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Induced Seismicity in Mines in Canada—An Overview

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Abstract—Monitoring of mine-induced seismicity in Canada has improved with the expansion of regional seismograph networks into areas of active mining. However, the severity, and in some cases the frequency, of mine-induced tremors has increased as mining extends to greater depths and at accelerated rates of extraction. Because of the complex design and large areal extent of many mines (potash, coal and metalliferous), the most feasible and practical way to monitor these tremors at the present time is to deploy a network of seismometers in and on the surface above mines experiencing microearthquake activity. A few of these mines already have a network of seismometers deployed around them and plans are under way to deploy seismograph networks around other mines that have experienced some rather severe tremors in recent times. Six possible mechanisms for mine-induced tremors are described and the associated *P*- and *S*-wave radiation patterns presented. A comparison of actual seismic radiation patterns with theoretical predictions is a quick way to diagnose the potential source mechanisms. In addition, recognizing the pattern of microearthquake activity preceding larger tremors can be used to mitigate the potential effects of severe tremors.

Key words: Elastic effects, inelastic after-effects, monitor seismicity, mitigate hazards.

Introduction

Initial attempts in Canada to analyse mining-related seismic activity by conventional seismographic networks were hampered because of an inadequate distribution of seismographs near mines. This problem was compounded further because many mines are in seismically active regions (cf. MILNE and BERRY 1976). Figure 1 shows mine locations on a seismicity map of Canada and Figure 2a, the location and opening date of standard and regional seismograph stations. The list of historical mine-induced tremors in Canadian earthquake catalogues from 1961 are more indicative of the threshold detection capability of the existing networks than the number of mine-induced tremors. The smallest mine-induced tremor listed in 1961 is magnitude (M_L) 4½ and in 1986, magnitude 1½. The lack of a sufficient

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number of high-quality, close-in records of tremors originating near a mine also precluded a detailed analysis of the seismic source mechanism. Information on the source properties of various types of mine tremors is sketchy and incomplete as a result.

Since the mid-1970's, the deployment and expansion of regional seismograph stations, in particular the Eastern Canada Telemetered Network (ECTN; see Figure 2b), has lowered greatly the detection threshold and increased the location capability of mine-induced tremors. In addition, seismic arrays designed specifically to monitor mine-induced tremors have also been deployed; at Science North (see Figure 2b) an autonomous local processor termed the Sudbury Local Telemetered Network (SLTN) has been deployed (starting in 1984) to monitor local mine-induced seismic tremors (e.g., see GENDZWILL *et al.*, 1982; HEDLEY and WETMILLER, 1985).

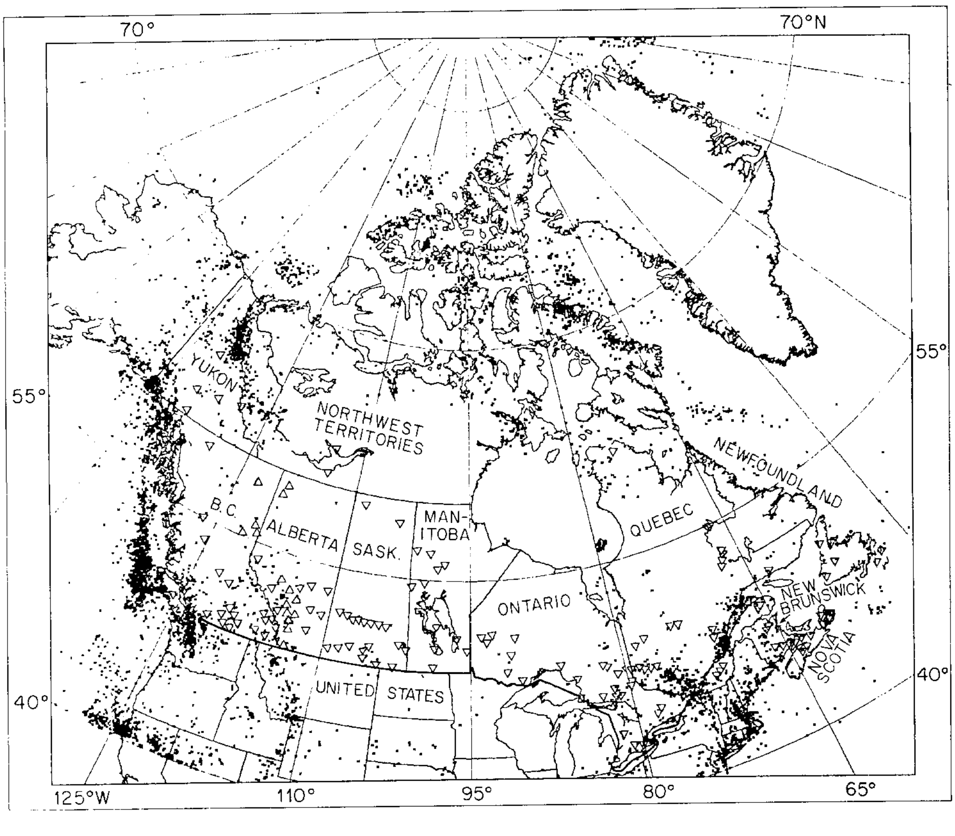


Figure 1
Seismicity (small dots) of Canada and periphery for magnitude (m_{bLg}) 3 and greater to 1986 and mine locations (open triangles). Inverted triangles represent mines in operation during 1979 and triangles, natural gas processing plants (from NATIONAL ATLAS OF CANADA, 1985).

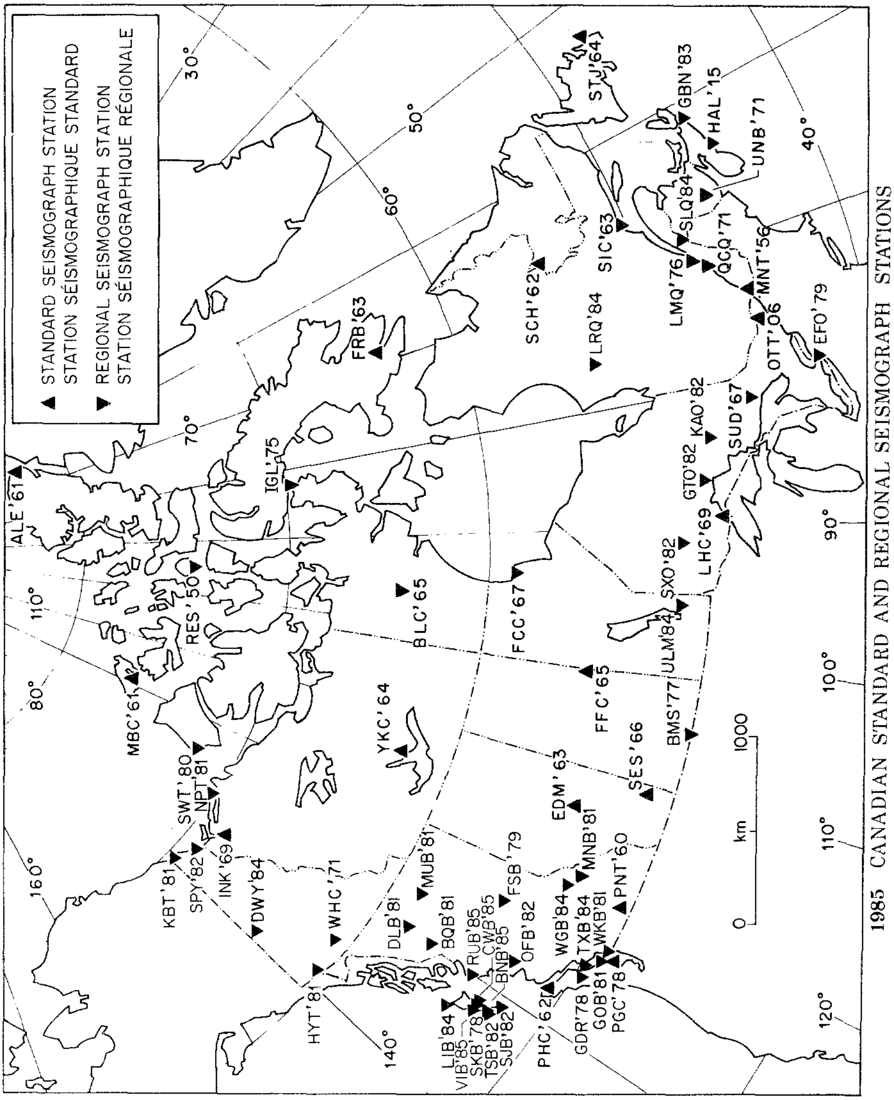
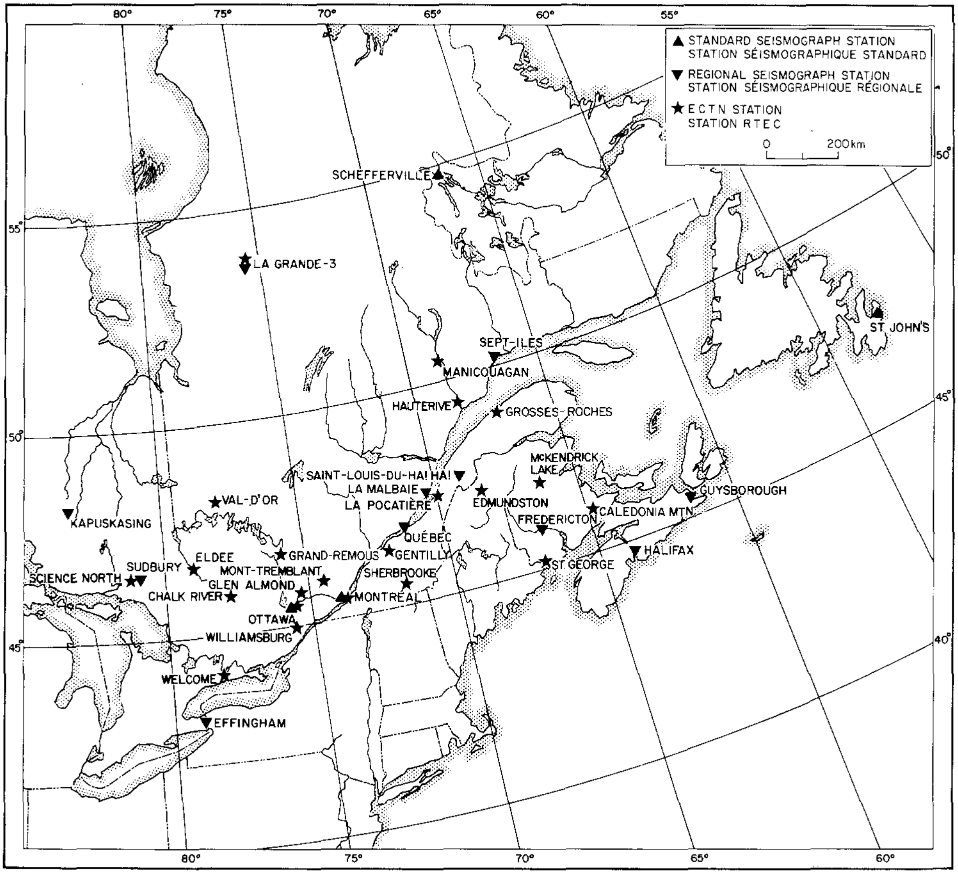


Figure 2a

Standard and regional seismograph stations in Canada in 1985. Number attached to station denotes year in which recording started (from MUNRO *et al.*, 1988); Sudbury '67 was closed in 1986.



