Valley, New York, in which the roof rock of the underground salt mine collapsed diverting ground water into the mine and completely flooding the mine. The Retsof Salt Mine was the largest salt mine in the United States at the time, covering ten square miles. Near Detroit, Michigan the collapse of an underground salt solution mine, which used boreholes to dissolve and extract the salt, resulted in large sinkholes forming on the Grosse Ile Island in the Detroit River.

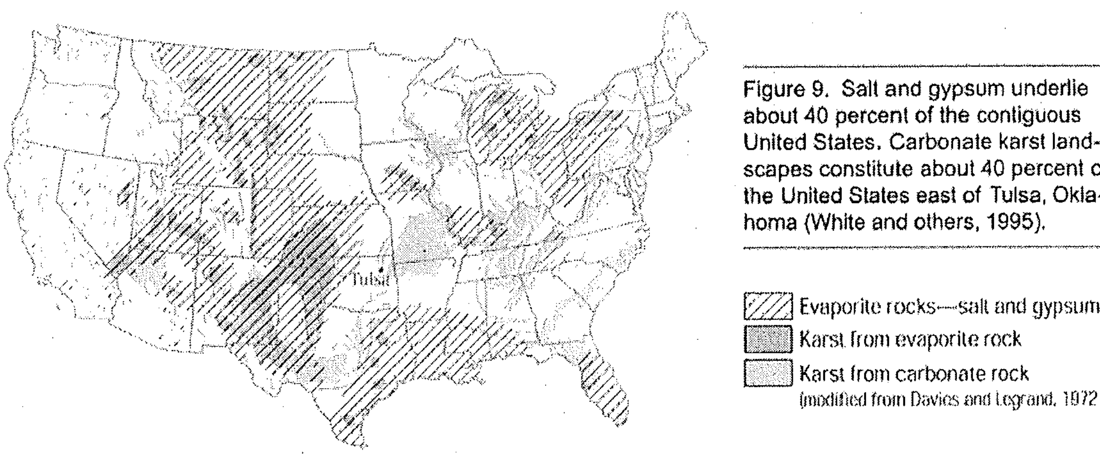

Figure 9. Salt and gypsum underlie about 40 percent of the contiguous United States. Carbonate karst landscapes constitute about 40 percent of the United States east of Tulsa, Oklahoma (White and others, 1995).

Figure 4. Figure 9 from a USGS report showing the location of evaporite rocks in the United States and karst development in both evaporite and carbonate rocks.

Gypsum Karst Development

The dissolution of gypsum and the development of sinkholes is a worldwide problem. In the United States the majority of problems associated with gypsum karst is due to natural processes as opposed to human-induced. The most well known area of gypsum karst affecting urban development is in the northern Black Hills of South Dakota (Epstein, 2001). In Europe, gypsum karst is a very significant problem, prompting the development of a European prediction and management system called ROSES. The acronym ROSES stands for Risk of Subsidence due to Evaporite Solution (ROSES, 2002). This project is funded by the European Union and has three main objectives: (1) the development of a process-based understanding of evaporite dissolution (karstification), (2) devising management techniques for preventing subsidence in areas of evaporite karst, and (3) developing risk assessment and zonation criteria for evaporite karst hazard mapping. Two recently published papers from project ROSES were reviewed for this investigation. The first paper titled "A decision-logic framework for investigating subsidence problems potentially attributable to gypsum karstification," (Lamont-Black et al., 2002) provided the mechanisms involved in the development of gypsum karst. The second paper titled "Road and bridge construction across gypsum karst in England, " (Cooper et al., 2002) provided engineering solutions involved in designing and constructing roadways over gypsum karst.

DOMTAR MINE

Background

The DOMTAR mine (formerly the Grand Rapids Gypsum Company mine) extracted gypsum from the #2, #4 and the #5 during its operational life. According to the Williams and Works report (1984) no mining of the #3 occurred at the Domtar mine. In general, while the mine had operated from 1854 it appears that the mining from 1854 through the mid-1970's primarily mined the #2 seam before closing. However, the United States Gypsum Mine, which is directly south of the Domtar mine, mined the #4 seam (based on an older mine map reviewed in this investigation). In the early 1980's the Grand Rapids Gypsum mine was purchased and reopened by Domtar Industries, Inc. with mining concentrating in the #4 seam and #5 seam as well as some limited pillar removal in the #2 seam.

To investigate the surface features good topographic maps generated from the county-wide Regis system were used. These maps were of good quality and provided 2-foot contours of the proposed site as well as over the entire Domtar mine. However, complete mine records showing the mining development were not available. Apparently, all (or most) of the Domtar mine files had been discarded at the time the last ownership change of the mine properties. Fortunately, some of the file were salvaged from the dumpster where they had been disposed (Mroczkowski, personal communications). Although some damage had occurred to the files they were useable for this investigation and provided signification information. However, the disordered nature of the files, as well as missing data, did introduce an element of uncertainty to the analysis, although it is believed that the major aspects of the mine, its geology, mining history and ultimate stability have been adequately understood for this investigation. The following sections provide the information collected concerning the Domtar Mine and used to determine the suitability of expansion of the John Ball Zoological Gardens (Zoo) over a portion of the Domtar Mine.

