Catastrophic Failures of Underground Evaporite Mines

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ABSTRACT

Deformation of underground salt, trona and potash mines is generally time dependent, providing for gradual adjustment of strata to mining induced stresses. Time dependence can allow for higher extraction ratios provided eventual failure can be tolerated. However, this eventual failure can be violent if creep deformation can shift stress and potential energy to strong, brittle geologic units. The mine failure case studies reviewed here illustrate this process. Yield pillars and defects in bridging strata figure prominently in these cases. Yield pillars provide local and temporary support to the roof, temporarily delaying the cave; and allowing extraction ratios and overburden spans to increase beyond the long term capacity of overlying strata. Defects (faults, voids, thinning) of strong overburden strata reduce the critical span, sometimes to less than panel width. Analyses of many of these cases have focused on a cascading pillar failure mechanism, but recent work and this review point to failure of strong overburden strata as the essential element. The suddenness of failure and attendant seismic events pose hazards to miners and, in some cases, to those on the surface. Characterizing these failures is a first step towards recognizing and managing the risk of catastrophic collapse in underground mines.

INTRODUCTION

Recent mine disasters have prompted the National Institute for Occupational Safety and Health (NIOSH) to look for opportunities for reducing the disaster potential of mining. A number of other agencies and groups are addressing the regulatory and management frameworks for controlling disaster potential. While the details of these schemes differ in assigning responsibilities and liabilities, all require technical means to discern and minimize the likelihood of catastrophic mine failure.

Deep and high extraction mining is possible only through management of rock mass failure. Generally, two types of failure may occur. First, yielding around mine openings shifts stress away from openings towards more confined rock. Second, caving shifts the weight of caved material from pillars and abutments to the floor of mined areas.

These types of failure may occur in two modes – ductile and brittle. Ductile failure consumes sufficient energy to prevent its acceleration, or at least enough energy to remove any hazard to miners. That is, the failure process will be sufficiently slow to give miners time to retreat. However, the economic and environmental consequences (inundation, sinkholes, etc.) may still be catastrophic. The alternative is sudden, brittle failure.

Brittle failures of any appreciable size around working areas can be hazardous. The unexpected transition from a controlled ground failure process (that is, ductile failure and/or brittle failure isolated from miners) to a brittle failure process that impacts work areas is a hallmark of many fatal accidents and mine disasters. At ordinary working temperature and pressure, salt rocks (evaporites) are considered to be the most ductile of all rock types (1). As such, mines extracting such rock might be expected to be immune from such failures.

This paper examines catastrophic failures of evaporite mines (including salt, potash and trona) that show that violent failure does, in fact, occur. It also attempts to identify common factors and characterize the mechanism of failure. While these cases are limited to evaporite mines, it is hoped that results are sufficiently general to provide insight into similar cases in other mining sectors.

CASE STUDIES

Cases selected for this review involved panel or mine collapse events that were initiated by strength failure of solid material. Events driven primarily by gas (gas outbursts) or groundwater (inundations) in the absence of an initial collapse of strata were not considered. However, many of the cases reviewed do involve release of gas and/or water.

Varangeville Mine Collapse (1873)

This, the oldest collapse case reviewed, occurred in 1873 at the Varangeville salt mine. Salt was extracted by blasting and solution mining for an ultimate extraction ratio of over 82%, leaving pillars with a width:height ratio of about 1:1 (2). Significant subsidence was noted, beginning in October, 1873. Creation of a fissure in a building at 5 am on October 31st prompted evacuation shortly before a collapse that reportedly took less than 2 seconds to occur. Fractures were formed within the subsidence zone in two concentric circles with 160-m and 350

-m diameters, respectively. Daw and Pollard (3) describe geology elsewhere in the deposit as having a surface stratum of 42 m of marl underlain by layered salt and marl. More recently, solution mining in the deposit has been conducted under 200 to 300 m of cover (4). The thick surface marl forms a brittle cap with increased calcium carbonate content. Apparently, there was a transition from ductile to brittle failure as caving entered the marl which formed a brittle cap with increased calcium carbonate content.

Louisiana Salt Dome Failures to Surface (1972-1992)

Rapid, but not seismic, collapses have occurred in Louisiana salt domes. The south coast of Louisiana contains five salt domes that have been mined since the beginning of the 20th century (5). More recently, two of the domes have experienced large-scale failures to the surface as a result of unsustainable ductile failure long after mining of pillars in the affected area. The salt domes are massive deposits with discontinuous jointing and inferred shear zones overlain by a more brittle "caprock" followed by surface soils.

At the Belle Isle mine, extraction ratios between 50 and 59% initiated creep in the salt structure with minimal disturbance of the active mine. Creep transferred loads to more brittle cap rock, eventually resulting in formation of a 70 meter diameter sinkhole in 1972. The sinkhole developed over about 15 minutes and engulfed the lone shaft accessing underground workings (5). 30,000 m^3 of debris flowed into the mine (3). Fortunately, and by chance, no miners were entrapped or injured. The shaft was backfilled, a new shaft sunk, and the mine returned to operation. Subsidence monitoring showed increased risk of a second, much larger event in 1983. The mine was then flooded to stabilize workings and prevent damage to nearby oil and gas production.