EASTERN CANADA TELEMETERED NETWORK-1985
and other stations

Figure 2b
Eastern Canada Telemetered Network (ECTN) and other stations in 1985. Initial stations (four) deployed in 1974; Val d'Or closed in 1986. At Science North, autonomous local processor referred to as Sudbury Local Telemetered Network (SLTN) consists of three stations monitoring induced seismicity from 13 mines in Sudbury Basin (from MUNRO *et al.*, 1988).

Mine-induced seismic events occur in many different modes, such as fault slip (earthquake), rockburst (violent ejection of rock into mine opening), pillar burst, bump (sudden slip of a quasi-viscous seam such as coal at great depth or a tremor of unknown origin) and outburst (sudden violent ejection of coal into mine opening). In addition, mine-induced faulting can occur near the stope face being mined (COOK, 1963; MCGARR, 1971), at places in the mine where volume closure is occurring at a high rate, and either above or below the mine along weakened faults (e.g., see HINZEN, 1982; SMITH *et al.*, 1974).

The frequency and severity of mine-induced tremors of various types tend to increase with increasing rate of volume extraction and depth of mining (e.g., see

JAEGER and COOK, 1971). The reason is, potential energy is added to the mine surroundings that is equal to the product of the weight of the excavated rock and the depth of the excavation. No more than one half of this energy can be stored as strain energy and the rest must be released by volume closure (COOK, 1963; JAEGER and COOK, 1971). However, since mine-induced tremors in different mines such as the metalliferous mines in Ontario and Quebec occur at different depths, the geology and response of the rock under load, as well as contemporary tectonic stresses, must also be important factors (HERGET, 1980). Thus, because of increasing mining depth in conjunction with increasing rate of volume extraction and ongoing volume closure due to inelastic after-effects in mined-out areas, older mines are more likely to experience the more severe mine-induced tremors. Consequently, a proper understanding of the cause-effect relation between mining and related strain energy release and induced seismicity has become imperative.

Since our focus is on seismic monitoring and analysis of seismic waveforms, different ways in which tremors can occur around underground mines (especially deep mines) and associated seismic (P and S) radiation patterns in a homogeneous medium are described and corresponding analytical expressions presented. The next part of this overview deals with our current understanding of the relation between mining operations and induced seismicity in three types of mines in Canada: potash, coal and metalliferous mines. For each case a particular mine, for which associated induced mine tremors have been analysed, is discussed. The mines selected are a potash mine in south-central Saskatchewan, a coal mine in western Nova Scotia and a group of metalliferous mines in northern Ontario.

The last section deals with plans to monitor possible precursory signals to large, mine-induced seismic tremors. The ultimate goal is to mitigate hazards associated with potentially dangerous mine-induced tremors.

2. *Source Mechanisms of Mine-Induced Tremors*

Six conceivable models by which induced seismicity may be capable of occurring in underground mines in Canada are shown in Figure 3 and the corresponding (normalized) seismic radiation patterns in Figure 4. A cavity collapse, as shown schematically in Figure 3a, represents either a rockburst in a mine ceiling that extrudes violently a large mass of rock downwards, or a large mass of rock loosened by mining and possibly falling under the pull of gravity (rockfall); the rockfall generates far less seismic energy than the rockburst. The corresponding (single force) radiation pattern for the far-field seismic body waves that propagate upwards is shown in Figure 4a. Pillar burst, as shown in Figure 3b, is due to a combination of convergent forces related to stope face advancement (elastic) and time-dependent after-effects (inelastic process). The corresponding (vertical dipole) radiation pattern as shown in Figure 4b, has opposite sense of first motion (i.e., an implosion)

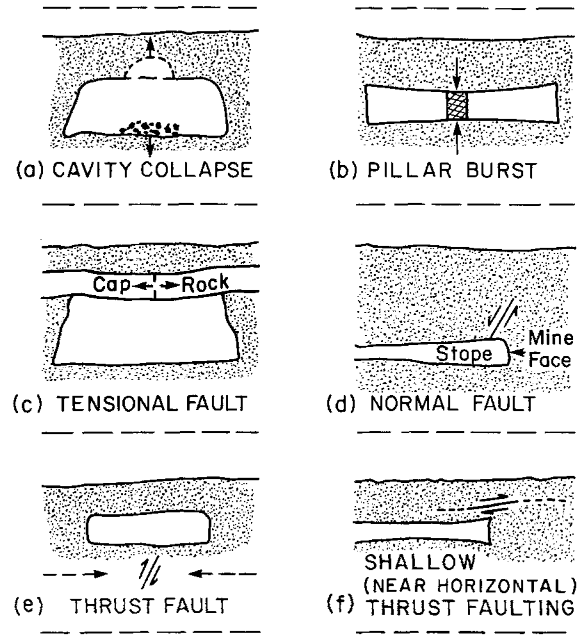


Figure 3
Schematic diagram of six possible ways in which mine-induced tremors can occur. Solid arrows indicate mine-induced force direction on host rock during induced seismic event. Dashed arrows in part (e) denote ambient tectonic stress (after HORNER and HASEGAWA, 1978).

to that for a single force. Tensile failure of competent cap rock above a mine, as shown in Figure 3c could occur near the middle of a wide excavation where roof subsidence is greatest (see HORNER and HASEGAWA, 1978). However, the most common types of fracturing and faulting are edge dislocations and comminuted faults, which occur near the stope face and are due to a combination of blasting and volume closure (MCGARR, 1971; COOK, 1963). Comminuted faults occur, for the most part, in intact rock and are generally of the normal fault type, as shown in Figure 3d. HEDLEY and WETMILLER (1985) refer to this type as "strain energy burst". WETMILLER and CAJKA (1988) show a normal fault composite mechanism for five large tremors in Ontario mines in 1984. Thrust faulting below a mine, as shown in Figure 3e, and also above a mine could occur for the case where the maximum principal stress is horizontal and the induced stress (decrease in vertical stress) is large enough either to initiate slip in the intact medium close to the floor, or to trigger faulting along a preweakened fault at greater depths (e.g., SMITH et al., 1974; WONG, 1985). Both normal and thrust (reverse) faults are represented by a pure vertical, dip-slip fault in Figure 4d. Shallow, near-horizontal, thrust faulting above a mine roof, as shown in Figure 3f, could occur between near-horizontal layers that become "unclamped" or experience shearing motion because of flexure related to sagging in the mine roof. The corresponding radiation patterns can be derived readily from Figure 4d by a rotation of about 90°.

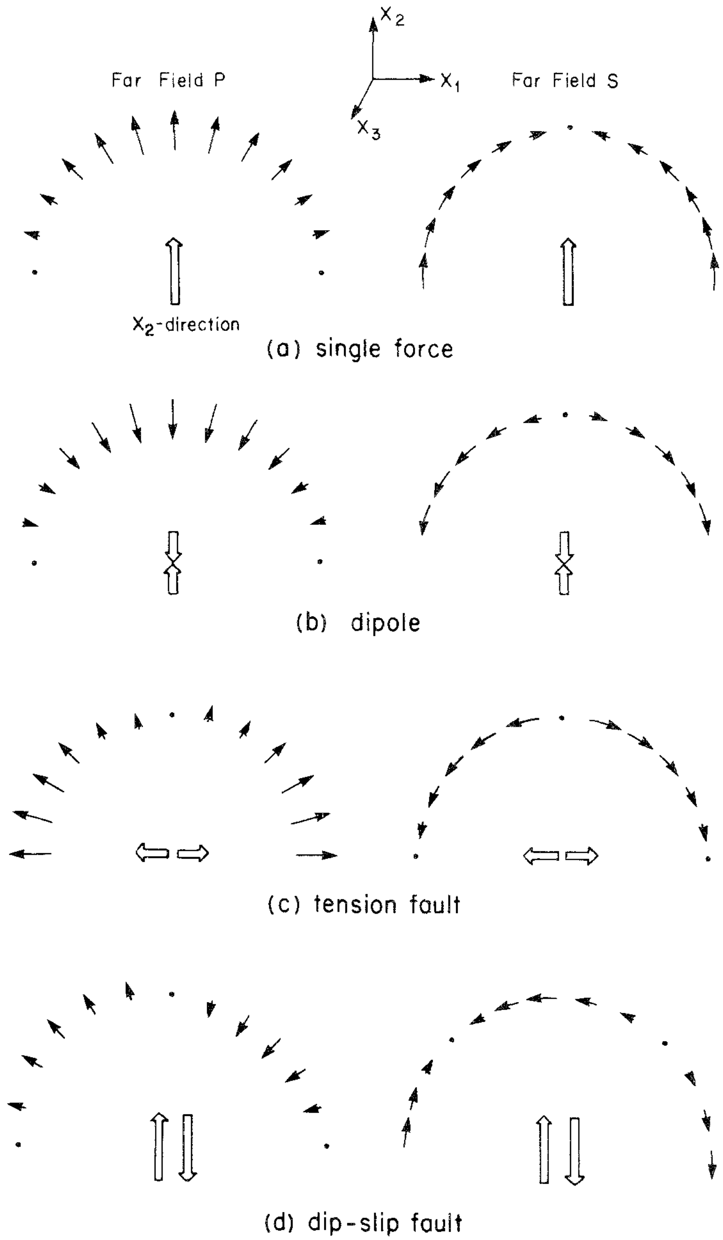


Figure 4

Normalized far-field P- and S-wave radiation pattern (solid arrows) in upper half of homogeneous half-space from four general types of point sources shown in Figure 3. With respect to coordinate system shown at top, all displacement profiles are in $x_1 - x_2$ (vertical) plane, i.e., $x_3 = 0$. With reference to Figure 3, vertical single force (open arrow) corresponds to cavity collapse, vertical dipole to pillar burst (implosion), horizontal pair of tensile forces to tensile failure of vertical fracture in $x_2 - x_3$ plane, and dip-slip faulting to either normal or thrust fault. Radiation pattern for near-horizontal thrust fault (see Figure 3f) is readily obtained from part (d) by 90° rotation and appropriate change in direction of arrows. Maximum solid arrow length in each part is normalized.