Existing Mine Reserves

The Domtar mine closed before completely mining out its reserve base. According to an inter-office memo, the mine has approximately four million tons of recoverable gypsum located in the #4 and #5 seams. No mining of the #2 seam, which had the highest quality gypsum in the mine, was included in the reserve tonnage. Mining of the #2 seam would have been through pillar removal or pillar size reduction (shaving), since the seam had been completely mined out on the property. Pillar removal (also known as recovery) is a common mining technique used in some cases to (1) produce easily mined tonnage when production is needed, (2) improve the quality of the run-of-mine production when needed, and (3) to allow an orderly collapse of the pillar so that ground subsidence can be gradual in nature and to minimize surface disturbance and to produce a stable surface and eliminating the potential for sinkholes. A 1983 rock mechanics report (Parker, 1983), in fact, recommended that the #2 seam pillar be removed "...to preserve the real estate above the mine." The removal of pillars would allow the gradual fairly uniform subsidence of the mine and minimize sinkhole formation. While some limited pillar recovery is identified on the existing mine maps, it appears that very limited pillar removal was conducted in the #2 seam.

The existing #4 and #5 reserves all lie in the northern section of the mine. Three inter-office memos (years 2000, 1999, and 1996) concerning the gypsum reserve estimate, as well as future mine plan details, are provided in Appendix D. The memos provide the following details:

1. The mining at Domtar, in general, has been from the south in an area of low cover and short haulage distances, to the north with longer hauling distances. Figure 5 shows the areas of the gypsum reserves lying mostly north of O'Brien Street, with some limited reserves south of O'Brien on the east side of the Domtar property.

2. Essentially, the proposed Zoo extension overlies the majority of the remaining mining reserves at the Domtar mine. Although the mining of these reserves is unlikely, the rights to mine these reserves must be considered in any surface development since mining may affect the stability of the site.

3. Only a small portion of the #4 seam was mined below the proposed Zoo site and from records reviewed none of the #5 seam was mined.

4. Although the #2 seam has been mined under the CMS power line and I-196, the 4 million ton reserve estimate excluded mining the #4 and 5 seams under both structures. The exclusion of the reserves under these structures can be seen in Figure 5.

5. The 1999 memo in Appendix D states that only 25% of the gypsum production was from the #5 seam, indicating that *not* all of the #5 seam was being mined along with the #4. It is unclear from the information inspected as too where the number #5 seam was mined or not mined. This appears to be significant in regards to the surface stability, since as noted above, stability of the pillars becomes important with the larger opening.

