ROCK BURSTS IN THE LAKE SUPERIOR COPPER MINES, KEWEENAW POINT, MICH.

BY

W. R. CRANE
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ROCK BURSTS IN THE LAKE SUPERIOR COPPER MINES, KEWEENAW POINT, MICH. ¹

By W. R. Crane

INTRODUCTION

Rock bursts are phenomena associated with mining operations, particularly with deep mining, although they occur throughout a wide range of depths from 600 feet downward. The intensity is usually in direct proportion to the depth, varying from a loosening and sloughing off to a violent rupture, giving rise to the term "explosive rock."

The more or less violent breaking of rock in mine workings has been variously designated as "flaking," "pressure bursts," "strain bursts," "bumps," "quakes," and "air blasts," which indicate opinions as to cause and effect. The term "air blast" has probably been most widely used, and naturally so, as a more or less rapid movement of air often accompanies the more violent phenomena of rock failure. Furthermore, there is an implied if not definitely expressed degree of magnitude in the action designated by a given term and in the cause and character of the action. For example, flaking, pressure bursts, and quakes are terms ranged to indicate action of increasing magnitude; and pressure bursts, strain bursts, bumps, and quakes are ranged according to the cause and character of the action.

The term "rock bursts" may be employed, although inadequately, to designate the whole range of phenomena of violent failure of rock, but a distinction should be made, particularly between different types of such failure—as, for instance, between the failure of pillars and of the wall rock. The former may be a direct result of the latter or it may induce the latter. In other words, a rock burst may be a mere incident to the larger and more important action of ground movement that may be called quakes, although, being the only visible and apparent action, the entire cause and effect of the disturbance often are attributed to it.

The direct cause of rock bursts is rock pressure that may be static or active and may be in the nature of strains or stresses exist-

¹ Work on manuscript completed February, 1929.
ing in the rock mass. The static or potential pressure may be responsible for the whole range of phenomena observed, although the action is probably slow and lacking in violence but extensive. The active or dynamic pressure produces action that is violent and destructive but less extensive than the effect of static pressure, while strains and stresses produce action that is both violent and local. The static load causes pillars to fail extensively, usually by sloughing or spalling; the active load causes bumps and quakes, while strains are probably responsible for explosive rock. All these may act together and contribute to the general effect, although the results of each may be so masked as to conceal the individual and predominating action.

The effect of rock pressure may be a general and continuous disintegration and reduction in size of pillars of ore and rock left for the support of the workings, resulting in the collapse of hanging wall and the closing of stopes, drifts, and shafts, or the action may be sudden and violent and aside from seriously affecting the workings may present a real hazard to the operation of mines.

The object in the preparation of this report is to add to the accumulated information and from the facts presented to make suggestions for protective measures to be taken when possible.

ACKNOWLEDGMENTS

Acknowledgment for data and suggestions is due to many persons who have been and are now actively engaged in mining in the copper country of Michigan, particularly the following: Theodore Dengler, general manager of the Mohawk Mining Co., former superintendent of the Atlantic and Wolverine mines; C. L. Lawton, general manager of the Quincy Mining Co.; James McNaughton, president and general manager of the Calumet & Hecla Consolidated Copper Co., and, in the same company, Ocha Potter, superintendent of the Ahmeek mines, Harry Vivian, chief engineer, and mine captains A. Cameron, P. J. McClelland of the conglomerate mines, and Richards of the Osceola mines; W. H. Schacht, vice president and general manager of the Copper Range Co., Albert Mendelsohn, general superintendent, and C. J. McKie, superintendent of the Baltic mine of the same company.

Acknowledgment is also made to the following persons, who by their experience and through their writings and discussions have contributed to the knowledge of rock bursts, their character, cause, and effect and have made it possible to obtain a comprehensive and concrete understanding of the whole range of action related to the phenomena: Dr. W. F. Smeeth, State geologist and chief inspector of mines, India; Maj. Umbreville Percy Swinburne, chief inspector
of mines and chairman of the Witwatersrand Rock Burst Committee; George S. Rice, chief mining engineer, United States Bureau of Mines; Dr. E. S. Moore, professor of economic geology of the University of Toronto, Canada; T. A. Rickard, former consulting engineer and later editor of the Mining Magazine (London) and the Mining and Scientific Press; and Bernard Beringer, Jack Spalding, and R. R. Wilson, engineers well known in Canada and Europe.