Analytical expressions for the far-field radiation pattern of P and S waves in a homogeneous half space are presented in the $x_1 - x_2$ (vertical) plane; that is $x_3 = 0$ (see Figure 4, top part). The displacement, $u_i(\bar{x}, t)$ the i-th component of displacement at the observer, is given by the following (see AKI and RICHARDS, 1980). For a cavity collapse (see Figures 3a and 4a),

$$u_i(\bar{x}, t) = \frac{1}{4\pi\rho V_p^2} \Upsilon_i \Upsilon_j \frac{1}{r} F_2\left(t - \frac{r}{V_p}\right) - \frac{1}{4\pi\rho V_s^2}\left(\Upsilon_i \Upsilon_j - \delta_{ij}\right)\frac{1}{r} F_2\left(t - \frac{r}{V_s}\right) \quad (1)$$

where the first term represents the contribution from the P wave and the second, from the S wave at the retarded time $\left(t - \frac{r}{V}\right)$, where t is time at source, r is distance to observer and V is velocity of wave (P or S), ρ is density, Υ is unit vector from source to observer, δ is the Kronecker delta function and F_2 a vertical force directed upwards, since the start of a cavity collapse imparts an upward impulse to the mine roof. For the present case (see Figure 4a), $j = 2$ and $i = 1, 2$.

For a pillar burst (see Figures 3b and 4b), the calculus operation $\Delta l_2 \frac{\partial}{\partial \varepsilon_2}$ is performed on eq. (1): thus

$$u_i(\bar{x}, t) = \frac{1}{4\pi\rho V_p^3} \frac{\Upsilon_i \Upsilon_j}{r} \dot{M}_{22}\left(t - \frac{r}{V_p}\right) - \frac{1}{4\pi\rho V_s^3} \frac{\Upsilon_i \Upsilon_j - \delta_{ij}}{r} \dot{M}_{22}\left(t - \frac{r}{V_s}\right) \quad (2)$$

where $\dot{M}_{22}$ is the time derivative of the limit of $(-F_2(\Delta l_2))$ as $\Delta l_2 \to 0$ and $(-F_2) \to \infty$ in such a way that the product, M_{22}, is finite. Δl_2 is the arm of the dipole in the x_2 direction and ε_2 is a spatial coordinate at the source in the x_2 direction also. In the present case M_{22} is a vertical dipole and is negative, as it simulates an implosion (see WESTBROOK *et al.*, 1980); for this case (see Figure 4b), $j = 2$ and $i = 1, 2$.

The radiation pattern for a vertical tensile fault (see Figures 3c and 4c) can be derived from eq. (2) by interchanging subscripts i and j and replacing $\dot{M}_{22}$, which is negative, with $\dot{M}_{11}$, which is positive. Thus

$$u_j(\bar{x}, t) = \frac{1}{4\pi\rho V_p^3} \frac{\Upsilon_j \Upsilon_i}{r} \dot{M}_{11}\left(t - \frac{r}{V_p}\right) - \frac{1}{4\pi\rho V_s^3} \frac{\Upsilon_j \Upsilon_i - \delta_{ji}}{r} \dot{M}_{11}\left(t - \frac{r}{V_s}\right). \quad (3)$$

For this case $i = 1$ and $j = 1, 2$.

For vertical dip-slip faulting

$$u_i(\bar{x}, t) = \frac{2\Upsilon_i \Upsilon_p \Upsilon_q v_q}{4\pi\rho V_p^3} \frac{1}{r} \cdot \mu A \dot{\bar{u}}_p\left(t - \frac{r}{V_p}\right)$$
$$- \frac{2\Upsilon_i \Upsilon_p \Upsilon_q v_q - v_i \Upsilon_p - \delta_{ip} \Upsilon_q v_q}{4\pi\rho V_s^3} \frac{1}{r} \cdot \mu A \dot{\bar{u}}_p\left(t - \frac{r}{V_s}\right) \quad (4)$$

where the subscript i represents i-th component of displacement at observer ($i = 1, 2$), p is direction of slip (in vertical direction) at source, q is normal to slip plane and v_q is the component in the q direction of the unit vector normal to slip plane of area A, μ is shear modulus and $\dot{u}_p$ is particle slip velocity on fault (in vertical direction). This familiar double-couple is represented by a quadrafoliate pattern, of which the top half is shown in Figure 4d. Equation (4) is also applicable to thrust-fault motion on a near-horizontal plane: the slip vector and subscripts p and q must be modified to correspond to this particular case. The free-surface effect can readily be incorporated into the above expressions (e.g., see EWING *et al.* 1957). Anelastic attenuation is not significant at short epicentral distances.

Equations (1) to (4) represent the seismic radiation patterns for a point source, whereas in actual situations an extended source is usually encountered. Thus these expressions should be considered to represent first-order approximations to radiation patterns of actual mine-induced tremors. However, these expressions should be indicative of the general trends.

3. *Induced Tremors in Potash Mines*

The areal distribution of potash in Saskatchewan is shown in Figure 5. Saskatchewan potash deposits are of Middle Devonian age and are situated in a thick sequence of halite and anhydrite known as the Prairie Evaporite. This formation, more than 200 m thick in places, lies at depths varying from 400 m to approximately 3000 m but all the underground mines operate at about 1000 m depth. The first commercial production of potash in this region was attempted in 1951 using a solution method, which was unsuccessful. Subsequent techniques used are the room-and-pillar, stress-relief and solution mining. Mining on a commercial scale started in 1962, and in 1973 there were ten potash mines in operation; the capacity in short tons (1 short ton = 907 kgm) per year was 13.7×10^6 for KCl (sylvite) and 8.3×10^6 for K_2O (potassium oxide) (POTASH IN SASKATCHEWAN, 1973).

Southern Saskatchewan is a region of low-level seismicity. Ten natural earthquakes have been located instrumentally since 1968 with the largest a magnitude (m_{bLg}) 3.7. However, a magnitude $5\frac{1}{2}$ (M_L from intensity data) was felt in 1909. Figure 6 shows both natural and mine-induced seismicity to end of 1985.

Since 1976, seismic tremors associated with potash mining have occurred more frequently than natural earthquakes. To the end of 1985 there have been 21 events with magnitude (m_{bLg}) in the range 2.3 to 3.6. Four of the ten mines in the province have generated seismic tremors large enough to be felt on the surface, namely the Cory (C) mine of Potash Corporation of Saskatchewan that is located 10 km west of Saskatoon, the Central Canada Potash mine of Noranda situated 60 km east of Saskatoon, and the K-1 and K-2 mines of International Minerals and Chemical Corp. (I.M.C.) located about 400 km south-east of Saskatoon. Isoseismal (MMI) maps of four Cory Mine events are shown on Figure 7; the centres of the isoseismal contours are located near the periphery of the mine. For all of these events, there

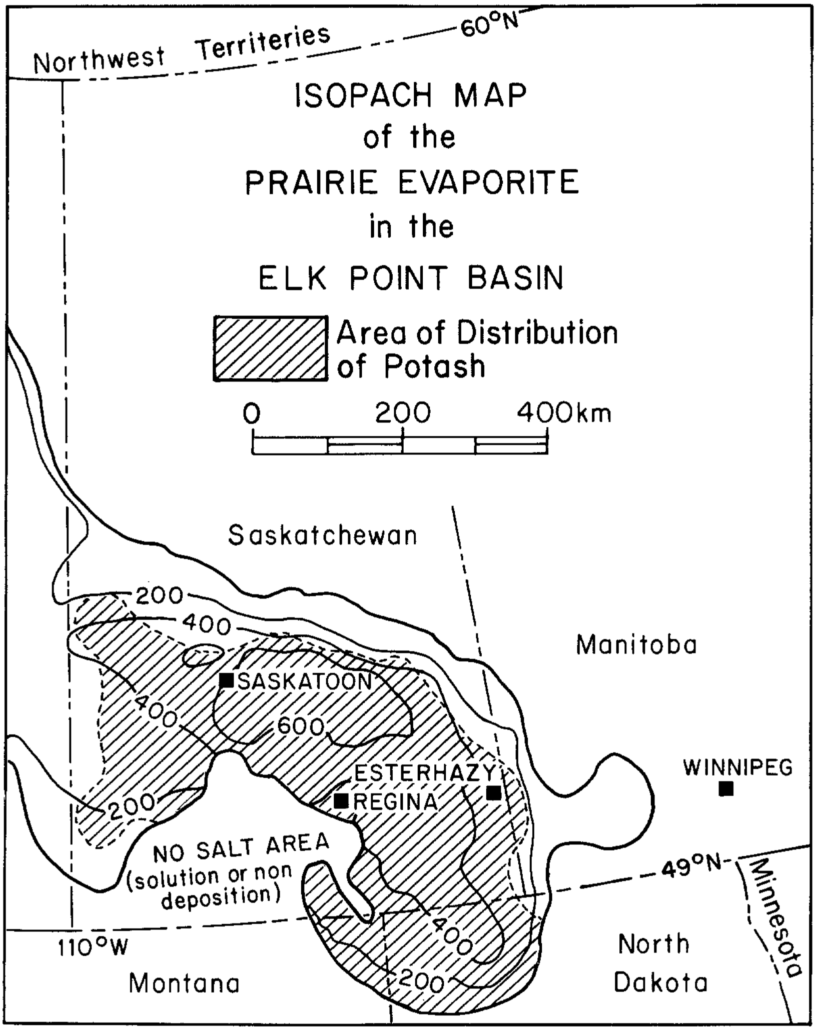


Figure 5
Area of distribution of potash (shaded area) in Saskatchewan (after HOLTER, 1969).

was no immediate damage observed in the mines. Some of the events were accompanied by noise and movement of air in the mine and some caused loose rock to fall from the roof. However, there has been no report of rockburst damage. There is a possibility that water inflow at two mines may have started some time after significant earthquakes occurred elsewhere. It is not known if the seismic waves from these events contributed directly to the water inflow or if both phenomena are different manifestations of the concomitant subsidence and deformation over the mine.