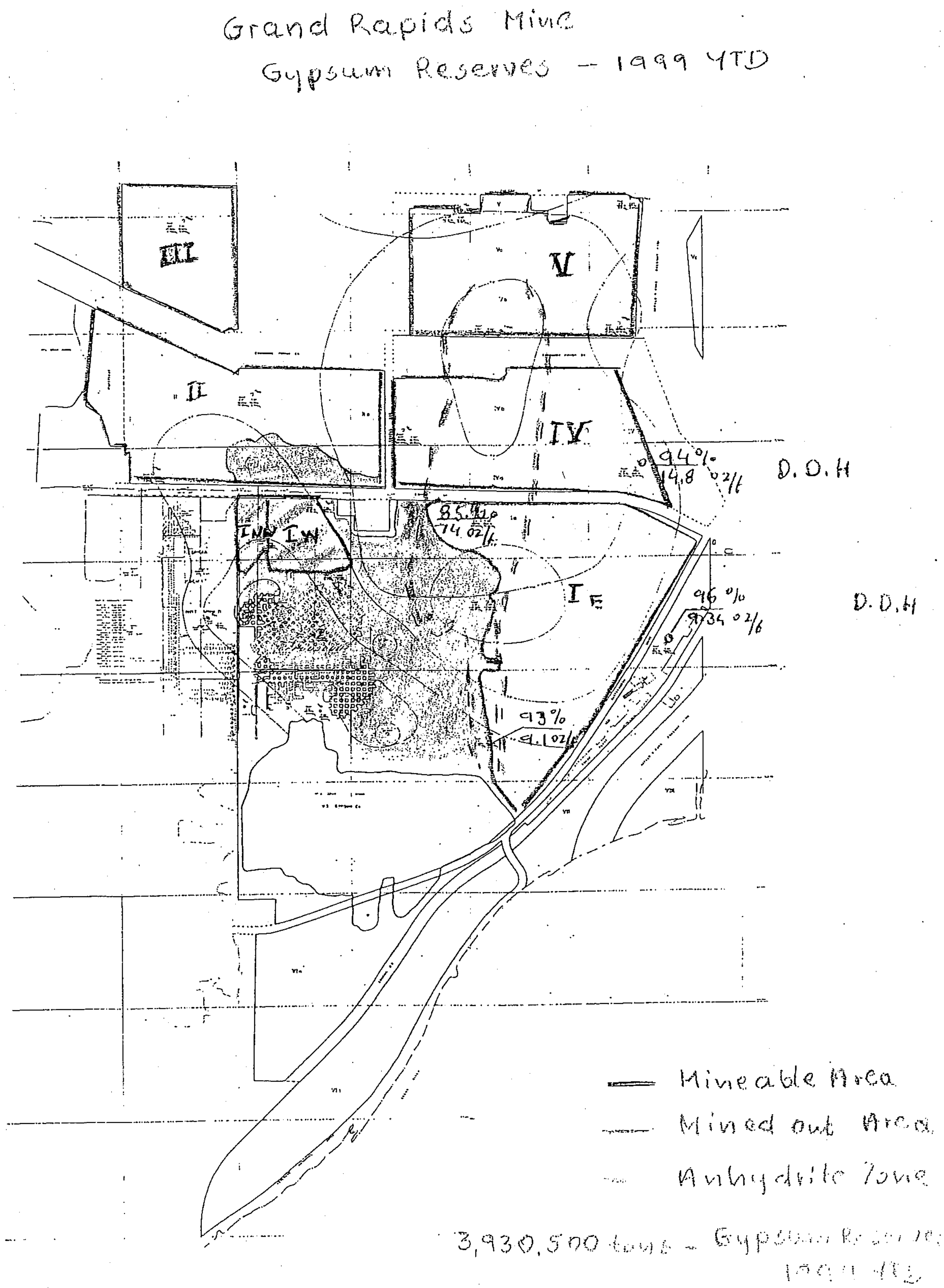

Figure 5. Domtar Mine 1999 gypsum reserve estimate map. Map shows the exclusion zone of mining around the CMS power line and I-196 in addition to the anhydrite zone located in the #4.

6. An anhydrite zone is located in the #4 seam as shown in Figure 5. Anhydrite, although a calcium sulfate as is gypsum, does not have water in its structures and is unusable for plaster board or other products that gypsum is used in. Consequently, this zone, which occurs in the upper portion of the seam, had to be excluded in the mining process. This significantly altered the mining of the #4 seam. A system known as "bi-level" mining was implemented to mine the base of the #4 seam and the #5 seam together, thus mining underneath the anhydrite zone. The 1996 memo in Appendix D provides the only map that was found showing the area where bi-level mining took place. The bi-level mining area was approximately 300 feet south of O'Brien Street starting on a line directly south of Covell Avenue and moving due east. It appears that the bi-level mining method is associated with surface disturbance and sinkhole development. However, the full extent of the bi-level mining activity at the mine was not determined in this investigation. It appears, though, that between 1996 and 1999 the bi-level mining continued due east working under the anhydrite zone. It does not appear that any bi-level mining occurred under the proposed Zoo extension site or was within 300 feet of O'Brien Street.

Existing Structures Over the Domtar Mine

There are two main lifeline structures over the Domtar mine, Interstate I-196, which is located over the northeast side of the mine and a high voltage CMS power line, traversing roughly east-west over the northern portion of the mine. Both structures, as noted above, had the #2 seam mined below them. A cursory field inspection of these structures did not indicate any distresses to the structures. The Michigan Department of Transportation (MDOT) was not aware of any special provisions that were made concerning the underground mine below the interstate (Larry Heinig, personal communications, 2002). Nor was it known whether mining had taken place after the Interstate had been constructed.

Underground Mining

Room and pillar mining was the primary form of mining used at the Domtar mine for mining #2, 4 and 5 seams. However, there were a number of different room and pillar mine plans used at the Domtar Mine as shown in Figure 6. In general, as the initial mining appears to have started in the southeast portion of the site where mining of the #2 seam began in the 1800's. In this area, the pillars are very irregular, with no clear patterns. This area appears to be confined to an area south of O'Brien Street. In addition, the roof is very thin, and in some cases nonexistent, leading to many caved areas. As mining progressed north and west the mine plan layout appears to have become more systematic. However, there were no mine drawings available for inspection indicating the sequence or timing of mining. As noted above, the majority of mining under the proposed Zoo expansion site was in the #2 seam, while only a small portion of the #4 was mined.

Known dates that may relate to the stability of the mine are as follows:

1. The mine started production in 1854.

2. The mine shut down in 1980 due to poor economic conditions and also poor mining conditions. It appears that at this point most of the #2 had been mined and that mining operations were beginning in the #4 seam. The mine was reopened in 1983 with primary production coming from the #4 seam.

3. The mine closed in the late 1990's and was allowed to fill with water.

4. The mine is currently completely flooded. The ground water table is in the glacial overburden based on the observation of the water level from the existing mine entrance.

An important factor concerning mine stability is controlling the water that flows into the mine. Therefore, the dip of the seams is important for the flow of water through the mine. Table 1 provides elevation data taken from five exploration holes drilled in 1963. In addition, the roof type was also noted as well as the roof rock thickness over the #2 seam. Additional exploration drilling was conducted in 1966, but these borings were not found at the time of this investigation. Figure 6 also shows the location of the 1963 exploration drill hole data presented in Table 1 as well as the location of the 1966 data.