At Weeks Island, parts of the original mine workings, dating to the late 19th century, were taken by the U.S. Department of Energy for use as a petroleum reserve (6). Mining operations were moved to an adjacent part of the dome and monitoring of surface subsidence and water inflow initiated. A number of production levels were established in the new mine and mining progressed without incident for more than a decade. As at Belle Isle, the brittle cap-rock became over-loaded and a sinkhole developed at the surface along the boundary between old and new mines (7). Increased leakage of surface waters into the reserve was detected. The progression of sinkhole and leakage was slow, but still posed a significant risk to the petroleum reserve. Grouting failed to stem progression of failure. The reserve was stabilized by brine flooding and abandoned.

Saskatchewan Potash Mining Seismic Events (1962-1989)

Some evaporite mines are a significant source of mining induced seismic events. Hasegawa et al. (8) reviewed large seismic events produced by mining of potash in Saskatchewan under 900 to 1000 m of overburden. These deposits lie in a thick sequence of halite and anhydrite known as the Prairie Evaporite, which is overlain by roughly 40 m of strong, dense Dawson Bay limestone (Figure 1).

Between the onset of mining in 1962 and the end of 1989, 21 mining induced seismic events with magnitudes of 2.3 to 3.6 were recorded. Horner (9) attributes these events to “brittle failure or sudden rupture” in the competent carbonate rock of the Dawson Bay limestone. Rockburst damage has not been reported but

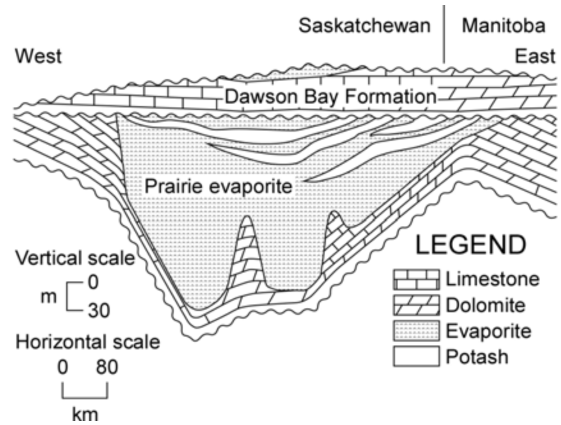

Figure 1. Idealized cross section through the long axis of the Prairie Evaporite structure (11; 12).

noise, movement of air (minor air blasts) and falls of loose roof rock have. Hasegawa et al. suggest that salt overlying mining provides protection by attenuating dynamic shocks.

Sepehr and Stimpson (10) created a simplified numerical model of strata failure, inspired by a potash mine near Saskatoon, Sakatchewan that had produced seven events with magnitudes of 2.3 to 3.5. The model simulated mining of evaporite beds under 1 km of overburden. They found failure propagation into the Dawson was “so rapid and extensive… that numerical convergence is not achieved, signaling a structurally unstable situation.” They concluded “such extensive and rapid brittle failure would certainly induce significant seismicity.” That is, they interpret failure of the solver algorithm in their finite element program as indicating physical as well as numerical instability.

Un-named Phosphate Mine Collapse

Chen and Peng (13) report on a relatively innocuous collapse that occurred two weeks after completion of mining. The collapse occurred within a pillar retreat panel with strong roof and floor, mined under 60 to 400 m of overburden near a cliff. The roof had remained intact during secondary mining. The collapse occurred suddenly, crushing 25 remnant pillars, all less than 6 m in width and 1.6 to 1.9 m in height, over a roughly 90 m by 55 m area (Figure 2). The collapse was also evident in surface subsidence and large cracks in the cliff face.

Cheng and Peng attributed the failure to “pillar sizes that were too small and uneven.” Implicit in this explanation is a failure of overlying strata to transmit overburden loading to pillars beyond the collapse area. Fortunately, the pillars succeeded in providing support during mining of the area.

Retsof Salt Mine Collapse (1994)

Major seismic collapse events can also be linked to other mining hazards, before and after the collapse. For instance, a chain of events at the Retsof salt mine, New York, began with ground control problems encountered under roughly 300 m (1000 ft) of overburden, including a roof fall that caused two deaths in 1990. In response, the yield pillar panel method of mining was tested and then implemented in two full production panels, 2YS and 11YW (Figure 3). Mining of these panels was initiated in 1993 but 2YS was halted in October “for safety reasons and due

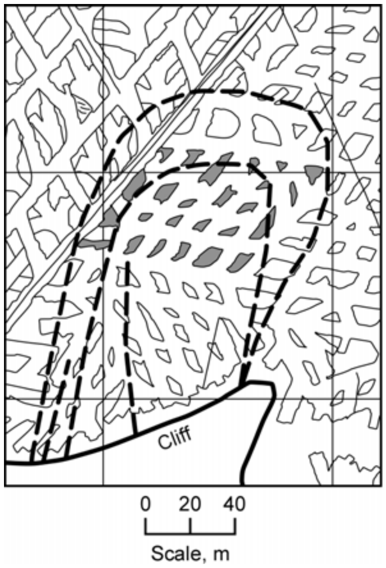

Figure 2. Collapsed pillars (shaded) and surface cracking (dashed lines) at a Phosphate mine (13).