**OCCURRENCE OF ROCK BURSTS**

Rock bursts have occurred wherever mining operations have been carried to considerable depths. The more important localities are as follows: The Kolar gold field, Mysore, India; the Witwatersrand gold mines, South Africa; the Morro Vello mine, Brazil; the tin and coal mines of Cornwall and Derbyshire, England; the Hill-grove district, New South Wales, Australia; the coal mines of Nova Scotia; the Cassidy colliery, Vancouver Island, British Columbia; the copper mines of Keweenaw Point, Mich.; and the coal mines of Utah and Washington.

Numerous other localities where minor disturbances bordering on rock-burst phenomena occur could be mentioned. In fact, there are few mines nearly or more than 1,000 feet in depth in which failure due to pressure can not be observed, but these may not have reached the sudden or explosive stage and are therefore of local interest only.

**INDICATIONS OF APPROACHING ROCK BURSTS**

**SIGNS OF ROCK BURSTS**

In certain localities signs of disturbance may be observed for hours, days, and occasionally weeks before rock bursts occur. They consist of sounds, such as cracking, popping, grinding, and rending, accompanied by spitting and flaking of small fragments from the walls. A simmering sound may change to that of cracking, like the breaking of matches or the explosion of detonators, when flakes become detached and fly from the working face. Occasionally flashes of light that can be observed in the dark accompany the flaking. In other localities no sound of breaking off of fragments from the rock face can be observed, but failure takes place suddenly, masses slumping off or fragments being hurled with varying degrees of violence.

Failure to observe warning signs indicating that rock bursts are about to occur is probably due in large measure to the fact that no one happens to be at the point where they are taking place before the outburst. This circumstance is common where the disturbances occur outside of the active workings. On the other hand, pronounced
cracking and rending sounds may be and often are heard unaccompanied by bursts.

The release of considerable volumes of gas and water and, in the latter instance, the disappearance of water from the upper levels and its appearance in the lower levels have proved to be good indications of approaching disturbances in certain localities. These effects often extend throughout the disturbance and become an important result of such action.

In certain parts of the copper mines of Keweenaw Point, Mich., no signs, visible or audible, have been observed, while in other parts, often no great distance away, unmistakable indications are the rule. The usual signs are cracking and snapping, accompanied by the detachment and flying of small fragments from the face of pillars and the walls of drifts. Grinding and rending sounds usually occur between bursts rather than before them, showing that the pillars are working. It is claimed, not without some reason, that the movement of rock in pillars and hanging wall, with resulting rending sounds, shows that the pressure is being taken up normally and indicates safety rather than danger; however, ordinarily such manifestations of pressure are followed by rock bursts. It has been suggested that the calcite filling of the brecciated amygdaloid lode rock is responsible for the cracking and snapping that precede a rock burst, as it is very friable. The spalling of pillars is probably one of the best signs of approaching failure, violent or otherwise. In certain mines the spalling of pillars, with accompanying cracking and snapping or grinding noises, is practically continuous and therefore loses its value as a warning or sign of bursts. Furthermore, timber supporting hanging wall adjacent to working ground often makes audible signs of distress due to increased load.

The above shows that little definite information is available on signs that indicate approaching rock bursts, yet it is probable that certain typical actions are taking place if the exact localities were known and careful scrutiny could be made. In confined areas, as in shafts and special excavations, the action preceding rock bursts is probably more accentuated because the stresses are concentrated, while in wide drifts and stopes the reverse is true because opportunity is afforded for wider distribution of load and consequently of pressure.

MEANS OF DETECTING APPROACHING ROCK BURSTS

Various attempts have been made to obtain evidence of pending rock bursts and under certain conditions of occurrence of ore bodies and methods of working have contributed to a more or less satisfactory program. "Telltales" or "policemen"—small pillars left
to give warning of impending failure or collapse—have served a useful purpose, particularly in preventing loss of life. Such pillars are left at regular intervals throughout the workings and by their rate of failure indicate the location and extent of pressure to which they are subjected. "Talking" props have also been employed as danger signals and have the advantages over telltales of being inexpensive and readily set at any desired point.