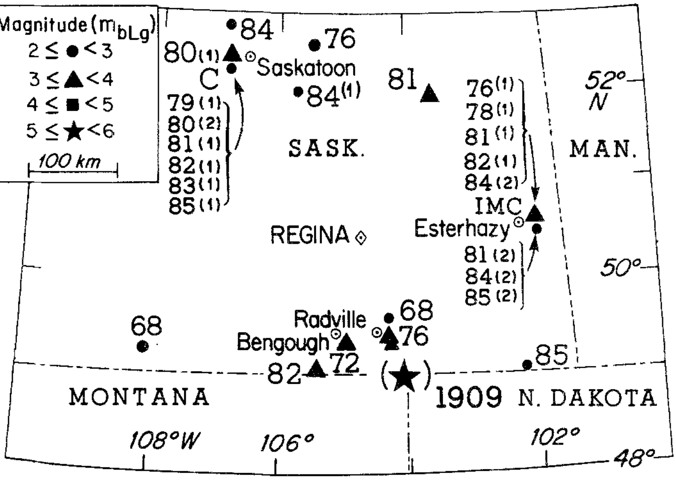


Figure 6
Known seismicity in southern Saskatchewan to end of 1985. Large number indicates year of occurrence and smaller number in brackets, corresponding number of detected tremors, *C* stands for Cory mine of Potash Corporation of Saskatchewan and IMC for International Minerals and Chemical Corporation. Mine-induced tremors are those with a number in brackets (after GENDZWILL *et al.*, 1982).

The failure mechanism of potash mine-induced tremors seems to be quite different from the mechanisms observed in many hard rock mines because no seismically induced surface faulting or rockburst has ever been observed in a potash mine. The failure is thought to be confined to the competent limestones some 40 m above the mine and caused by subsidence.

The general geology in the potash district of southern Saskatchewan includes a basal sandstone lying on Precambrian rocks. About 500 m of lower Paleozoic carbonates lie above the sandstone. Above the lower Paleozoic carbonates is the Prairie Evaporite, a bedded salt formation up to 200 m thick, underlying most of southern Saskatchewan. Potash ore (mainly sylvite) is found 15 to 40 m below the top of the Prairie Evaporite and is essentially a thin horizontal bed, 2.5 to 4 m thick, with few interruptions. Another 400 m of Paleozoic carbonate overlies the Prairie Evaporite. Above this layer is the Dawson Bay limestone, which is about 40 m thick and generally strong and dense. Over this layer there is about 500 m of Cretaceous sands and shales with glacial deposits at the top.

Potash mines operate in the depth range from 950 to 1000 m. Mining is carried out with continuous mining machines. Operation of the mines is possible only with careful rock mechanics design because potash ore and the host rock salt tend to be weak rocks that deform rapidly under mine-induced stress. Rooms are cut in planned sequence and widths so as to transfer, as much as possible, the overburden load to support pillars, thereby relieving much of the stress on the working areas.

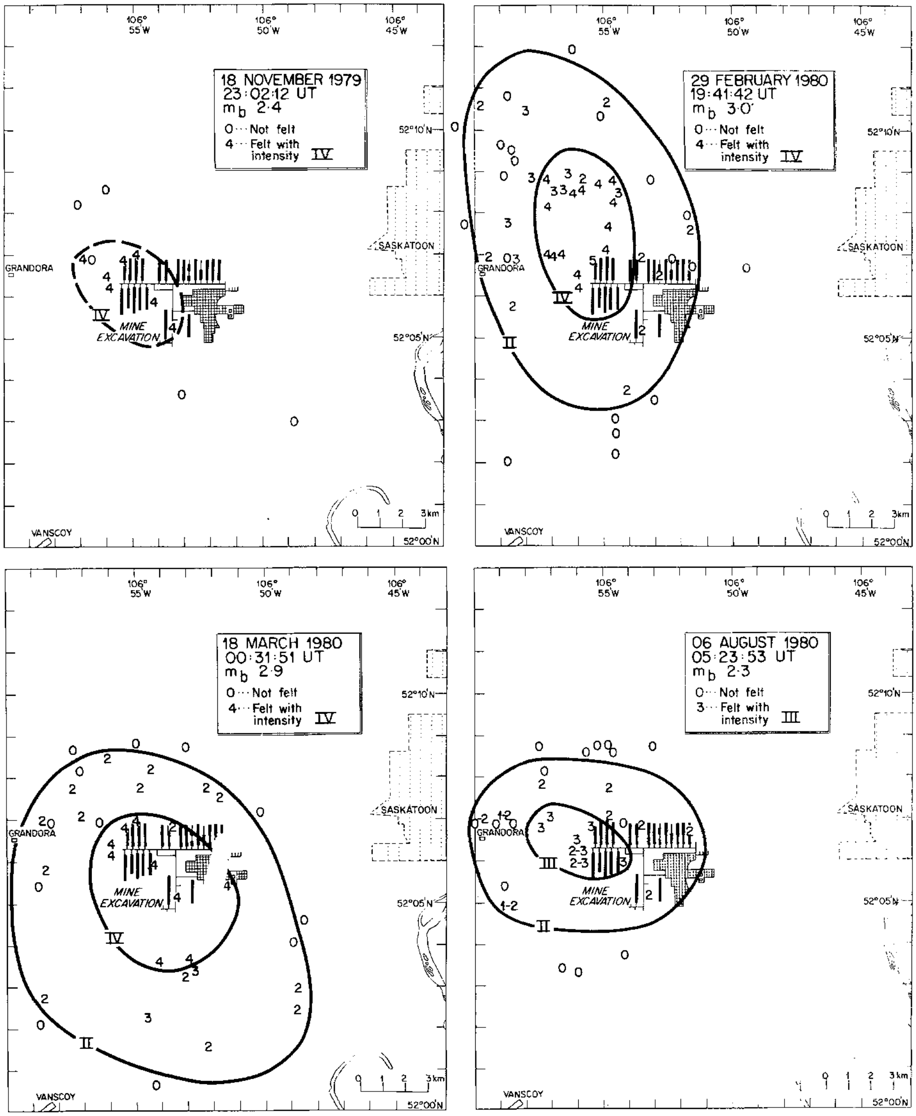


Figure 7
Modified Mercalli isoseismal maps of four earthquakes superimposed on plan view of Cory Potash Mine (from GENDZWILL *et al.*, 1982).

Consequently access roads and haulageways are protected from excessive stress and maintained as long as is necessary.

Deformation of mined rooms begins as soon as the room is excavated. Volume closure rates depend on the age and width of each room and the pattern of nearby rooms. Initial closure rates may be as high as several centimetres per day but soon decrease to fractions of a millimetre per day. Most of the deformation takes place by plastic flow of the salt but cracks and bed separations form near the openings. Flow of salt above the mine moderates the flexing of the overlying Dawson Bay limestone as the subsidence migrates upwards. During active mining, subsidence at the base of the Dawson Bay limestone may amount to about 10 cm per year (MRAZ and GENDZWILL, 1986). Total subsidence at the surface may exceed 50 cm over large mined-out areas.

Salt is generally too weak to store enough strain energy to generate significant seismic events, but in freshly mined openings a crackling sound can be heard as exposed salt crystals adjust to the changing stress field. In older openings, audio-frequency pops can sometimes be heard via the amplified output of accelerometers bolted to the rock. These audible noises have very low energy.

In contrast to the compressional wave velocity of salt, which is about 4400 m/s, the compressional wave velocity of the Dawson Bay limestone is typically 5500 to 5800 m/s. These limestone velocities suggest that the dynamic elastic moduli and strength of the limestones could be comparable to those of granites. Laboratory tests on samples have verified this inference, showing that low porosity Dawson Bay limestone has an unconfined compressive strength in the range of 150 to 200 MPa (GENDZWILL, 1983a). However, the strength is reduced by both porosity and the presence of bedded shale. Primary and secondary sedimentary structures in these rocks are strongly controlled by the horizontal layering. Thus, relatively thick layers of dense, strong limestone are separated by shale layers of zones of porosity that constitute horizontal planes of weakness.

The failure mechanism for Saskatchewan potash mine-induced tremors has been the subject of much debate. Fluid injection has been suggested in the past as a possible cause but there is no spatial relationship between earthquake epicentres and injection wells. Only one earthquake was centred on an injection well but there was also active mining at the time in the epicentral region. The pattern of microearthquakes indicates a possible correlation between roof subsidence and mine-induced tremors.

Differential subsidence between mined and unmined areas induces flexural strain in the limestone layers. The elastic energy is usually dissipated aseismically through small-scale fractures or viscous deformation of the limestone (PANDIT, 1983). However, if subsidence proceeds faster than small-scale processes can dissipate energy, there may be a sudden release of appreciable seismic energy (GENDZWILL, 1983b). Although subsidence involves vertical displacement and vertical shear couples, equilibrium of the rock demands that there be also an equal and opposite horizontal shear couple. As the principal planes of weakness in the bedded sedimentary rock are near-horizontal, failures most likely occur on highly flexed, near-horizontal planes (cf. KOVACH, 1974). The preferred near-horizontal thrust mechanism, as shown schematically in Figure 3f, is consistent with the absence of any observed vertical failure zones in the mines (GENDZWILL, 1983b; 1984).

The convergence rate for the Cory mine varies with time in a manner that suggests a power law dependence. Also, according to McGARR (1976), seismic moment is equal to the product of volumetric mine closure and the shear modulus. However, in viscous rocks, stress may be reduced by viscous deformation so that a seismic potential will gradually dissipate. For a Maxwell substance, viscosity follows a simple exponential behaviour. The resulting combination gives

$$M_0 = \sum_{t=0}^{300} \mu A b t^P e^{-\mu t/\eta}$$

where μ is the shear modulus of limestone (Pa), A is mining rate (m^2/day), b is related to volume closure and has the dimension of length (m), P is closure constant (0.51), t is time in days after mining starts (excavation lasts for 300 days in this example), η is viscosity of limestone (Pa.s) and M_0 is seismic moment (N.m).

This equation is illustrated in Figure 8 for a model of the Cory mine for four values of viscosity. The physical properties of limestone were determined on small samples of drill core that had been stored for a long time. Also, the closure rates refer to the inside surface of the mine and not to the base of the limestone. Therefore the graph should be considered as an approximation, indicative of general trends only. Nevertheless, there seem to be some noteworthy features. For a given set of physical properties, there is an upper limit to the induced seismic moment. For high viscosity rocks, seismic moment tends to increase even after

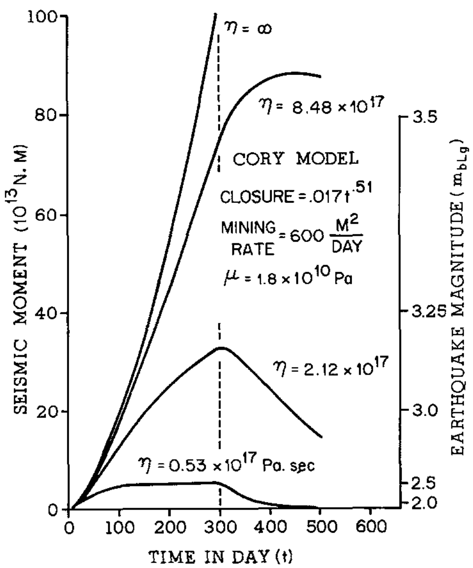


Figure 8
Theoretical seismic moment and earthquake magnitude (derived from empirical relation) versus time (t) for four values of viscosity (η) of limestone layering. Excavation commences at $t = 0$ and terminates at $t = 300$ days. Other systems are described in text (from GENDZWILL, 1983b).