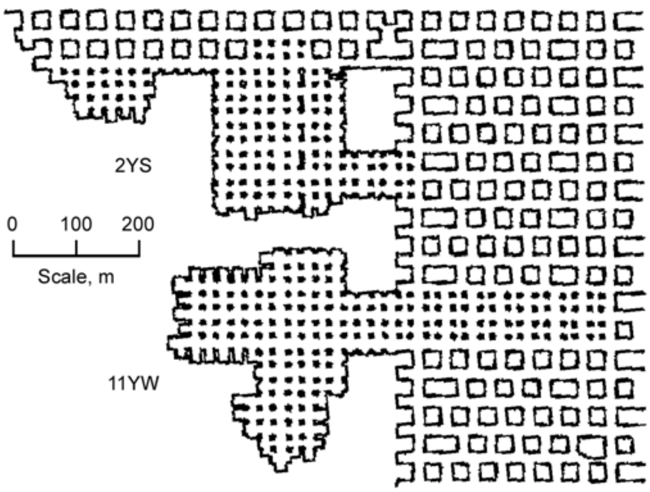

Figure 3. Yield pillar panels at the Retsof mine. The 2YS panel collapsed on March 12, 1994, leading to inundation and loss of the mine (14).

to clearance problems for the mining equipment" (14). A sudden increase in closure rates in both panels 2YS and 11YW led to cessation of mining in panel 11YW on March 1, 1994.

Collapse of the 2YS panel on March 12, 1994 produced a 3.6 magnitude seismic event as a 150 by 150-m (500 by 500-ft) section of shale roof collapsed. Methane and hydrogen sulfide gases were detected and brine water began flowing into the mine at nearly 19,000 lpm (5000 gpm) (15). The collapse stabilized closure of 11YW panel but flooding could not be stopped, eventually leading to loss of the mine.

Subsequent investigations found evidence of fracture zones and a brine and gas pool 50 m (160 ft) above the mining horizon (14; 16). The fractures and pool weakened the overlying "bridge" of strata. Fractures hydraulically connecting the pool to surface waters allowed recharging of the pool and maintenance of hydrostatic pressure. Since this pressure was exerted within the bridging arch, it could not be entirely supported by intervening strata – nor by the yield pillars for which such loading was not anticipated.

Solikamsk-2 Potash Mine Collapse (1995)

Collapse of the Solikamsk-2 potash mine, Verkhnekamsky deposit, in the Upper Kama district of western Ural, Russia resulted in a 4.7 magnitude seismic event on January 5th, 1995 and 4.5 m of surface subsidence (17). Underground, a "massive falling of the mine roof" was noted over a 600 m by 600 m area (Figure 4). The event released an estimated 900,000 m^3 of gas (a mix of methane, hydrogen, carbon dioxide, carbon monoxide and other gases). These release led to gas explosions the following day. Timely placement of a "large volume" of backfill is credited with preventing further catastrophic consequences. Malevichko et al. describe the potash as "almost incompressible, highly ductile and rather easily deformed by creep." Potash and salt beds were overlain by carbonates and sandstones.

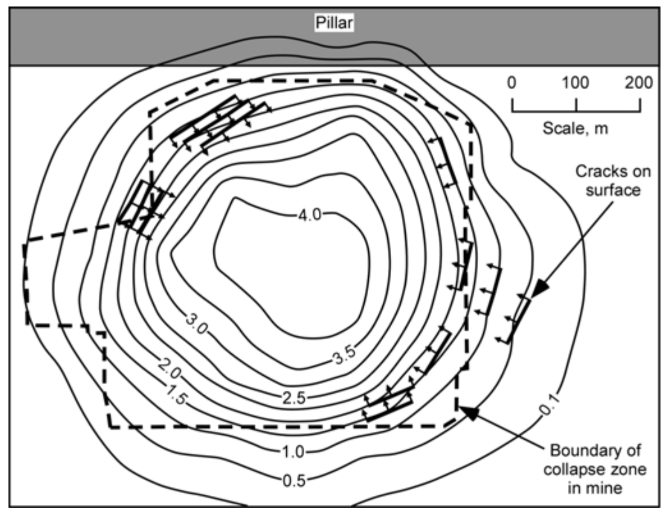

Figure 4. Subsidence resulting from collapse of the Solikamsk -2 Potash Mine, Russia, in 1995 (Modified from 17).

Sylvinite (potash) was extracted from two to three beds with 10 to 16 m of total extraction height in the collapse area. The mine used a panel system of rooms and pillars under 200 to 400 m of overburden. Rooms were 13-16 m wide and pillars 11-14 m wide by 200 m long.

An investigation across the Upper Kama district found that surface subsidence typically reached 50% of excavation height 4 - 8 months after excavation. This event occurred 15 years after mining began, and 7 years after mining was completed (18). The unusual delay in subsidence implies extensive bridging of overburden, consistent with its uncommonly high release of seismic energy. The next largest collapses occurred in 1993 and 1997 with magnitudes of 2.6 and 2.8, respectively.

3rd Bereznki Potash Mine Collapse (1986)

Collapse of the nearby 3rd Bereznki potash mine in July 25, 1986 (19) is another interesting case. Mining was active at depths of 235 and 425 m below surface, and was overlain by a 100 m thick "salt complex" of halite and carnallite beds, overlain in turn by clays, carbonates, aquifers and sediments. Mining formed yield pillars with 5.3 m wide rooms, 3.8 m wide pillars and a 5.5 m mining height. After mining, conditions were described as "pillars crushed and roofs sagged."