Although rock bursts occasionally occur in active workings of the Lake Superior copper mines, by far the larger number have occurred in the abandoned portions of the mines and therefore are inaccessible to systematic inspection. However, could inspection be extended as far as possible beyond the active zones and be made regularly both within and without, more information would probably become available than is imagined possible at present.

CAUSES OF ROCK BURSTS

Although the causes of rock bursts are fairly well understood in a general way, numerous points are open to controversy, including application of the load of superincumbent rocks, limits of the "arch block" or "direct-pressure block," stresses in the hanging-wall rock, and the effect of active or dynamic loads. Probably the whole problem will ultimately be solved satisfactorily, after a large volume of fundamental data has been collected and analyzed, and will yield to the intensive investigative study of mine support, to which it is closely related.

The failure of rock, whether quiet or explosive, depends upon its character and occurrence, including the presence of bedding and joint planes or slips, the presence of faults and contacts between different formations, stresses in rock masses, the pressure of superincumbent rocks, and other factors, which will be considered in this connection particularly with regard to rock bursts.

CHARACTER OF ROCKS

The physical character of rock is of prime importance in the consideration of rock bursts; consequently a classification based upon hardness and brittleness or friability, on the one hand, and softness and ductility, on the other, within certain limits indicates the type of rock that is subject to rock bursts. A strong, hard, solid rock capable of sustaining considerable weight without deformation will yield suddenly when the limit of its crushing strength is reached and will therefore produce rock bursts. Trap, quartzite, quartz, slate, horneblende, sandstone, limestone, and similar rocks predominate in rock-burst localities, while schists, shales, certain sandstones and limestones, and partly altered rocks, often argillaceous, will
yield without disruption and gradually close an excavation. Should there be a choice of rock, as when poor rock occurs in stoping areas, the harder and stronger is usually selected for pillars, and rock bursts may result; however, the selection of pay rock or ore for pillars might prevent bursts by permitting more gradual failure. As a rule, however, a greater difference in character of rock would be necessary than is possible under the conditions cited.

Although the ductility of rock increases with depth, considerable depth would be required to alter a rock enough to affect materially its tendency to violent rupture under pressure. Through change in ductility the ratio between compressive and tensile strength is less than with rocks at the surface, but this, too, probably has minor importance. However, it should be borne in mind that rocks are weaker under tension than under compression. Hard footwall rock breaks in angular fragments which are often thrust upward with considerable violence, while softer and weaker rock heaves in loose masses.

Three kinds of rock in the copper mines are subject to failure through the action of rock bursts—conglomerate, amygdaloid, and trap. The first two form the lode rock; and the trap is hanging and footwall rock, except in the conglomerate lode, which has an amygdaloid footwall. The amygdaloid is quite variable in character, texture, and strength, while the trap is much more uniform, being hard and strong. The conglomerate is usually weaker than the amygdaloid rock but is friable and subject to rock-burst action. The amygdaloid rock ranges from hard to soft, even in the same mine, so that one part of a mine may be subject to rock bursts and other parts not. The hard gray and the reddish-brown amygdaloid rocks are brittle and are usually the explosive rock of the copper mines. As a rule, barren rock is more subject to rock bursts than copper-bearing rock, although in certain localities copper rock fails suddenly and violently. Amygdaloid rock is probably more subject to rock bursts than rock of the brecciated type, and, generally speaking, rock that is hard to drill may be classed as explosive when subject to high pressure.

**EFFECT OF FAULTS, SLIPS, AND CROSSINGS**

Faults, slips, and crossings may have an important influence on rock bursts in that they may concentrate or distribute rock pressure. By subdividing rock masses faults may cut off and diminish the lateral support, thus increasing the load upon certain areas of mine workings. On the other hand, faults may cause concentrations of pressure on their respective walls that may result in local disturbances, an action that may be accentuated by the presence of
water, permitting more ready transfer of pressure from one point to another. Crossings, while not as extensive as faults, may have a similar effect on the concentration, distribution, and transfer of pressure.