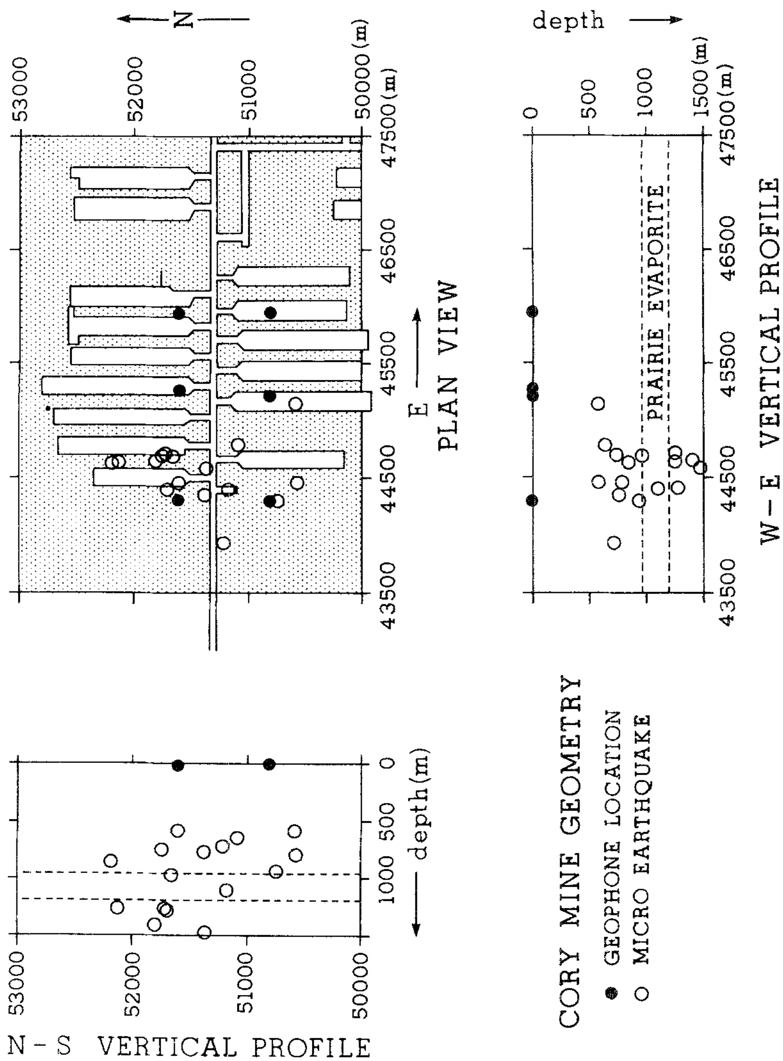


Figure 9

Microearthquake hypocentres for six-month period (July to December, 1983) and geophone locations, superimposed on plan view (upper right) and vertical profiles of part of Cory Potash Mine (from PRUGGER, 1985).

mining has stopped. For the case of finite viscosity, seismic moment gradually decreases. Whether or not an induced earthquake actually occurs depends on whether the induced stress exceeds the strength of the rock before the potential energy is converted to heat. Microearthquake monitoring systems have detected thousands of events in the mines, mostly in the -1 to 0 magnitude range (e.g., see GENDZWILL and PRUGGER, 1985). At all the mines monitored to date, the dominant frequency of the microearthquakes lies in the range of 20 to 30 Hz. The spectral amplitude of these microseisms falls off rapidly beyond the peak frequency. Microearthquakes in the potash mines tend to concentrate in areas of rapid subsidence but these areas are rather broad, as shown in Figure 9 (PRUGGER, 1985).

A collaborative venture (University of Saskatchewan, Geophysics Division of the Geological Survey of Canada and mining companies) on seismic monitoring in Saskatchewan is continuing (e.g., see PRUGGER and GENDZWILL, 1983). Verification of the proposed seismic source mechanism described above (see Figure 3f) is one of the objectives. The relation between seismicity and water inflow could be significant. Water inflow poses serious hazards to potash mining operations and, consequently, understanding both the natural and mine-induced flow patterns is important.

4. *Induced Tremors in Coal Mines*

The location of coal fields in Canada is shown in Figure 10. In western Canada the bulk of the coal beds have accumulated through successive deposition periods from the lower Cretaceous to the Tertiary; maximum depths are less than 800 m. In the east (Maritimes), coal deposits exhibit characteristics normally associated with the Carboniferous, and maximum depths exceed 1200 m.

Room-and-pillar and longwall systems are employed in underground mines, depending on local geology, topography, physiography, seam inclination and thickness of overlying sediments (see PARLEE, 1957; KONDA and KOCHHAR, 1986). Soft floors are prevalent, which under high horizontal compressive stresses tend to "heave". Roof conditions in some Canadian coal mines, particularly in the east and in the central plains, may not be good (see PARLEE, 1957). Below 300 m in the bituminous coal areas, mine tremors in the form of 'outbursts' of gas (see PATERSON, 1986) and coal, and "bumps" occur. The mountain areas of western Canada have a lengthy history of mine tremors. In the east, the Cumberland field of Nova Scotia has also experienced severe mine tremors.

In the Cumberland field, the Springhill No. 2 mine has the longest history of bumps; official records show bumps from 1916. Figure 11 shows a quasi-plan view (normal to incline of mine) of mined-out areas and bump locations at different levels of the seam workings. The 13,800 foot (4200 m) level corresponds to a depth close to 4350 ft (1327 m).

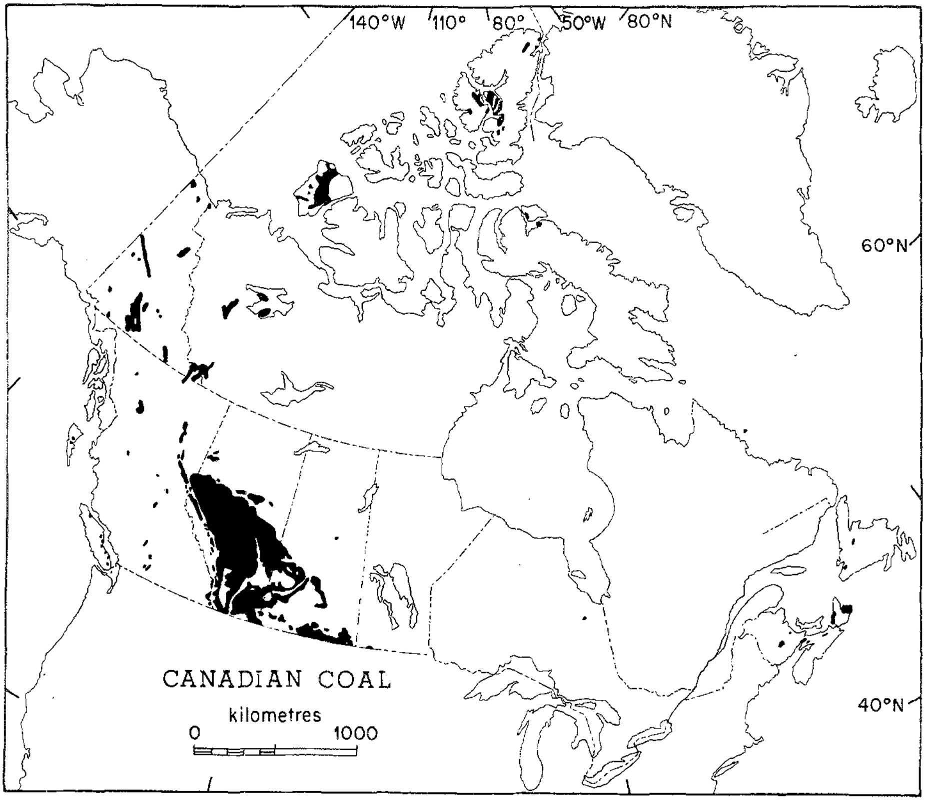


Figure 10
Coal areas (dark shading) in Canada (from NATIONAL ATLAS OF CANADA, 1982).

A histogram, from 1916 to 1958, of the annual occurrence of bumps in Springhill No. 2 mine, as detected by seismographs, indicates a peak between 1923 to 1930, a low level of activity from 1930 to 1950 and a gradual increase to 1957. Bumps were first experienced at a depth of about 2000 ft (600 m) below ground surface; above this depth the method of working was roon-and-pillar and below this level, retreating longwall. This switch in mining technique was made in 1932 to reduce the incidence of tremors near the mine face.

The final, disastrous outburst happened in October of 1958 in the cross-hatched area in Figure 11. This outburst resulted in 75 deaths and closure of the mine (see NOTLEY, 1984).

Underground records in the Springhill No. 2 mine from continuously recording convergence metres, which record sudden displacement events, contain information on 208 bumps. Since convergence is related to volume seismic moment, which in turn is related to seismic energy release and earthquake magnitude (e.g., see MCGARR, 1976; AKI and RICHARDS, 1980), these records are referred to as

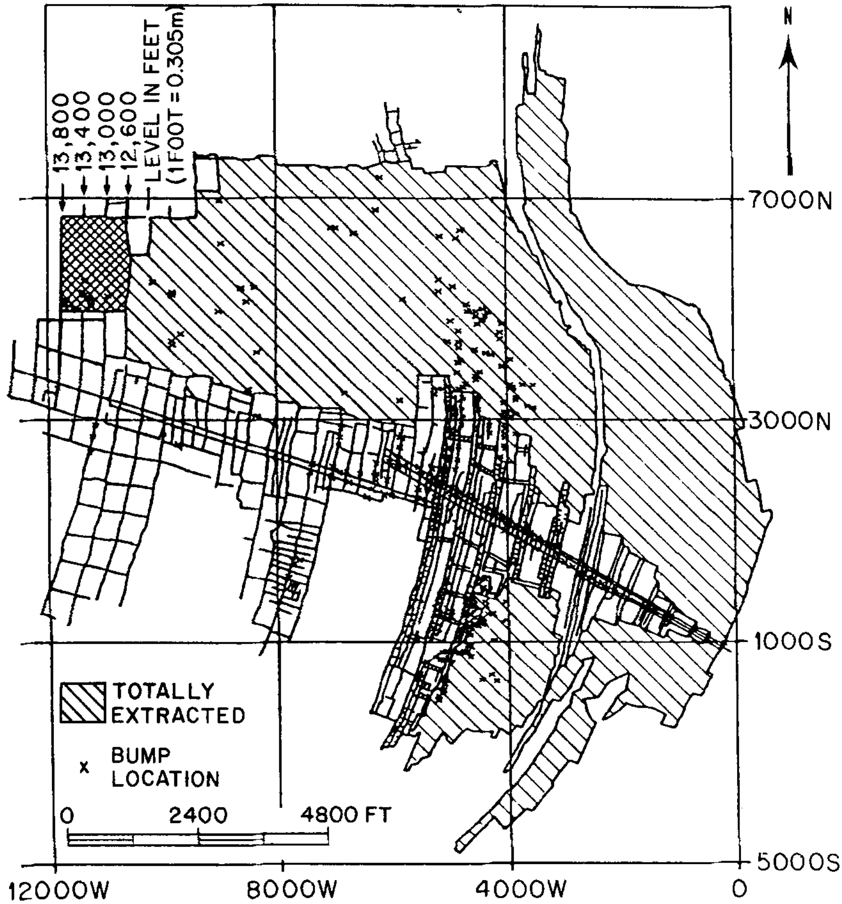


Figure 11
Quasi-plan view of seam workings of Springhill No. 2 seam in Cumberland coal basin of western Nova Scotia and induced seismicity (× 's). Cross-hatched area (upper left) is site of fatal 1958 bump (from Notley, 1984).