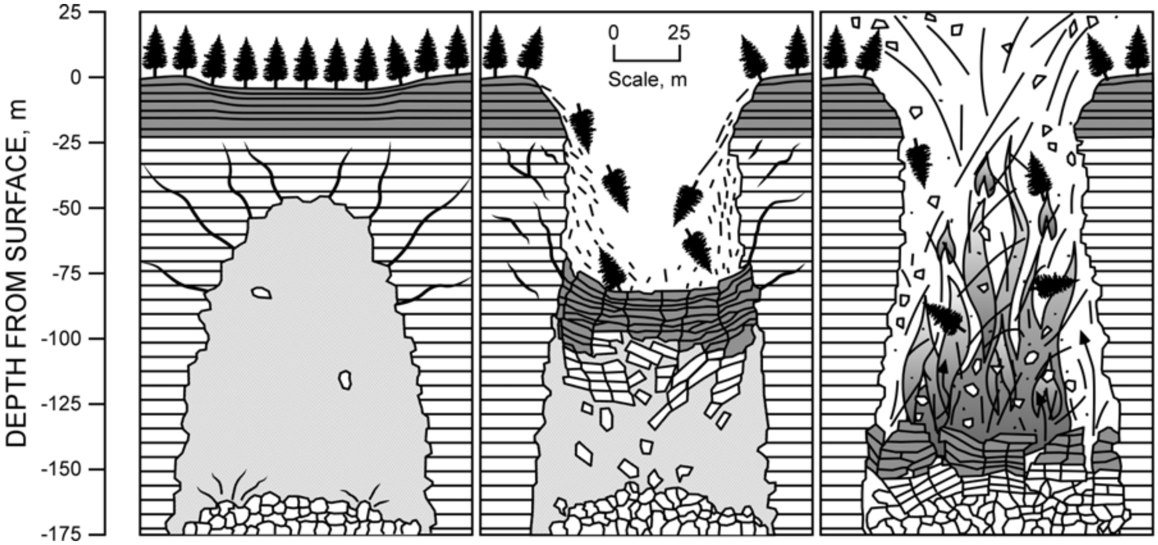

Figure 5. Collapse and explosion of cavity on July 25, 1986 at the 3rd Bereznki Potash Mine in Russia (redrafted from 19)

At the collapse site, mining induced fractures connected with natural fractures in a fold structure, providing a conduit for flooding of the mine. Loss of hydraulic control in January of 1986 led to creation of a large cavity beneath a sandstone/limestone sequence nearly 200 m thick that was relatively stable until July. Failure of this sequence began at 18:30 hours with "clearly felt underground shocks" culminating with a final collapse at midnight "accompanied by an explosion with flashes of light" (Figure 5).

Solvay Trona Mine Collapse (1995)

A roughly 1 by 2 km section of the Solvay Mine, Wyoming collapsed on February 3, 1995, causing a 5.1 magnitude seismic event (20). Seismic first motion showed dilation (collapse) at all seismic stations. The "dominant movement of the ground" took place on a "time scale of a few seconds or less" (21). Miners described the event as "a rumbling, a big boom, and then a deafening sound lasting 5 to 6 seconds in all." The collapse caused an air blast fed by methane and ammonia emissions as well as closure. The failure was believed to have released an eventual total of 3 million m^3 of methane from broken shales with a peak release of nearly 1 million m^3 / day. Ammonia (broken trona and oil shales) and CO (kerogen-rich oil shale in the immediate floor) were released in smaller quantities. The single fatal injury was attributed to ammonia poisoning.

The failure occurred over a multiple yield panel section within the southwest portion of the mine but was contained by barrier pillars along the main entries (Figure 6). All 13 panels in the southwest section were "completely collapsed or extensively caved" (22). Panels 4W through 12W were "caved tight at or near the submain ends."

The panel was mined under 450 to 520 m (1500 to 1700 ft) of overburden, including the massive Tower Sandstone. Failure of yield pillars within panels occurred in the immediate floor and lower portion of narrow pillars, while the immediate roof and upper portion of pillars remained intact. Gateroad pillars were shattered.

Surface subsidence of 0.75 to 0.9 m (2.5 to 3 ft), with a maximum of 1 m (3.3 ft), was noted over the collapse area (22)

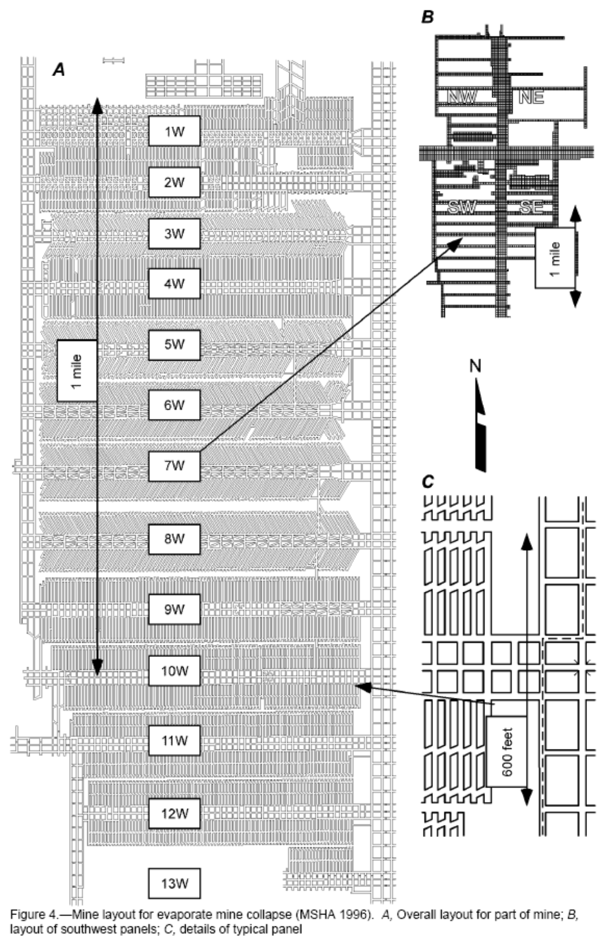

Figure 6. Schematic of Solvay mine in 1995 showing (A) southwest panels (1W through 12W) closed by the collapse, (B) location of the southwest panels within the mine and (C) detail showing barrier pillars that bounded the collapse