Joints or slips and bedding planes tend to obviate rock bursts in that they permit movement and adjustment of pressure in rock masses. In fact, so marked is their effect that hard, dense, flinty rocks ordinarily subject to violent bursts are usually free from such action when extensively broken by joints or slips. Dip slips that subdivide massive igneous formations into layers resembling stratified rock may relieve the pressure of superincumbent rock by distributing it or under certain conditions may cause local concentration of pressure through buckling.

There is reason to believe that the extensive jointing that has occurred in the copper mines has dissipated the local strains and stresses inherent in the igneous formations but is probably responsible in part for rock bursts resulting from mining, through local concentration of pressure on and along the dip slips.

The great Keweenaw fault, which parallels the copper-bearing lodes throughout the entire length of the district, is commonly held directly responsible for the rock bursts in the mines. This contention is not tenable, as no earthquakes or tremors have been recorded by seismographs at the State observatory since its establishment some 20 years ago. It is evident, then, that rock movements in the mines are responsible for the tremors observed and are of local origin, being the direct result of mining.

**EFFECT OF DIP OF BEDS OR LODES**

The effect of the dip of formations on the support of top rock or hanging wall of underground workings is too well known to be discussed at length in this connection. Suffice it to state that the maximum weight of overlying rock must be supported when the formations are horizontal and that the load diminishes as the dip increases until a minimum is reached with verticality. With respect to the weight of formations and the resultant components this is true; however, other conditions have to be dealt with, such as thrust acting parallel with the dip and therefore increasing with it, which with high dips may even exceed the normal component of the superincumbent load and is important, particularly with regard to the production of rock bursts.

While it can not be stated as a fact, the record of mines in which rock bursts occur makes it seem probable that rock is more susceptible to disturbance when the dip of deposit exceeds 50° with the horizontal, although other conditions may have a predominating
influence. In the Mysore mines, India, the dip is 45° to 50°; in the Champion Reef and Ooregum, South Africa, the dip is 60° to 80°; while at Pribram, Bohemia, the veins have an inclination of 70° to 80°.

In the copper mines of Michigan the lodes occur at a wide range of dip, and mines on dips of 35° to 70° have experienced rock bursts. Probably, however, the great depth of workings has more than offset the diminishing effect of thrust on low dips. The most violent bursts have occurred on dips of 37° to 45°. In other localities in the States, particularly in the iron mines of Birmingham, Ala., explosive rock has been found at less than 1,000 feet in depth and on inclinations of 20° and less. It is evident, then, that the dip of the deposit is not always of prime importance, although under certain conditions it may have a controlling influence in the production of rock bursts.

In the copper mines rock bursts have occurred on all dips of lodes—that is, at 70° at the south end of the district, 45° in the middle, and 35° at the north end—and at depths of 1,800 feet, 4,000 feet, and 5,000 to 6,000 feet. The most extensive and violent have occurred from 4,000 feet downward, irrespective of the inclination of the lodes.

STRAINS AND STRESSES IN ROCKS

The terms “strain” and “crush” or “pressure” bursts indicate distinctions in the nature of degree or extent of effect. The former are of less magnitude but are violent and local; the latter are of great magnitude and widely distributed. Strain bursts are probably largely independent of depth and being localized indicate concentration of pressure. On the other hand crush or pressure bursts are strictly pressure phenomena and therefore depend largely upon depth of workings.