"quasi-seismic" events by Notley (1984). A histogram of these quasi-seismic events per month up to the large, destructive event in October, 1958 is shown in Figure 12. The generally smooth envelope to these histograms indicates an exponential trend of stress-strain release. The obvious breaks in the curve are due to temporary cessations in mining activity (e.g., July and December, 1957 and August, 1958). However, a reduction in microearthquake activity following a conspicuous buildup often precedes a large mine-induced tremor in a deep hardrock mine (see Brady, 1977).

With increase in depth, the corresponding increase in overburden pressure and, to a lesser extent temperature, causes the coal seam to change from a brittle to a

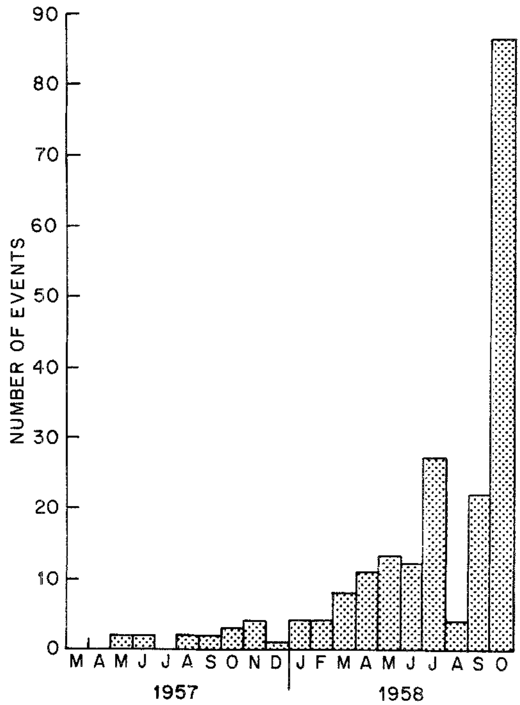


Figure 12
Histogram showing quasi-seismic events per month during coal mining of last three longwalls in Springhill No. 2 seam (cross-hatched area in Figure 11) (from NOTLEY, 1984).

quasi-viscous material and also effects appreciable convergence in volume of the mined-out region near the coal face. Figure 13 illustrates a model for which stress can build up near the face of a deep coal seam to such a level that a large volume of quasi-viscous coal can be extruded violently into the mined out area. With respect to this figure, the stress in the coal seam, $\sigma_x = \sigma_y = C \cot(\phi)(e^B - 1) + Pe^B$ (NOTLEY, 1984) where C is the cohesive strength of the coal seam, $\tan \phi$ the coefficient of friction between the coal and the adjacent layer, P is the effective restraining stress on the coal face and $B = 2.x.\tan(\phi)/h$, where x is the distance from the coal face and h the thickness of the coal seam. The high stress build up just prior to the severe bump on October, 1958, appears to be due to a combination of factors (NOTLEY, 1984). A large face pressure (P) built up due to convergence of roof and floor, mainly in the mined-out region; major contributory factors to this buildup in face pressure were (i) large overburden pressure because of depth (over 1200 m) (ii) poor caving characteristics of the roof (iii) appreciable distance from mining face to gob (loose material from unsupported roof that piles up on floor) because of fairly

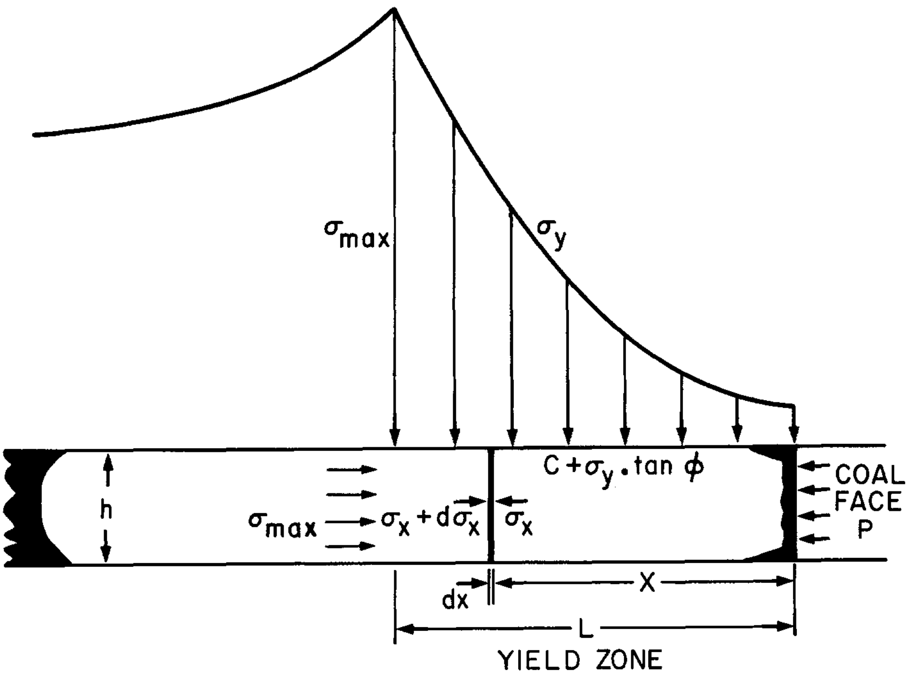


Figure 13
Idealized model of stress build up in weakened coal seam. Symbols are described in text (from NOTLEY, 1984).

large (2.4 m) h value and (iv) alignment of mining faces in adjacent levels leads to cross-coupling of induced stresses which enhances closure volume (see MCGARR and WIEBOLS, 1977). The presence of a high neotectonic stress field at shallow depths (e.g., see WETMILLER *et al.*, 1984; ADAMS, 1985; MCKAY *et al.*, 1985; HASEGAWA, 1986) could also be a factor. The frictional resistance (C) that inhibits sliding between coal seam and host rock would be large because of the absence of clay on the floor to reduce friction. Thus the extrusion stress, σ_{max} in Figure 13, can build up to a high level at these depths. Also the fact that the overburden stress exceeded the uniaxial strength of this coal seam was another factor contributing to the extrusion of coal. The combination of the above factors can account for the high incidence of coal bumps and the violent outburst of coal into the mine opening.

The most promising and feasible method at the present time to determine when extra precautions should be taken in deep coal mining operations is to install an array of geophones and scrutinize records for significant changes in micro-earthquake activity (see NOTLEY, 1984; BRADY, 1977; MCKAVANAGH and ENEVER, 1980), which may be diagnostic of poor roof conditions and overstressed pillars (HARDY and MOWREY, 1976).

5. Induced Tremors in Metalliferous Mines

In recent years there has been a significant increase in mine-induced tremors in deep metalliferous mines in Ontario and, consequently, attention will be focused on the nature and causative factors of mine-induced tremors in this region. Figure 14 shows the location of mines in Ontario. An unusual feature of mine-induced tremors in 1984 was the multiple tremor sequence that occurred in four mines, over time intervals from a few hours to months (HEDLEY and WETMILLER, 1985).

Mine-induced tremors were first noticed in the Sudbury and Kirkland Lake mines during the early 1930's. Figure 15 shows a histogram of induced seismic events in Ontario mines from 1935 to 1986. There was a flurry of induced seismic events in the 1930's and early 1940's in the Sudbury and Kirkland Lake mines. HODGSON (1958) summarizes mine-induced tremors in the Kirkland Lake mines. MORRISON (1942) describes how the spatio-temporal variation in stress-strain and structural weakness planes contribute to mine-induced seismic events. HERGET (1980) has observed that the depth at which mine-induced seismic events is greatest

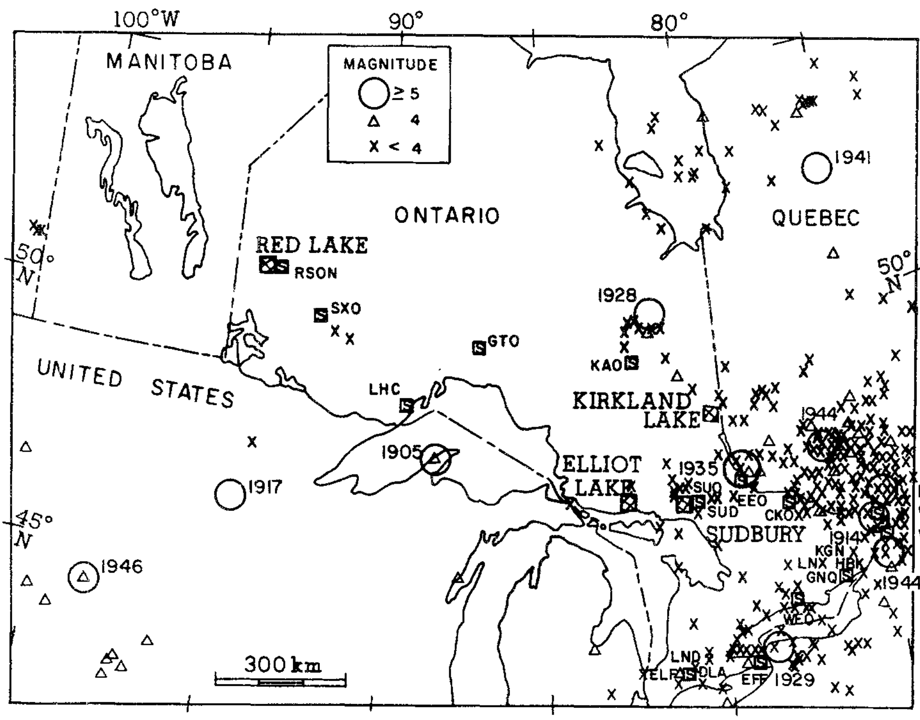


Figure 14

Known seismicity (× 's) in Ontario to 1980 and surrounding areas shown in relation to four mining areas (checkered squares) with significant mine-induced tremors in 1984 and seismograph stations (square with letter *S*) (from BASHAM and CAJKA, 1984).