Figure 7 shows the mining method for the #4 and 5 seams. The remaining discussion in this section concerns issues relating to the stability of the #2, 4 and 5 seams and consequently, the stability of the surface.

Table 1. Elevation data on the gypsum seam of the Domtar Mine.

Hole ID	#1	#2	#3	#4	#5
Ground Elevation	683	713	655	722	609
Top of Bedrock	587	587	601	618	598
OB Thickness	95	126	54	154	11
Top of #2	575	580	580	583	587
Bottom #2	568	568	571	571	575
Thickness #2	7	12	9	12	12
Top of #4	541	532	533	537	542
Bottom #4	532	522	524	526	531
Thickness #4	9	10	9	11	11
Top of #5	530	521	521	524	529
Bottom #5	522	511	513	515	523
Thickness #5	8	10	8	9	6
Roof Rock Thickness	12	7	21	35	11
Roof Rock Type	Shale/Gyp	Gypsum	Soft shale/ Soft gyp	Limestone/ shale/gyp	No #1 shale
Ratio: OB/Roof Rock	7.9	18	2.6	4.4	1.0

Seam #2 Mining Issues

1. Inspection of the mine maps indicates that there was limited karst or natural dissolutioning of the gypsum within the mine. This would indicate that shale beds overlying the gypsum formed a relatively impermeable layer preventing dissolutioning of the gypsum. However, there is a documented case of karst development on the west side of mine. This karst feature was discovered in 1976 and named the Pellerito Cave after the foreman who discovered it. The cave was approximately 300 feet in length and indicated that significant amounts of water had flowed through the cave. The cave was inspected by the National Speleological Society and reported on by Elowski and Ostrander, 1977.

2. The Pellerito Cave may have formed as a result of the glacial erosion to the west of the mine exposing the #2 seam and allowing fresh water to access the #2 seam and the dissolution of the gypsum. However, it is not clear as to why the cave did not further develop beyond 300 feet. One possible explanation may be that the dissolutioning process may be relatively young and associated with the mining of the #4 seam in the (GP) Butterworth Mine, directly below where the Pellerito cave was discovered. In fact, the cave system lies directly above the #4 seam with the cave ending at the end of the #4 mining. It is possible that deformation of the roof of the #4 seam may have caused cracks to form allowing water to enter the #2 gypsum layer. If this is the case, the rate of dissolutioning of the gypsum is significant in this mine depending on the flow of fresh water.

3. The #2 seam is relatively flat in some locations, but does drops approximately ten feet from west to east across the mine allowing water to flow from the west to east on the #2 along the mine floor. The floor material consisted mainly of shale and some limestone. In two locations the seam formed underground lakes, which provided locations to dewater the #2 seam.

4. The bedrock above the #2 seam varies in thickness across the mine ranging from 7 feet on the north east side of the mine, to no roof rock on the south, to 20 feet on the west side. However, the north central portion of the mine appears to have the most roof rock ranging between 20 and 30 feet.

5. The bedrock above the #2 seam varies considerably in composition. In some places the roof consists of interlayered shale/gypsum, while in some places it is completely shale or gypsum.

6. There are a number of different room and pillar types used below the proposed Zoo expansion site. The room and pillar mining method can be classified into the following groups based on what appear to be from older to newer mining methods:

    a. Very long rectangular pillars orientated either north-south, east-west or in a couple of small areas orientated at 45 degree angles to the north.

b. Somewhat regular 60 degree block pillar design, possible from mining with a continuous miner.
c. Very regular square pillar design.

7. South of O'Brien some pillar removal appears to have taken place in a couple of areas, based on the underground mine map. However, there is no other confirmation that pillar robbing occurred in the Domtar Mine, consequently this observation is only speculative.

<u>Seam #4 and #5 Mining</u>

1. The mining of the #4 and #5 seam, which was primarily conducted after the reopening of the Domtar Mine in 1983, was concentrated north of the old United States Gypsum Mine and south of O'Brien Street starting on a line directly south of Covell Street moving eastward towards I-196. A review of the mine's stability was made by Mr. Jack Parker in 1983 and 1984. Based on the Parker reports and the review of the existing mine files the following issues have been identified, which include observations of the mine conditions in the #2 seam relating to mine stability of the #4 and5 seams.

2. Observations of the #2 seam stability include the following:

   a. The #2 seam had good pillar conditions showing normal mine conditions in some portions of the mine.
   b. In other areas there are numerous roof falls in the #2 seam along with pillars failing by splitting.
   c. Artesian water conditions occur at the base of the #2 seam as well as water running beneath pillars.
   d. Areas where the roof had discontinuous gypsum and shale layers were associated with roof instability.
   e. Some areas with significant roof falls were supported by wooded timbers.
   f. Gunite was sprayed on exposed shale layers to protect the exposed shale in an attempt to minimize the effect of the mine's high humidity conditions on the shale's strength and stability.
   g. Shale layers at the base of the #2 seam were swelling, causing instability of the pillars.