Strains and stresses in rock mass are due to the following causes: Regional pressure that has resulted in folding, faulting, and crushing of formations, intrusion and cooling of igneous rock, changes in mineral composition, thrust parallel with the bedding of formations, etc. In the majority of cases, regional strains have probably been relieved in large part by the orogenetic movements induced by them, such as folding and faulting. Faults, crossings, and jointing when pronounced have undoubtedly relieved excessive strains. The same is probably true of strains resulting from the intrusion of igneous rock, as the compressive stresses are partly, at least, counteracted by the tensile stresses that result from cooling of the rock. The introduction and crystallization of mineral, such as calcite, in fractured rock masses may extend fracturing by compression, thus setting up strains; but it is evident in some cases that this can not be so, as the
calcite is itself not fractured, as is always the case when under great compression. The weight of top or hanging-wall rock acting parallel with the dip and therefore along the beds develops into a thrust that may set up strains in the rock, which may be relieved suddenly and violently when penetrated by the mine workings. The thrust strains act normally to the beds and are therefore added to the normal component of the weight of the overlying rock. Such strains may be localized, due to resistance to movement between beds or layers of rock, and to the presence of faults, crossings, and slips, but where other strains have been eliminated wholly or in part the thrust strain may be the controlling factor in the production of rock bursts.

There would appear to be slight ground for assuming that strains and stresses in the copper mines of this district are due to other causes than the effect of weight of the superincumbent rocks acting normally—that is, vertically—or the development of thrusts along the bedding. The presence of faults, crossings, fracture zones, and an extensive system of jointing makes it appear quite impossible for regional strains to have remained unrelieved to the present time.

The change in strike of lodes from N. 35° E. at Houghton to S. 63° E. at the end of Keweenaw Point, with changes of dip of 56° to 22° through the same distance, provides enough horizontal and vertical flexing of formations to produce extensive strains; but it is noteworthy that at the points of maximum flexure the beds have suffered extensive fracturing, and strains if formerly present have been relieved. However, at the Quincy mine, where extensive rock bursts have occurred, the lodes have been flexed from an angle of approximately 60° at the surface to 36° at a depth of more than 5,000 feet and are remarkably free from faults and crossings, although cut by an extensive series of joints. Under such conditions of occurrence strains may exist; but, with the pronounced dip slips cutting the formations, thrust on them is probably more likely to be responsible for the strains that are evidently present.

PRESSURE OF SUPERINCUMBENT ROCK MASSES

The weight of rock masses overlying mine workings is the main cause of rock bursts. This pressure is resolved into two parts, one acting normal to the bed or lode, the other parallel to the lode. To the parallel component may be added the force due to thrust acting throughout the vertical extent of the beds. With horizontal and vertical beds the weight of the rock mass is wholly normal and parallel, respectively. Strains may be set up by the pressure of the rock masses acting along certain lines being directed by conditions of occurrence of beds, or they may be the remnants of regional strains unrelieved by movement of the formations, such as faulting,
fracturing, jointing, and erosion. Pressure resulting from the weight of rock masses and strains set up by any cause may act singly or in combination to produce rock bursts, but all contribute to the ultimate effect. In general, it may be said that rock bursts are due directly or indirectly to the weight of rock masses, the suddenness and violence of the failure of pillars varying with the character of the rock, and the presence of concentrated stresses.

If the weight of superincumbent rock masses is the direct cause of rock bursts, the depth at which they occur in mines should conform to their occurrence and to the relative percentage of extraction. The fact that rock bursts have increased in severity in all localities with increased depth of mining is ample proof of the contention that depth and consequently pressure are the main causes. Unfortunately, data regarding the depth at which rock bursts occur and the area worked are usually not available for the same mines, so that estimates are uncertain at best. Pillars fail at depths of 600 feet downward. At 1,000 feet failure is infrequent; at 1,000 to 2,500 feet failure of pillars by crushing and slabbing is common and often pronounced, but bursts are rare; from 2,500 feet downward rock bursts occur and increase in violence with depth. They are always present at 4,000 feet, at 5,000 and 6,000 feet they constitute a decided hazard, while at greater depth the maintenance of workings becomes a special and extremely difficult problem.

The effect of the area of workings has an important bearing upon the failure of pillars by crushing and spalling or the more violent form, as in rock bursts, the pressure being increased materially by mining and varying directly with the per cent extraction. Albert Mendelsohn, superintendent of the South Range mines, Keweenaw Point, Mich., has shown that it is possible to predict the occurrence of rock bursts by calculating the per cent extraction. Rock bursts occurred in different portions of the Champion mine when extraction had reached 35.5, 51.8, and 54 per cent, averaging about 47 per cent. Similar calculations for the Baltic mine, which was partly closed by rock bursts, gave bursts occurring at 75 per cent extraction. Calculations at other localities gave 42.7 per cent, the average of the various mines giving 52 per cent. The lodes to which the calculation applied ranged from 15 to 25 feet in width and 56° to 70° in dip, the latter dip being that for the Champion and the former for the Atlantic mine. It is safe to say, then, that for dips of 35° to 45° rock bursts may be expected when 55 to 65 per cent of the lode has been removed and depths of 2,500 to 3,000 feet have been reached.