and subsidence bounds have been described as sharp scarps (23). A number of mechanisms, including a chain reaction pillar collapse have been proposed (21; 22; 24). Most recently, Board et al. (23) attribute the failure to "violent shear failure of a thick and strong overburden bed that was capable of application of full overburden loading over the entire pillar geometry."

Pechmann et al. (20) successfully fit the seismic event to a crack closure (implosional) mechanism, the crack being the mined trona seam. Seismic energy released was about 10% of the potential energy lost by observed subsidence of the overburden (25). A near-vertical shear failure of the sandstone is consistent with both brittle failure and a sharp subsidence scarp. In such a case, both pillars support and the bridging Tower Sandstone failed, and failed quickly during the collapse.

German Potash Mine Collapses

German potash mines are often overlain by sandstone strata regardless of whether the evaporites are within stratabound or domal geometries as in Figure 7. Beneath the sandstone, there are typically several hundred meters of "yield, i.e., creepable, saliferous rock layers, which hold the minable seam horizons of the potash mining" (26). Failure is characterized as involving "the entire structure" with caving up to the surface (subsidence) and "tremors, similar to those experienced during an earthquake."

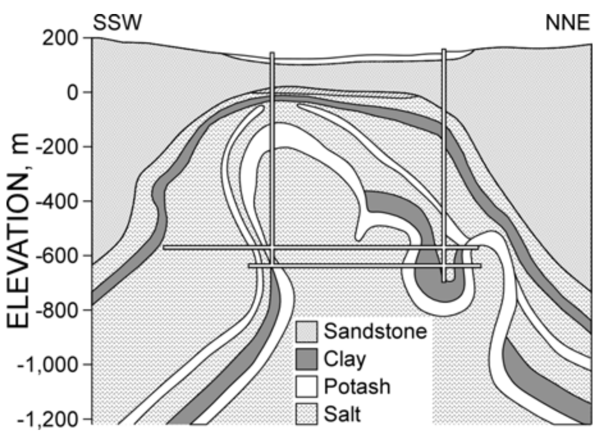

Figure 7. Example of German salt dome potash occurrence with capping sandstone strata. Salzdetfurth mine (29; 12).

Many collapses have occurred during mining of carnallite potash seams. Generally, the lower the halite content of a rock (with carnallite replacing halite) the more brittle its behavior. Initiation of collapse is generally attributed to a blasting event that begins a chain-reaction failure incorporating both pillars and roof strata, resulting in significant surface subsidence and a large seismic event. These collapses, named after overlying villages (27), include:

- A collapse at Teutschenthal in 1940 under 730 m of overburden (26). Failure propagated 1300 m in 0.9 seconds through slender pillars with a width:height ratio less than one. Back-calculation estimated a local magnitude of 5 for the resulting seismic event.
- A collapse at Herringen with a local seismic magnitude of 5.
- Collapses at Merkers on July 8, 1958 and June 29, 1961 with seismic magnitudes of 4.8 and 3.7, respectively.
- Collapse at Suenna in 1975 with a seismic magnitude of 5.2. This collapse was located in the Werra potash district near Suenna, Germany and involved crushing of carnallite pillars over an area of 3.35 km^2 (12). Damage was entirely contained within known fault planes.
- The Teutschenthal potash mine collapse of Sept. 11, 1996 involved failure of 700 long pillars over an area of 2.5 km^2 and under 620 to 770 m of overburden in approximately 2 seconds. The collapse produced a 4.8 magnitude seismic event and 0.5 m of surface subsidence (28).

An additional event, and the largest of these, is the March 13, 1989 collapse of the Merkers mine, 750-900 m beneath the town of Volkershausen. The collapse involved an area of 6.5 km^2, produced a 5.6 magnitude seismic event* and caused "catastrophic" damage to the town (30). Two levels were mined. A primary level in carnallite was extensively mined, leaving 30 by 6 m pillars with a width to height ratio of 4 to 7. A secondary, overlying seam was mined in hard rock salt to a lesser extent, initially leaving large, stable pillars. In 1987, mining in the upper seam was modified to leave yield pillars with a width to height ratio of 1.7:1. Heavily "working" rock and roof control problems were encountered. The actual event appeared to originate with blasting of carnallite in the lower seam within the pressure abutment of the upper seam. Failure of 3200 pillars within the lower seam occurred within a time span of 2 to 3 seconds, resulting in up to 1 m of surface subsidence.

The ground subsidence area was described as "rather sharply bounded by known or inferred fault or shear zones, and pillars on the other side of these faults remained intact" (12). Damage to structures straddling the shear zone was extensive (Figure 8). These faults and shear zones apparently weakened the bridging Buntsandstein sandstone, about 200 meters above the mining level. Injection of wastewater into this and adjacent dolomite strata may have contributed to weakening of these features.