2. Numerous roof rock falls were observed in the #4 seam. This instability was believed to be primarily due to the blasting procedure in mining the gypsum.

3. Cracks were observed in the #4 roof suggesting sagging of the roof.

4. Shale layers in the mine indicated that the shale was relatively weak. Williams and Works conducted unconfined uniaxial compression tests on dry shale samples from the mine, resulting in rock strengths from 3,000 to 4,000 psi. However, the uniaxial compression testing on the shale under high humidity conditions, conducted at Michigan

Tech, showed that the rock strength dropped to approximately 500 psi under high humidity conditions.

5. Because of the low strength of the shales from both the roof and floor rock, Parker suggested that all mine air flow be first directed through the #2 seam before accessing the lower mine workings - to condition the air to a constant humidity. This would help regulate the pillar stability while mining the #4 and 5 seams.

6. Pillar dimensions in the #4 and 5 seam are square with a dimension around 30 by 30 feet. Parker reports suggest a pillar dimension of 36 feet square should be used to maintain long-term stability of the mine roof.

7. It appears that in at least one location the #4 seam in the Domtar Mine mined into the #4 seam in the United States Gypsum Mine (USGM) - at the south end of the Domtar mine. This provided a route for ground water flow. Water that migrated into the USGM was then pumped out through the Pittsburgh Pumping station located on the south side of Butterworth Street.

8. Four pumping stations were used to discharge water from the Domtar mine: The #2 seam was de-watered by the Portfliet station in the northwest section of the mine, the Scranton station in the south central part of the Domtar mine, and the Butterworth station, on the east side of the mine. The #4 seam was de-watered from the Pittsburgh station located at the south end of the USGM.

<u>Geohydrology Issues Related To Mine Stability</u>

One of the most critical issues involving the long-term stability of the mine is the effect of water on the mine. As with any mining operation it is essential to control the water flow during mining so that mining operations are not affected. Besides the control of water to minimize its impact on mining, four additional concerns can be cited in regards to the stability of the mine works. The four main issues that can negatively affect overall mine stability are as follows:

1. Dissolution of the gypsum from flowing ground water.

2. Strength reduction of the shale and gypsum rock with increased moisture content.

3. Artesian water conditions, i.e., upward flow of water into the mine, due to the lowering of the water table at the mine and significantly increasing the potential head for water flow into the mine from lower rock layers.

4. The chemical change of anhydrite to gypsum results in significant swelling estimated to be approximately 60%.

The effect of these four issues on the stability of the Domtar mine are discussed as follows:

1. As discussed above gypsum is an evaporite that has relatively high solubility. In general, salt has the highest solubility followed by gypsum and then anhydrite. The Domtar Mine contains all three of these evaporites, with gypsum and anhydrite being the most abundant. However, there were a number of locations in the #2 seam where small blocks of gypsum were not mined due to a high salt content. Most of these high salt locations were in the northern part of the mine and below the proposed Zoo site. In general, the salt content increased towards the north central part of the mine. The rate of dissolution of gypsum by ground water is a function of a number of factors with the flow rate and amount of dissolved solids being the two most important. As the ground water flow rate increases dissolution will increase but as the percent of dissolved solids increases the rate of dissolution will decrease. Water that is high in dissolved solids is referred to as saturated water and which has limited potential for causing additional dissolutioning. Unsaturated waters or under-saturated, on the other hand, would be lower in dissolved solids with a high potential for dissolutioning.

2. According the Williams and Works report the ground water that entered the mine comes from three possible sources: (1) vertical seepage of precipitation falling directly over the mine, (2) lateral seepage from surface sources such as Portfliet Creek and Grand River (note, the elevation of the #2 seam is below the level of the Grand River), and (3) vertical seepage from the Marshall sandstone or from the flooded GP Butterworth Mine. The report was unable to determine the percent of each of these sources of water entering the mine, however, it was believed that a significant amount of water was entering the mine from the Portfliet Creek and possibly the Butterworth mine through lateral flow.

3. The groundwater flow through the glacial overburden into the mine would probably be relatively low in dissolved solids and therefore unsaturated. Once in the mine it would have a high potential for dissolving gypsum. The water then leaving the mine could, if dissolutioning was occurring, be high in dissolved solids. According to the NPDES permit levels the discharge waters from the mine were all very high in dissolved solids at approximately 3% by volume, i.e., near sea water.

4. Based on observations made in the Domtar mine during the Parker report period, as well as with personal communications with Tom Mroczkowski, significant dissolutioning was taking place during the mining operation. Dissolutioning was directly water was observed flowing under some pillars in the #2 seam.

5. During the mining operations and de-watering of the mine the flow rate in the mine would have been relatively high, since the rate of flow would have been a function of the discharge rate used to keep the water levels within an operational limit for mining.

6. Although the shale/gypsum layers are relatively impermeable, mine personnel were concerned about water flow from the Marshall formation. While the primary concern was the additional cost to de-water, upward flow of water also presented a significant stability problem for the #4 and 5 seam pillars, which would be undercut if water flow was occurring.