The pressure of overlying rock masses is not applied directly and wholly upon the supports in mine workings but is modified by the formation of domes or arches in the rock. The “arch block” or “direct-pressure block” is a mass of ground limited by the extent of
the workings on both dip and strike and extends to a height in the top rock or hanging wall that depends upon the width of workings on the dip. The weight of the direct-pressure block determines the support in the mine workings and is directly responsible for more or less violent failure of pillars. Beyond and above the direct-pressure block is the arch of undisturbed rock, which brings about subsidence when it fails. The arch has little effect upon mine support, as the foot on the up-dip side is usually at slight depth, while the other foot is below the workings in undisturbed ground. However, as

![Diagram showing angle of break in hanging-wall rock. Observation taken throughout active district.](image)

**Figure 1.**—Diagram showing angle of break in hanging-wall rock. Observation taken throughout active district.

the workings proceed downward the width of the direct-pressure block increases as top rock fails, in like manner increasing the width of the inclosing arch.

The width of the direct-pressure block may be assumed as that of the workings on the dip, the height varying directly with it; that is, the height may be determined by applying the angles of break in top rock or hanging wall at the top and bottom of stopes, thus forming lines that limit the block. (See figs. 1 and 2.) The height of the block thus determined exceeds that of the actual block of broken ground, because the breaks are limited by being pinched out as the top is approached; on the other hand, the height increases as failure of support progresses and the stopes below merge. In any case the
tops of the stopes terminate in a roughly formed arch, as shown in Figure 2. Various conjectural estimates have been made of the height of the block and range from three to four times the width; but with the angles given a close estimate may be made, as the angles were obtained from a large number of observations of breaks of hanging wall in caving stopes.

Figure 2.—Sketch showing direct-pressure blocks $a$, $b$, $c$, and $a'$, $b'$, $c'$, with dips of lode 40° and 30°, respectively, and secondary blocks above single stopes. Lines of draw are also shown in hanging wall. Heavy lines show breaking and separation on dip slips, due to weight and thrust. Variation in pressure block with dip of lode is shown to advantage.

Aside from the main block there are other smaller blocks within and composing it. The bases are the distances between pillars and remnants of ground still standing. These smaller blocks overlap and interlock, so that none are independent of the others; consequently, the failure of one often affects others at a distance, and the general procedure is the production of larger blocks. Evidently, then, faults, crossings, and other lines of weakness may have a marked effect upon the intensity and distribution of pressure due to the pressure block, factors that undoubtedly are responsible for the erratic
action often observed in the occurrence of rock bursts and allied phenomena.

The fractured and loosened mass of rock composing a pressure block is that part of the overlying rock mass that affects support. Moreover, it is largely unstable and is subject to sudden change and movement through breaks or on lines of weakness. Thus, a static load is changed to a live or dynamic load and the effect greatly augmented thereby. Probably one of the most common causes of change of the state of load of the hanging-wall rock is the sudden failure of a pillar under the static load of the pressure block. The release of pressure at one point increases it as suddenly at one or more other points, usually with disastrous results. The breaking of the bond between beds or layers in the top rock and their readjustment by gravity in the building up of the pressure block is probably responsible for jolts and bumps, with resultant vibrations and tremors. The movement of large masses of rock through distances of a fraction of an inch would suffice to produce rock bursts and quakes. Pressure transmitted through hanging-wall rock or through pillars to the footwall rock causes drag in the former instance and heave in the latter. The action may be slow or violent.

The weight of the pressure block may act hydrostatically, that is, in all directions, as where fairly hard rock is extruded, where pillars and walls are permanently distorted in various directions, and where both drag and heave act between narrow limits. It is not, however, easy to separate such phenomena from the effect of the component of static pressure acting horizontally.