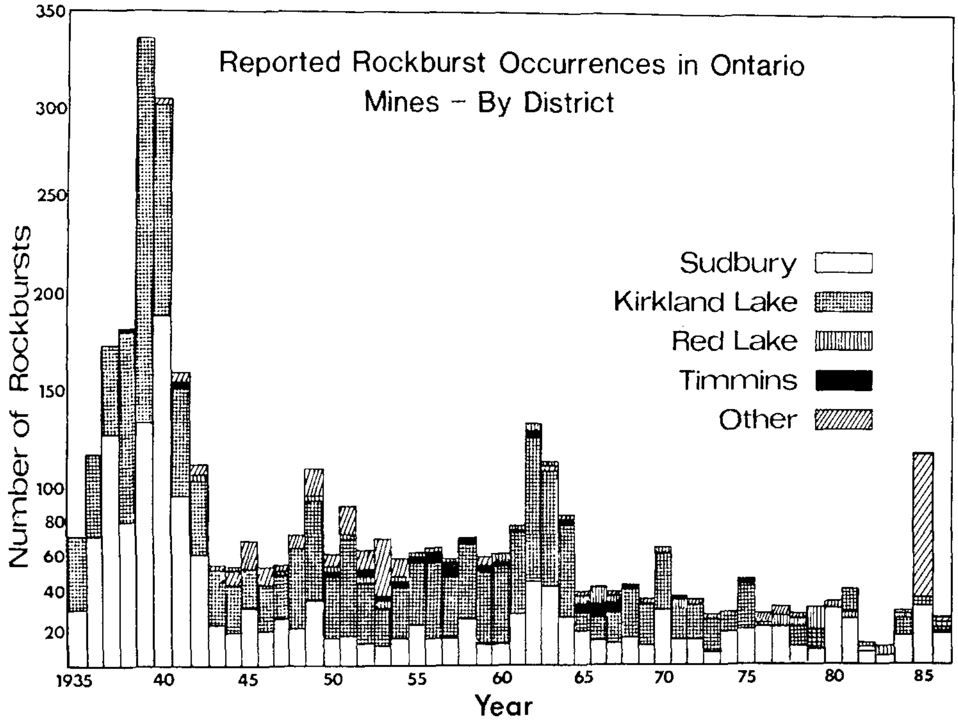


Figure 15
Histogram of reported rockbursts (mine-induced tremors) in Ontario mines from 1935 to 1986 (after HEDLEY and WETMILLER, 1985).

varies in different mines, which indicates that, in addition to the depth of mining, the behaviour of the rock layers under load is also important.

Examples of mine-induced tremors and induced fault slip (earthquake) in mined-out regions in the Elliot Lake and Sudbury areas are shown in Figures 16 and 17. Figure 16 shows the zone of pillar failure prior to 1984 and subsequent (1984) locations of induced tremors at Elliot Lake mines. On-going volume closure in the pre-1984 pillar failure zone that induced a migrating stress-strain pattern around its periphery is one of the primary causes of the 1984 induced tremors. Figure 17 indicates that stress-strain changes, (e.g., unclamping effect) due to on-going pillar bursts may have initiated sudden slip (i.e., induced earthquake) along some of the pre-existing faults above a Sudbury mine.

An interesting feature of induced tremors in Ontario mines is that when the areal extent of induced tremors (predominantly pillar burst) activity is plotted against the duration of this activity on a log-log scale as shown in Figure 18, a linear trend is observed. The significance of this power law dependence is not fully understood, but a crude corollary with earthquake activity is areal extent of aftershock activity with duration of this activity as both tend to increase with

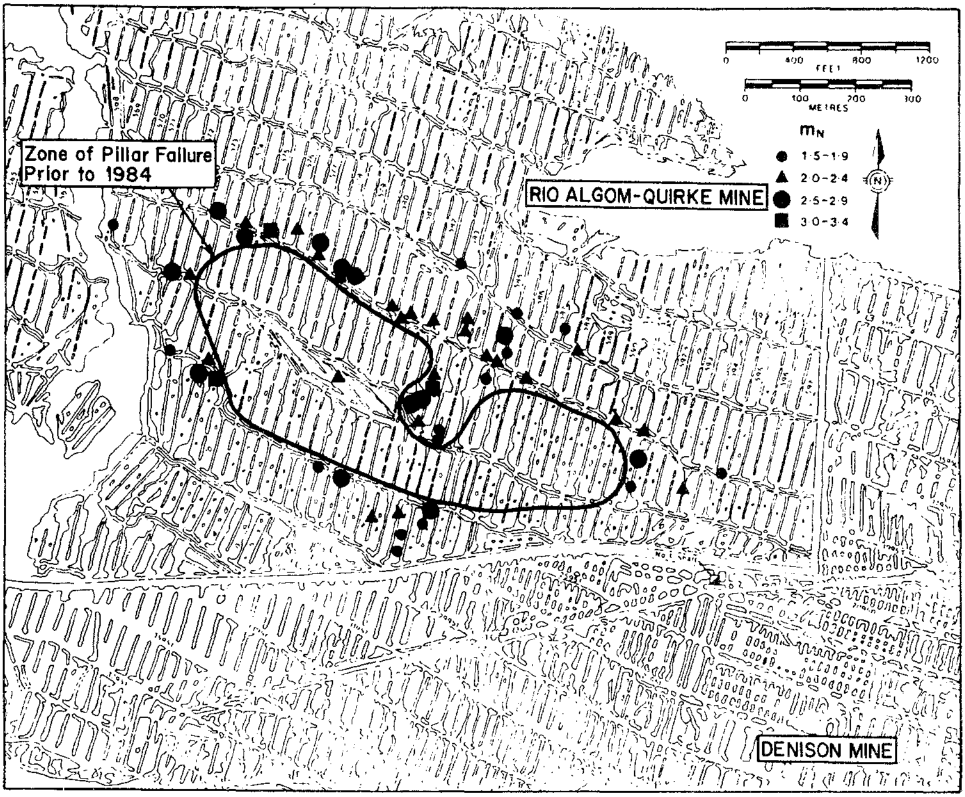
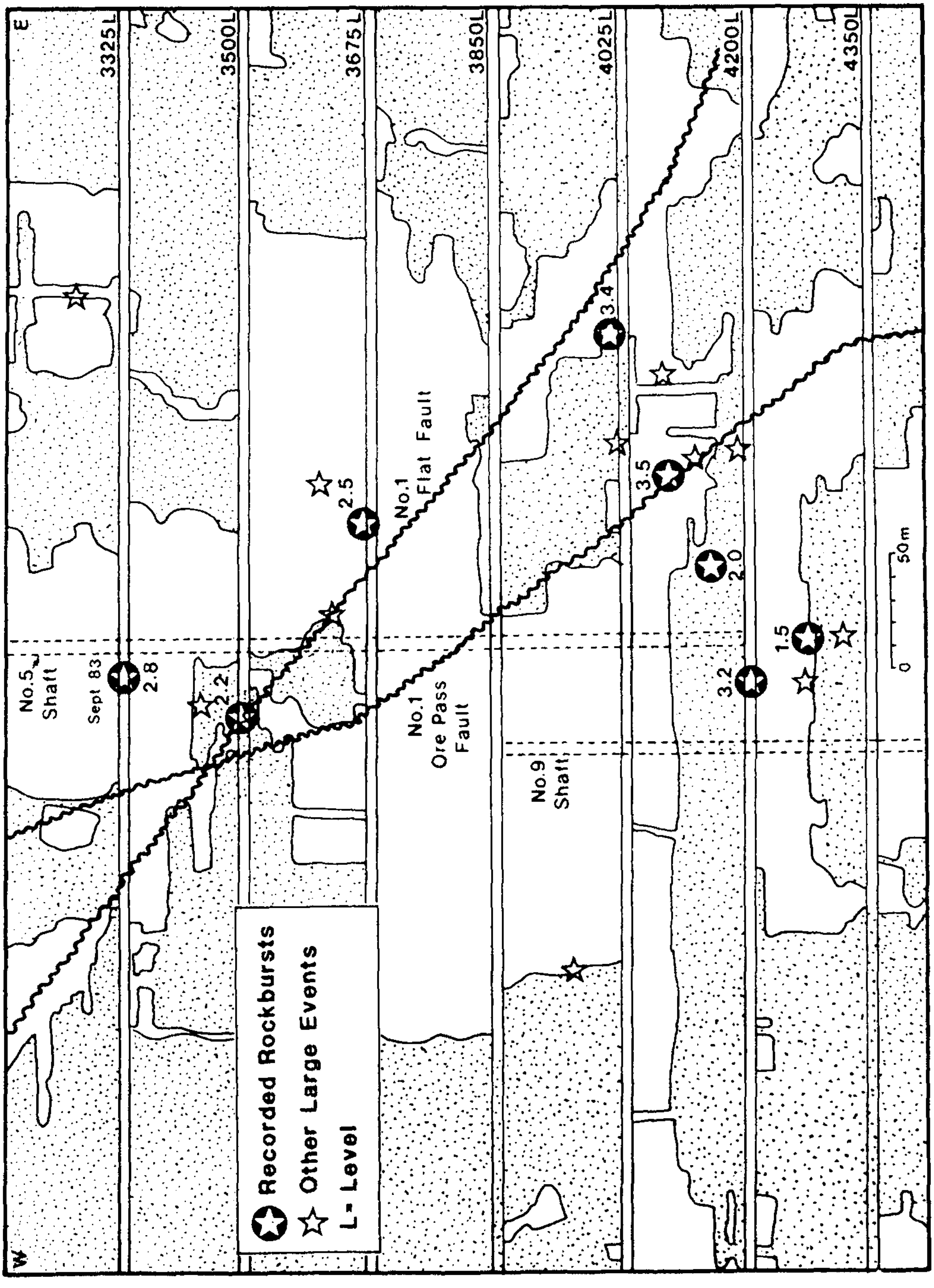


Figure 16
Partial plan of two (Quirke and Denison) mines at Elliot Lake, Ontario, showing 1984 rockburst (mine-induced tremor) locations in relation to previous pillar failure zone (from HEDLEY and WETMILLER, 1985).

increasing magnitude of main shock. BRADY (1977) shows that when precursor time of mine-induced microtremors preceding a large induced earthquake is plotted against fault length of the earthquake on a log-log scale, a linear relationship is observed.