7. Since the Grand River is above the #2 seam, the river level will affect the groundwater hydrology of the mine. Flooding of the Grand River must also be considered. Flood events for the Grand River are as follows:

Flood Date	Stage (ft)
1904	610
1905	609.4
1947	606.8
1948	607.6

Domtar Mine Elevations	
Average elevation of the Domtar Facilities:	607 ft.
Top of #2 Seam	580 ft.

National Flood Insurance program (mid-1970s):
100 year flood at the Domtar Mine is 607 feet (will flood most of the Domtar plant site)
500 year flood at the Domtar Mine is 620 feet

8. Since the mine is now flooded, the flow rate through the mine has likely decrease to whatever the flow rate the discharge points of the mine will naturally allow. This will decrease gypsum dissolutioning to some degree, while some parts of the mine will become stagnant. However, the flooding of the mine has also resulted in the shale layer being saturated which will result in a decrease in the strength of the shale as well as swelling potential of both the shale and the anhydrite rock.

MINE AND SURFACE STABILITY

To maintain the stability of the surface above underground mine works, the mine support system must be designed such that it *permanently* supports the overlying rock and overburden. In addition, the mine must be designed so that any changes in the condition of the mine do not alter the long-term performance of the support system. This, based on available information, is not necessarily the case with the Domtar mine. It appears that portions of the mine pillar support systems were neither designed for long term support nor were they designed to function when the mine became flooded. This opinion is based on the following observations:

1. Significant sinkhole development as well as large subsidence has occurred in the GP-Butterworth mine in the #4 and 5 seams as well as a sudden subsidence collapse, which resulted in flooding of the West Plant and occurred after the mine was closed. Large surface cracks have been observed by Tom Mroczkowski in the past couple of years, indicating continued mine instability.

2. Sinkhole formation continues to occur over the Domtar Mine. Figure 6 shows sinkholes associated with the Domtar Mine. Most of them have formed south of O'Brien Street and appear to correlate with the mining of both #4 and #5 seams. Additional sinkhole development is occurring north of O'Brien Street but south of the CMS power line. It appears that this sinkhole development is primarily correlated to the main mine entryways and secondarily to the long rectangular pillars used in the support of this area. It is also possible that the roof rock in this area was relatively soft. The #3 exploration borehole, which was located near this sinkhole activity, indicates very soft shale and gypsum for the roof rock although the thickness of the roof rock was 21 feet. As noted

above, the roof rock thickness increases to the north and may help explain the lack of sinkhole development in the northern part of the mine.

3. The pillar dimensions were adequate to maintain stability during the mining operations in the #2 seam. In areas of unstable roofs, timber was used to support the roof and later mechanical bolts and possibly resin bolts were used to stabilize the roof. These types of systems will not support a roof long-term and are subject to deterioration and corrosion. According to the Parker Report (1983), larger pillar dimension (36' by 36') should have been used to better support the roof. And, also suggested that pillar removal be considered to preserve the surface real estate. Pillar removal would have allowed the surface to subside in a controlled manner minimizing disturbance to the surface as well as eliminating sinkhole potential.

4. Dissolutioning of the gypsum in the mine has occurred and will continue to occur. While the rate of dissolution is difficult to determine, it can be expected that dissolutioning over time will further reduce the strength of the pillars, allowing the ultimate collapse of the mine. Factors in the rate of dissolution will be the rate of water flow through the mine and the level of dissolved solids in the groundwater.

5. According to mine personnel, the #4 and 5 seams were stable during gypsum mining. As noted in point 2 above, however, significant sinkhole activity has occurred above the area where both the #4 and 5 seams since the end of mining operations. If the Butterworth mine is any indication of long-term stability, then it appears that the overall stability of the pillar support systems of the #4 and 5 seams may not be adequate. The Butterworth Mine, where only #4 and #5 gypsum seams were mined, was closed in 1971 and over the approximately thirty-year period significant surface disturbance has occurred. A concern with the mining of the #4 and 5 seams is also the potential for water inflow from the Marshall sandstone located below the #5 seam. This inflow could result in damage to the mine's pillars through dissolutioning and a decrease in strength of the shale parting between the two seams. Fortunately, the strata between the #5 seam and the Marshall Sandstone should be adequate to prevent water migration. It is possible though that water pressure, developed when the mine was dewatered and the swelling of the floor shales and gypsum, may have resulted in Marshall water accessing the Domtar mine, causing a further decrease in the mine's stability prior to the flooding of the Domtar Mine.

6. In general, the strength of gypsum is not high. There is relatively little strength data on gypsum. Research by Gysel (2002) reports that the strength of Triassic gypsum located in Switzerland ranged between 2,000 and 4,000 psi. However, Gysel also notes that the strength significantly decreases when shale is incorporated in the gypsum, which is then referred to as a marl, to as low as 500 psi. Based on the 1963 exploration drilling information, much of the roof rock, which is mainly the #1 gypsum seam, was of a gypsum/shale composition. This suggests that the strength of the roof rock was not high. This is also correlated with many long tension cracks observed in the roof of both the # 2 and #4 seams. According to Parker (1983) the long tension cracks in the roof indicated a sagging roof condition, indicating that the strength of the roof "beam" was not adequate to span the distance between the pillars at that time.