Rock bursts in mines are so varied in position and intensity that it is evident no single manifestation of pressure can explain them satisfactorily. They occur in large open stope, shafts, drifts, and crosscuts. In the former instance pillars and hanging and foot wall fail; in the latter the walls of the passages fail—evidently the same cause can not fit the different effects. The failure in stope is undoubtedly due to pressure, while that in narrow openings is probably the result of localized pressure or strains. Either may act singly or both may act together, thus contributing materially to the effect.

**MISCELLANEOUS CAUSES**

Aside from the causes of rock bursts discussed above, others have been suggested, such as the cooling of igneous rocks, crystallization of minerals in fractured rock, chemical action through percolating waters, and occluded gases in coal and rock. Under various conditions of occurrence certain formations may render one or more of these factors effective, but it is doubtful whether they are of much
importance under normal conditions, although they may contribute to the general effect.

COOLING EFFECT OF IGNEOUS ROCKS

The cooling of igneous rocks, such as dikes, sills, and flows, may be considered of considerable importance, both on account of their common occurrence and their size. Intruded rock is much more important in effect than extruded rock, because the compressive strains set up by masses of intruded rock must have a profound effect upon the inclosing formations, requiring extensive readjustments; on the other hand, extruded rock may have a superficial effect alone upon the adjacent formations. The cooling of intruded rocks sets up tensile strains in the inclosing formations, which unrelieved may cause local disturbances when penetrated by mine workings or may tend to counteract the compressive strains produced by the intrusion, but tensile strains must be considered of minor importance compared with the compressive strains that accompany the intrusive action and precede the shrinkage due to cooling.

In Michigan copper mines the igneous rocks are considered extrusives, although some authorities contend that intrusive rocks also occur, in which case they may have set up strains through cooling. Considered as extrusive rocks alone the strains in the mass of the rock itself resulting from cooling could not exist long after fracturing and movement, even though the flows were of considerable thickness.

EFFECT OF CRYSTALLIZATION OF MINERALS

The introduction of minerals and their crystallization in the porous and fractured rocks forming the ore zones or lodes may when extensive produce compressive strains of considerable magnitude, but the minerals would themselves be subject to compression and would show the effect by their shattered condition. The calcite, quartz, and laumontite that occur in the amygdaloidal and brecciated lode rock are often clear, indicating an unshattered condition; however, fissures in both the conglomerate and amygdaloidal rocks, from a few inches to several feet in width, are often extensively broken, shattered, and even reduced to small fragments. In such instances it is difficult to say whether the shattering was the result of compression that accompanied crystallization or the effect of rock movement entirely independent of crystallization.

Probably, if any change of volume of rock occurred through chemical action brought about by percolating waters, often superheated, it would be principally in the nature of solution of certain
constituents of the rocks and thus produce a shrinkage rather than an expansion of the rock mass.

EFFECT OF OCCLUDED GASES

The escape of gas under pressure causes the face of pillars and ribs in coal mines to burst, blowing out considerable masses of coal, much of it finely subdivided. Such bursts have occurred at the Cassiday mine, British Columbia, and in the coal mines of England and Wales. However, so far as occluded gas in rocks is concerned, the effect even as a contributing cause of rock bursts may be considered negligible. No gases, at least under pressure, have been observed in the copper mines of Michigan, but considerable quantities occur in the iron mines of the Birmingham district, Alabama, and in other localities in the States where an approach to explosive rock is encountered. There is, however, no indication of any connection between them.

EFFECT OF ATMOSPHERIC PRESSURE

Certain remarkable coincidences with respect to rock bursts occurring with marked variation of barometric pressure, particularly their occurrence over a considerable territory, have given the impression that there is a connection between them. Careful observation for a period of six months, when rock bursts were both numerous and intense, has demonstrated that there is no definite connection but that they occur both when atmospheric pressure rises and falls, and equally under uniform pressures; however, during certain periods they seem to favor a “rising” barometer, in others a “falling” barometer.