Figure 8. Damage to structure in Volkershausen directly above the shear zone (27).

* Descriptions of seismic event(s) vary. Garrett (12) describes the collapse as occurring in "three major shocks over a 5 second period of 4.4, 5.1 and 5.5." Bennet and McLaughling (31) described the seismic event as having a seismic magnitude of 5.4, representing 0.5% of the potential energy lost through subsidence. They also found the seismic characteristics of this event to be quite similar to that produced by the 1995 Solvay event.

<u>**Discussion**</u>. The value of a set of case studies like these lies in their ability, through a composite view, to more fully reveal the mechanisms at work. The most important observation is that there is a strong correlation between dynamic collapse events and the presence of relatively strong, brittle bridging strata above the bed being mined. Other characteristics of these events, including

collapse mode, seismic energy and the interplay of creep, energy and dynamic failure are explored further.

Collapse Mode

Two collapse mechanisms have been evoked in explanations of these cases. The first is a cascading or chain reaction failure of mine pillars. The second is sudden vertical shear failure of strong, brittle overburden strata.

Whether or not collapse is controlled by chain-reaction failure of pillars can be addressed most directly by examining cases where there are no pillars. For evaporite mining, such cases are conveniently created by solution mining. Daupley et al. (4) explored collapse mode for various overburden (Figure 9). They found that generally soft strata were associated with slow development of a subsidence trough while the presence of stronger strata was associated with sudden subsidence events. Failure of strong strata was found to occur on near-vertical shears.

The vertical shear mechanism was briefly explored in a two-dimensional numerical model (Figure 10). The numerical model used a strain softening constitutive law for the strong, brittle stratum. Softer, weaker overlying strata bend rather than fracture, leaving a more gradual slope. The vertical shear failure mechanism has also been explored in physical models (Figure 11).

Board et al. (23) used the ground reaction curve concept to explore this mode of strata collapse. They modeled the panel as supported by a pressure that was slowly reduced from in situ stress levels to pressures equivalent to pillar support with increasing extraction ratios. At some point, stable redistribution of stress to barrier pillars is interrupted by sudden failure of bridging strata (Figure 12). Board et al argue that panel pillar design must preserve the integrity of bridging overburden and avoid the unstable ground reaction curve associated with its failure.

Seismic Energy

The seismic event created by sudden collapse carries information on the source mechanism of the event. The most comprehensive seismic analyses in this review were conducted for the Solvay case and include two important findings. First, the first motion of the ground recorded by seismographs is downward, indicating a collapse or implosion often described as a horizontal crack closure motion. Second, the potential energy released through subsidence is sufficient to produce the observed seismic event.