7. The Parker report was also concerned with the moisture state of the shale and attempting to maintain a constant humidity of the mine air. Flooding the mine would increase the potential for softening the shale rock and decreasing the stability of the mine over the long-term.

8. Flooding the mine there is the potential for swelling of both the anhydrite and shale. The 1983 Parker report showed pictures of the shale floor layer swelling up into the mine. This would decrease stability of the support pillars.

9. It is almost certain that subsidence will occur over portions of the Domtar Mine but we do not know when. Based on the Butterworth Mine it is possible that sinkholes may form soon after the flooding of the mine, while the broader subsidence may take longer. One can expect that sinkholes will form in the areas with thin roof rock and low overburden cover while broader land subsidence may occur in the north center part of the mine where the roof rock is thicker. Special consideration must be given to the location of the bi-level mining, since it appears that this may be the most likely place for sinkholes.

SURFACE STABILITY OF THE PROPOSED SITE

Based on the above criteria, we can designate zones of probable stability or instability, as follows: Zone A identifies the area with the greatest potential for stability, while Zones B through F indicate increasing instability with Zone F having the highest potential for instability. The zones are shown in Figure 6

Zone A - No gypsum mining has occurred in this zone. The stability of this zone is high and is outside any potential underground mining instability. The boundary of the zone is based on an angle of draw of thirty degrees, i.e., the limit of mining is an additional distance from this zone measured by a vertical angle of thirty degrees.

Zone B - Only the #2 seam has been mined in this zone and no evidence of sinkholes was found. It is assumed that the mining below this zone was relatively recent, occurring in the1960s and 70's using systematic room and pillar mining methods. It is also based on no reduction (shaving) of pillars or pillar removal has occurred in this area. The roof rock appears to be relatively thick in this area and the floor rock appears stable. Therefore, short-term stability of this zone appears good. However, the issue of dissolutioning of the pillars over time must be considered, since decreasing stability may result if the pillar dimensions are reduced in size.