For generating induced seismicity, the relative importance of induced stresses due to mining vis-à-vis regional tectonic stresses at shallow depths depends on several factors. In the vicinity of the face that is being mined, induced stresses associated with blasting and volumetric closure would predominate (cf. COOK, 1963; MCGARR, 1971). With increasing distance from the mine, the interaction between mine-induced and tectonic stress becomes more important. In this region, the type of induced faulting would depend on the orientation of the weakened fault and the combined interaction of mine-induced and tectonic stresses.

The orientation of the maximum principal stress at 1 to 2 km depths in Ontario may be quite variable, as shown in Figure 19. Since some of the measured stress


E
W
3325L
3500L
3675L
3850L
4025L
4200L
4350L
No.5 Shaft
Sept 83
2.8
2.2
2.5
No.1 Flat Fault
3.4
3.5
2.0
1.5
3.2
No.1 Ore Pass Fault
No.9 Shaft
0
50m
Recorded Rockbursts
Other Large Events
L - Level

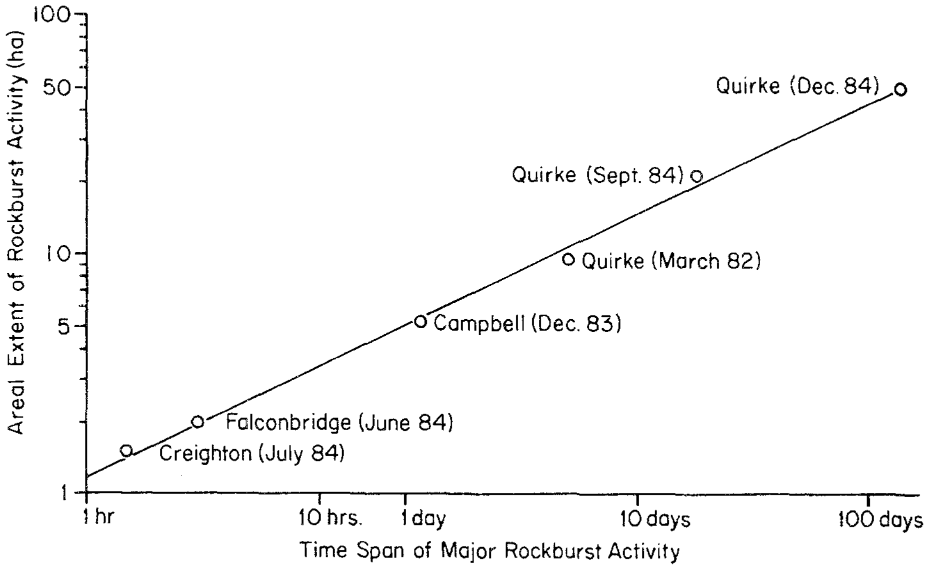


Figure 18
Areal extent of rockburst (mine-induced tremor) activity in hectares (10,000 square metres) plotted against time span of major induced tremor activity in Ontario mines on a log-log scale (from HEDLEY and WETMILLER, 1985).

orientations correlate closely with the stress direction associated with the last major tectonic orogeny in this area rather than the continent-wide NE to ENE field, HERGET (1980) suggests remanent stress may be present in this region. Nevertheless, as more and more seismograph networks are deployed around mines, with the resulting increase in the number of records of induced earthquakes in conjunction with more stress measurements both in and away from mines, our understanding of the role of induced stresses vis-à-vis neotectonic stresses should become clearer (cf. SMITH *et al.*, 1974; HASEGAWA and ADAMS, 1981; HASEGAWA, 1984; HASEGAWA *et al.*, 1985).

Faults above the mine that are on the verge of failure due to perturbation of the ambient stress field by mining could be triggered by external phenomena as well. The combination of an increase in permeability of a fault due to mining activity with increase in rainfall and water table could result in groundwater seeping into this fault (e.g., see BATH and WAHLSTROM, 1976; AL-SAIGH and KUSZNIR, 1987). The intrusion could cause a reduced effective normal stress across the fault and the

Figure 17
Longitudinal (vertical) section of (Falconbridge) mine at Sudbury, Ontario, showing location of rockbursts (mine-induced tremors) and faults (from HEDLEY and WETMILLER, 1985).

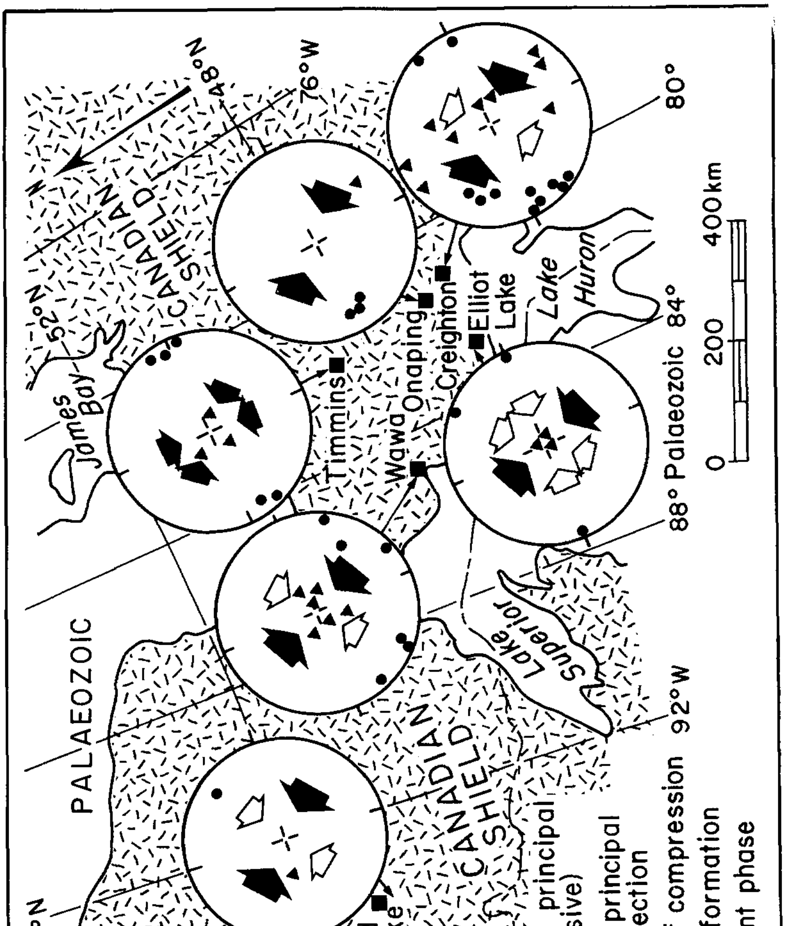


Figure 19
Suggested azimuth of compressive stress during previous major tectonic deformation (arrows) and measured principal stresses (solid dots) plotted on lower hemisphere of equal area net (from HERGET, 1980).

lubricating effect of the intrusion could result in a smaller coefficient of friction (especially if fault gouge in the form of clay is present), which would reduce the stability of the fault. In addition there is evidence of lunar (earth) tide triggering of mine-induced earthquakes at the Grangesberg iron ore mines in Sweden (BATH and WAHLSTROM, 1976). Thus the time of occurrence of induced earthquakes should be compared with tidal stresses (especially the semi-diurnal lunar tide and possibly the fortnightly lunar tide) and periods of excessive rainfall or increase in height of water table to determine if they correlate.

P-wave first motions of five of the larger (m_{bLg} 3.3 to 4.0 in 1984) mine-induced earthquakes in northern Ontario indicate a composite normal-fault mechanism (WETMILLER and CAJKA, 1988). For each event, there is an insufficient number of readings to constrain, tightly, the allowable range of orientation of the orthogonal pair of nodal planes. However, the composite data, although sparse in number (23 readings), is internally consistent and is able to constrain one plane rather tightly and the other, moderately well. The composite normal-fault solution likely reflects the unclamping effects of the mine excavation since the hypocentres are above the mine excavations. In sharp contrast, tectonic earthquakes are generally of the thrust-fault type. Analysis of smaller mine-induced tremors will have to await the deployment of a network of instruments in the vicinity of mines, such as the SLTN network (Science North in Figure 2b) in the Sudbury Basin.

6. *Future Plans*

Regardless of the type of mining operation and the material (potash, coal or ore) mined, the deployment of a network of geophones or seismometers in Canadian mines appears to be the most feasible approach towards the monitoring of the spatio-temporal pattern of induced microearthquake activity and the detection of anomalous patterns that may precede a large event.

Plans for the deployment of seismograph networks in Ontario mines are described by HEDLEY and WETMILLER (1985). A prime requirement is a quick, accurate determination of the epicentre, focal depth and magnitude of the seismic event. Then the analysis of *P*-wave first motions plus in some cases local S/P amplitude ratio (KISSLINGER, 1980), provide information on the nature (e.g., pillar burst, faulting) of the induced seismicity as deduced from the six different types of theoretical *P*- and *S*-wave radiation patterns of mine-induced tremors described previously.

Specific projects directed towards mitigating the hazards of induced seismicity in Ontario mines include a 5-year cooperative program between the Governments of Canada and Ontario and the mining industry (see BREHAUT and HEDLEY, 1986). This 5-year plan calls for the following projects: the deployment of special monitoring systems to locate accurately, rockburst activity; the identification of foreshock patterns preceding induced earthquakes (see BRADY, 1977); the determination of the type of failure (described previously and shown schematically in Figure 3) and the measurement of seismic energy liberated by waveform analysis (e.g., SPOTTISWOODE and MCGARR, 1975); the calculation of changes in potential energy due to mining using computer models; the monitoring of *in situ* stress close to stope walls; and pressure buildup on backfill and load on other support systems. Other research projects may follow: blast fragmentation and vibration monitoring; development of rock mechanics instrumentation (cf. MCGARR and GREEN, 1975); methods to determine the effectiveness of rock-bolting systems (see VOM SCHEIDT, 1987); studies on structurally controlled rock falls (e.g., see HARDY and MOWREY, 1976). (For further details the reader is referred to BREHAUT and HEDLEY, 1986).

The analysis of strong ground motion provides information on focal parameters such as dynamic stress drop and source radius (MCGARR *et al.*, 1981). Peak particle velocity is a measure of the damage capability of a rockburst (see JAEGER and COOK, 1971). Spectral analysis of larger events (induced earthquakes) gives information on seismic energy release (HINZEN, 1982) and other source parameters such as fault dimensions and stress drop (GIBOWICZ *et al.*, 1977). Provided there is direct measurable evidence of focal parameters (e.g., fault displacement) in the mine, then the predicted and actual fault motion can be compared, which facilitates the calculation of total (strain) energy release. Thus the deployment of seismograph networks around mines can be used not only to provide a forewarning system for larger induced events (e.g., see BRADY, 1977) but also to enhance our understanding of the seismic triggering process at shallow depths.

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