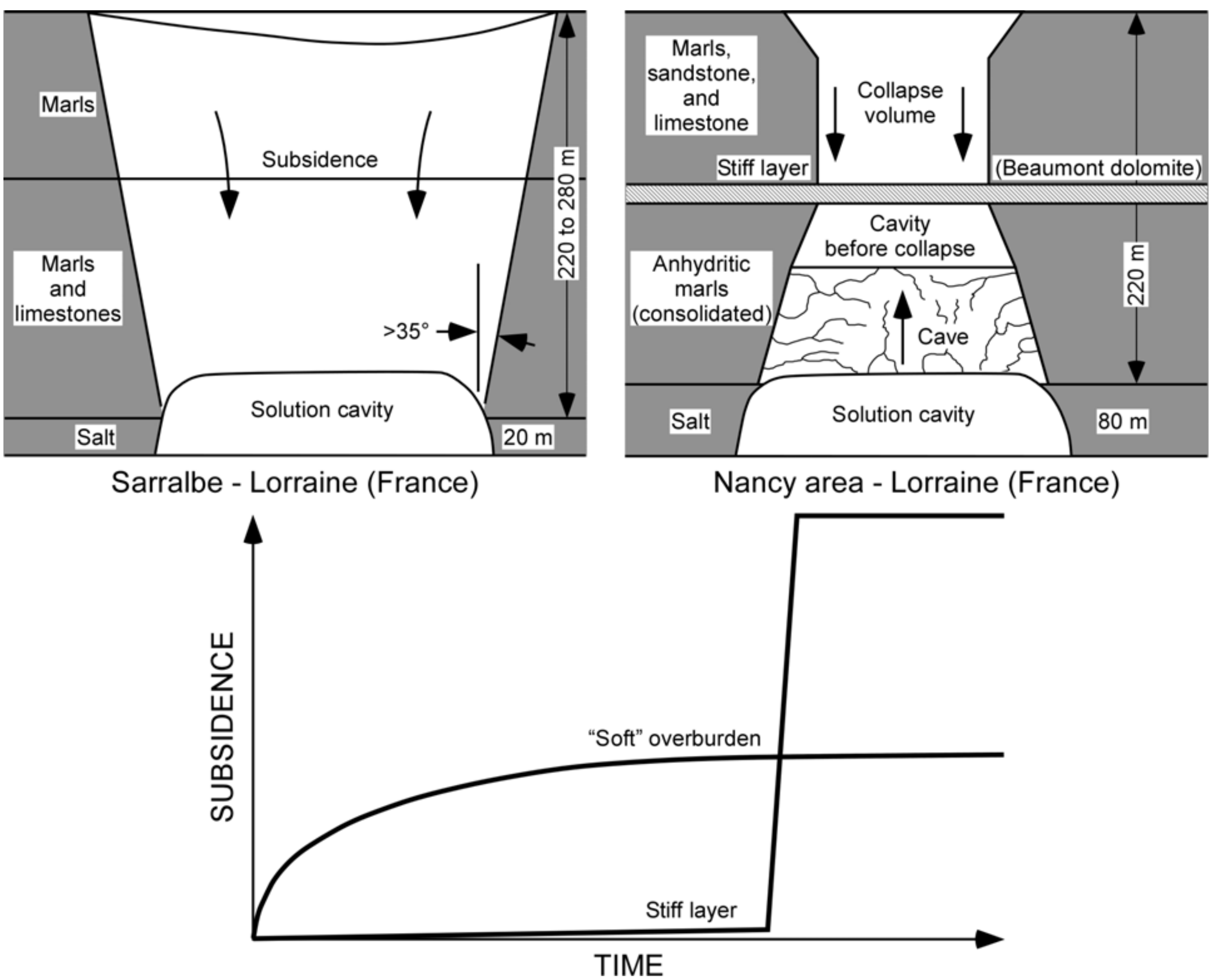

Figure 9. Relationship between strata movements over time and overburden stratigraphy above solution-mined salt seams. Sudden subsidence caused by caving of stiff layer is often accompanied by a sizable seismic event. After Daupley et al. (4).

Figure 10. FLAC model showing development of vertical shears along the face of abutments and tensile failure in the center of the roof beam.

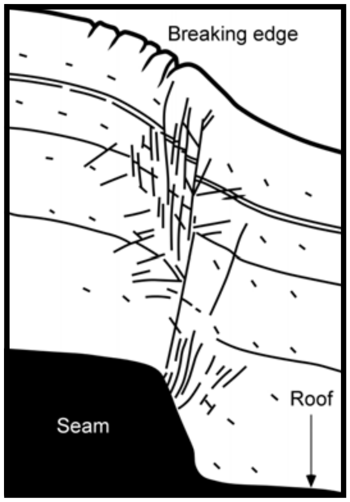

Figure 11. Physical model of vertical shear failure (32).

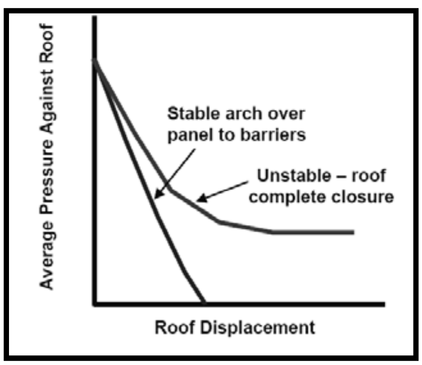

Figure 12. Stable and unstable ground reaction curves for strata bridging a pillar mining panel. The unstable curve reflects failure of bridging overburden strata (23).

The consistency of potential energy changes and seismic energy release was examined. Estimates of the relative change in potential energy, based on the volume and displacement of collapsing overburden, were made for several large collapses and compared to reported seismic energy. The linearity of these results (Figure 13), shows that seismic energy release scales consistently with changes in potential energy loss. This consistency suggests a similar consistency in failure mechanism.

The crack closure (implosional) character of seismic records from these events does not provide good insight into whether the event was triggered by failure of a pillar or strata. The short duration and wide extent of these events suggest that strata failure occurred early, as either the initiator or immediately after the initiating failure, providing a shock load that rapidly drove failure throughout the collapse area. In some cases, as in the Retsof collapse, weakening defects in bridging strata were discovered during post-failure analyses. The importance of such defects highlights the critical role of the strata bridge. That is, these defects violate a fundamental assumption in the design of yield pillar panels; that overlying strata can bridge the panel, shifting all but immediate overburden loading to adjacent barrier pillars.

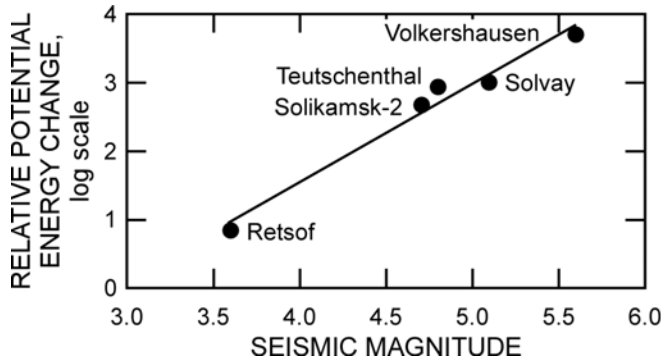

Figure 13. Seismic magnitude, a logarithmic measure, plotted against relative change in potential energy of the subsiding block.

Creep, Energy and Dynamic Failure

The energy approach begins with the fact that underground mining, by creating the opportunity for overlying strata to fall, creates substantial amounts of potential energy. This energy may be contained in perpetuity if sufficient support is provided. Otherwise, it must be expended either in gradual closure of mined spaces or in a sudden collapse. The magnitude of available energy can be immense, as demonstrated by the magnitude of seismic energy released during collapse events. Management of this energy and its release is essential to prevention of violent mine failure.