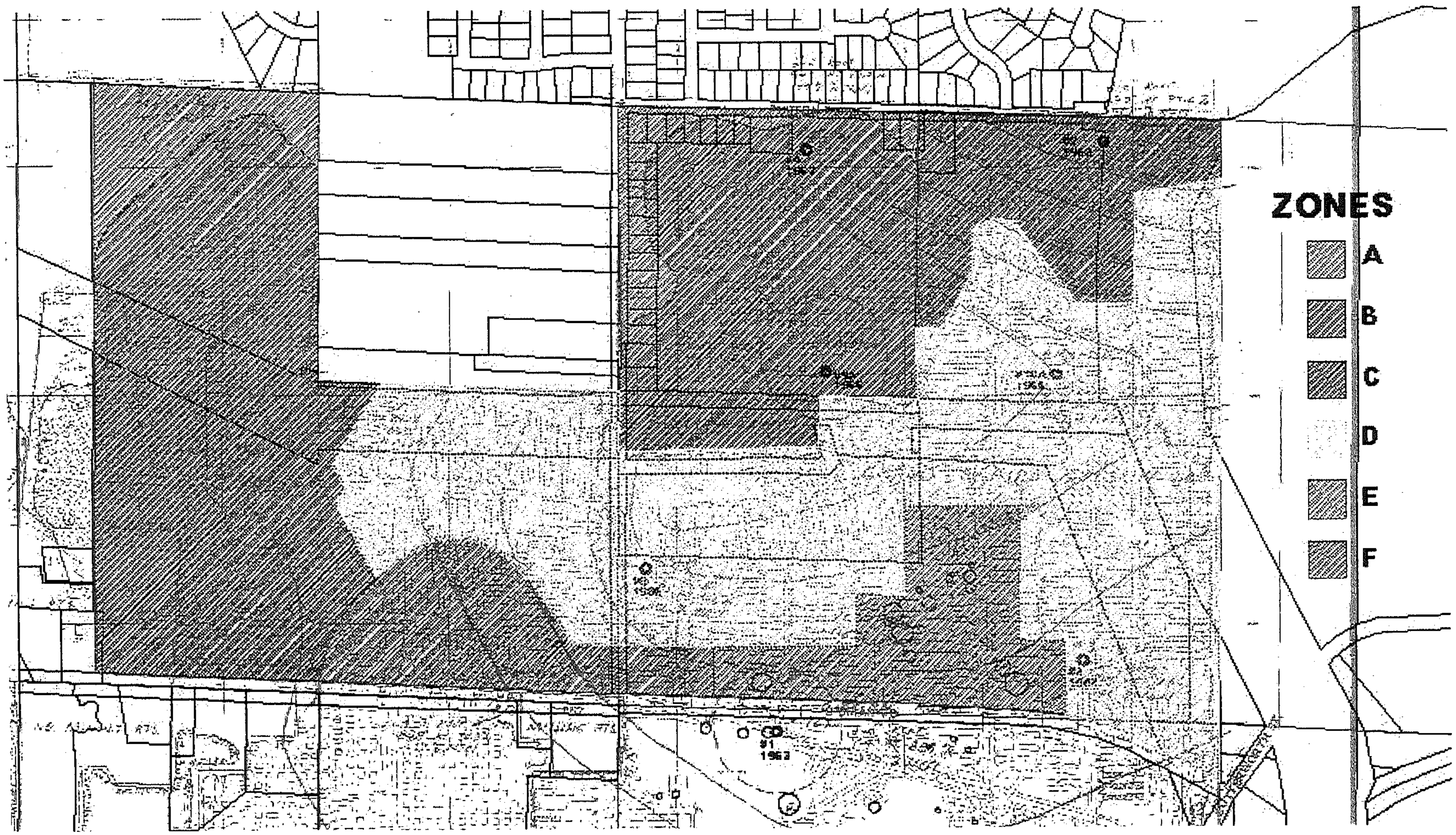

Figure 6. Map of Stability Zones.

Zone C – Only the #2 seam has been mined in this zone and no evidence of sinkholes has been found. This zone has a less systematic mining method and with very irregular pillar shapes and sizes. It is not known why this type room and pillar method and orientation of mining was used. As with Zone B it is also assumed that no reduction (shaving) of pillars or pillar removal has occurred. However, the roof rock in this zone is significantly thinner and according to exploration borehole #3 is composed of only 5.5 feet of gypsum and 1.5 feet of shale. This is the only exploration borehole that showed the gypsum being in direct contact with the glacial overburden. However, no sinkholes or land subsidence are evident in this zone. While the short-term stability of this zone appears to be adequate, there are stability issues that increase the probability of future instability. Again, the issue of dissolutioning of the pillars over time must be considered, since decreasing stability may result if the pillar dimensions are reduced in size.

Zone D – Only the #2 seam has been mined in this zone. An older mining method using long rectangular pillars at various orientations was used in this zone. The roof rock in this zone varies from 35 feet in the west while thinning to seven feet in the east. While this zone appears stable it is unclear if the mining method using the long rectangular support pillars is adequate over the long-term to support the mine roof. It is also assumed that no shaving of pillars or pillar removal has occurred in this zone. Again, the issue of dissolutioning of the pillars over time must be considered, since decreasing stability may result if the pillar dimensions are reduced in size.

Zone E - Only the #2 seam has been mined in this zone along with the same mining method used in Zone D. However, this zone has sinkholes forming, which appear to be related to the mining method used. The roof rock is relatively thin in this area. Along with the formation of sinkholes and the older mining technique used, the short-term stability of this zone is questionable.

Zone F – The #4 or the #4 and #5 seams were mined in this zone. Potential for instability of the lower seam is relatively high. Portions of this zone have already subsided. There is a high probability of surface instability in this zone.

SUMMARY AND CONCLUSIONS

1. The proposed zoo expansion site has all three major gypsum seams located beneath the site. The seam closest to the surface, the #2, has been extensively mined underground, while only a small portion of the #4 has been mined on the south edge of the site just north of O'Brien Street. Based on the salvaged mine maps no #5 seam has been mined below the proposed site.

2. Approximately 4 million tons of reserves exist in the Domtar mine, with a significant amount located under the proposed zoo expansion site. While future mining of these reserves is unlikely, the rights to mine these reserves must be considered since future mining of the #4 and #5 seams might cause increased instability of the surface.

3. The gypsum seams in the Domtar mine appear to have little to no natural karst development (dissolutioning) prior to mining operations. This indicates that shale beds above the gypsum seams provide protection from ground water. The one karst feature found in the mine is the Pellerito Cave (Elowski, and Ostrander, 1977) may have been induced by the mining of the GP Butterworth Mine. However, additional investigation may be needed to verify this hypothesis.

4. The support pillars of the mine do not appear to have been designed for long-term stability. The stability of the support pillars is further compromised by the possible dissolutioning of the base of the pillars during mining.

5. Extensive sinkhole formation has occurred over the adjacent Georgia-Pacific Butterworth Mine. A large subsidence event resulted in the flooding of the processing plant south of the mine.

6. Sinkholes have formed over the Domtar Mine, with recent sinkholes forming since the flooding of the mine over the past two years. It appears that the majority of sinkholes are related to the mining of the #4 and 5 bi-level mining and to possible pillar removal of the #2 seam. In addition, some sinkholes appear to be related to the type of mining conducted using long rectangular support pillars.

7. The issue of gypsum dissolutioning is critical to the stability of this mine. Over the long-term it is highly likely that the remaining support pillars will collapse resulting in either sinkhole development or larger scale subsidence.

8. Zones indicating the short-term stability of the surface have been developed. The time period of short term is difficult to establish, but based on the experience of the Butterworth mine, the short-term can be approximated by a period of less than 50 years.

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APPENDIX C

REPORT OF INVESTIGATION OF WATER PROBLEMS AT THE GRAND RAPIDS GYPSUM MINE, GRAND RAPIDS, MI

BY

EDWARD M. BURT

1965