Highly stressed evaporite minerals typically deform as a viscoplastic material, gradually dissipating potential energy. Creep deformation sheds load from highly stressed pillars and abutments towards other portions of the rock mass. This behavior is advantageous for yield pillar panels, realizing good initial support pressure with high extraction ratios, and has been applied widely in evaporite mining. However, the support capacity of evaporite pillars, particularly yield pillars, will degrade with time, particularly in the presence of groundwater. Since pillars are the main difference between the work of Daupley et al., (4) on solution mining and conventional underground mining, degradation of yield pillars will serve to increase their similarities over time.

Most evaporites also accumulate damage during creep and will eventually lose cohesion and fail. Moreover, creep may shift stress to and through structures (faults, strong sandstone beds, etc.) that are inherently brittle. Differential deformation between the evaporite deposit and overlying strata can also form voids, which may fill with pressurized gas and/or fluid. Failure of brittle elements, particular failures that compromise bridging of overburden stress, can exert a sudden dynamic load on pillars, resulting in their sudden failure.

In some cases, creep contributes to the heightened level of energy release by providing a temporary stability, albeit one that is inherently unsustainable. Temporary stability provides an opportunity to extract more resource, increasing the magnitude of the eventual failure. Properly managed, such a process can provide high extraction and completion of mining before collapse. However, projecting when collapse will become imminent is problematic and subject to many geologic uncertainties. Even if collapse is delayed until after the mine is abandoned, there may still be consequences for surface structures and ground water. Improperly managed, the consequences can be substantial, as these case studies have shown. Total extraction in a longwall configuration will also induce collapse, but the lack of pillar support will cause collapse to start earlier and occur in smaller increments.

The relationship between extraction ratio and the potential violence of failure is illustrated conceptually in Figure 14. The "first cave" line represents the extent of mining before first cave. Overburden strata, depth, etc. will define this curve for a given site. Support (pillars, etc.) can extend this span, pushing the mine along this curve to the right. However, if these supports fail to provide indefinite support, the eventual failure will be more violent. Subsequent caves extend the cave zone as cantilevering strata fail. This caving is represented by horizontal lines extending to the right from the first cave line whose intensity is, once again, dependent on local overburden, support and stress conditions. Provision of temporary support with creeping pillars, etc. can extend the cantilever distance and increase the violence of eventual failure of this subsequent caving as well. In other words, the intensity of caving can be reduced by early and sustained caving.

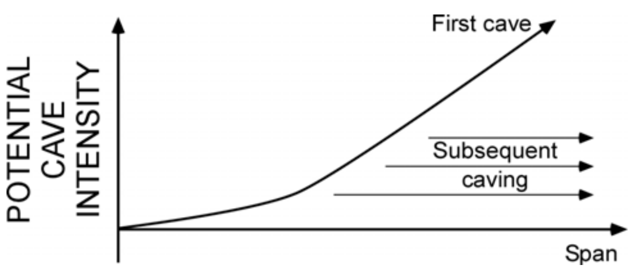

Figure 14. The intensity of energy release during first cave increases as a function of span. Early and sustained caving limits the intensity of cave events.

Strong overburden also complicates longwall mining, interfering with the steady progression of caving. In such cases, caving may need to be induced artificially or, alternatively, a bridge of strata maintained over the panel. Permanent maintenance of bridging strata requires a substantial safety factor, purchased by a substantial loss of resource to supporting barrier pillars and a thorough geomechanical exploration of the overburden bridge. Backfilling and/or brine flooding may enhance long-term stability (33).

CONCLUSIONS

Undermining of strata creates a significant reservoir of potential energy that may be supported indefinitely, subsided gradually over time or released in sudden collapse. Maintaining the safety of miners depends on properly anticipating whether a sudden collapse is possible – and if so, proper planning of mine operations.

The cases reviewed here show a clear association between violent collapse and strong overburden strata. In these cases, failure of bridging overburden creates a shock load that drives rapid failure of pillars, all within a very few seconds. These cases also show that collapse events can occur where the mined horizon is not brittle and pillars are properly sized. Brittle overburden is sufficient. Yield pillars in ductile seams may delay collapse, allowing further mining that increases the potential energy released in the eventual collapse.

This conclusion concurs with a similar association recently reported for pillarless solution mines and a recently published analysis of the Solvay collapse. The conclusion applies to any mine operating under sedimentary overburden with strong strata.

This conclusion is inconsistent with the cascading pillar collapse mechanism that has been proposed for some of these cases. The distinction between overburden and cascading pillar failure is an important one. The potential for cascading pillar failure is evaluated and controlled by application of pillar design tools. Strata failure, on the other hand, is addressed by panel design, especially analysis of bridging strata spans and loads. The design can either protect these spans or, in caving methods, assure early and sustained failure. In addition, the overburden failure mechanism identified depends primarily on the nature of overburden strata, not the commodity being mined.

Recognition of the presence of strong strata and proper consideration of its potential for failure is essential to proper management of the potential energy reservoir created by mining. Such recognition is important since many contemporary design tools, especially those based on empiricism and boundary element formulations, address only the pillar run mechanism.

ACKNOWLEDGEMENTS

Ron Hughes, General Manager of the Solvay Mine, and Dr. Mark Board, Itasca Consulting Group are acknowledged for many helpful discussions in developing the focus of this paper. Assistance provided by Dr. Mark Larson (NIOSH), who contributed the collapse model, is also gratefully acknowledged. The views expressed herein are entirely those of the authors and do not necessarily reflect those of NIOSH or those who have provided assistance.

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