Certain observers claim that the cooling effect of air currents, such as when a fan is started, and an increased flow of water in the workings have been responsible for the occurrence of rock bursts. However, more exact information will have to be obtained before definite conclusions can be accepted. With regard to the starting or stopping of a fan, it might be a debatable question as to whether the cooling effect of the air or a change in pressure was responsible for the disturbance or whether it was a mere coincidence.

ACTION AND EFFECT OF ROCK BURSTS

Various types of failure of pillars and walls of drifts and stopes, ranging from slow disintegration to sudden and violent action, are manifest in a great variety of phenomena, all more or less intimately related and subject to simple and definite classification as to action and effect.
NATURE OF ACTION OF ROCK BURSTS

Rock fails by flaking, spalling, wedging, and more or less violent rupture, the order given indicating roughly the degree and extent of the action. Flaking or spitting is the separation from the face of a pillar or the wall of a drift of small irregularly oval fragments which when detached often fly several feet with a simmering or crackling sound. Distortion of the face under pressure explains this phenomenon. Such distortion may be concave or convex outward, the former being more common with flaking. A thin fragment or scale of rock is broken from the face by the bending action and, when free, springs straight, in so doing striking the face with practically the full length of the perimeter and being projected to a distance. The fragments or scales are small and thin and not uncommonly break into very small pieces or powder. Flaking may be caused by excessive weight on pillars or walls, causing distortion, or by live loads, resulting in bumps, the latter being a more violent action than the former. A similar effect may be observed in blasting, when the shock of the explosion causes fragments and scales to fly from the face of the rock wall some feet beyond, the energy being transmitted through the solid rock.

Spalling is the breaking of fairly large fragments from the face; as a rule these fragments are thin in comparison with their width. They are usually formed on convex faces or the reverse of the surface that produces flaking. Either because of size or mode of detachment, the spalled fragments are seldom found far from the foot of the pillar or wall from which they came and usually accumulate there unless moved by gravity. Spalling is the direct result of the pressure of top rock or hanging wall acting on and through the pillars and walls. The various stages in spalling are shown in Figures 3, 4, and 5. The last gives a combination of spalling and wedging. Spalling on a convex face is shown in Figure 6.

Wedging is the breaking of large masses, often weighing tons, from pillars and is due to drag, heave, or any other cause that shortens the vertical length of the face, thus shearing off masses that fall and pile up around the pillars; or, if the dip is steep enough, the broken rock may be moved some distance by gravity.

Pillars may break up and collapse through static pressure or live loads transmitted through the hanging and foot walls. The effect is similar, but the exact action is difficult to identify from the resulting condition of the pillar, except that disintegration of the pillar is usually more marked next to the wall transmitting the action. For instance, in A, Figure 7, the condition of the pillar on the footwall side indicates that it may have been shattered by a bump, although static pressure has been known to produce similar
results. It is not uncommon for the action in both hanging and foot wall to be combined, static or live loads acting in both walls and thoroughly demolishing the pillar between. (See fig. 7, D.)

A pillar shattered by static pressure or by moderate live loads transmitted through the hanging wall is shown in Figure 7, C, and in Figure 8. The quiet failure of pillars, as by spalling or slabbing, may leave a core of unbroken rock surrounded by fragments largely in place which, later failing suddenly and violently, projects into the workings the broken shell, producing the effect of a large rock burst when, in fact, the action may have been quite moderate. There is nothing to indicate that the action in large pillars differs much
from that in small pillars, except that the demolition may be more complete in the latter and less complete in the former in that a core of unbroken rock usually remains and is subject to additional rock bursts. However, a core of unbroken rock inclosed in a shell of broken, shattered, or fractured rock may prove to be a protection against further bursts, the shattered rock acting as a shield or buffer.

As a rule, slow failure of pillars and drift walls is extensive and widespread, while sudden and violent bursts are more usually local-

Figure 4.—Failure of pillar by spalling

Figure 5.—Failure of pillar by combined spalling and wedging (Birmingham, Ala.)

ized. In the Michigan copper mines the walls of drifts have been observed to fail under rock bursts for 50, 100, and 200 feet continuously, so that the passages are practically closed with broken rock.
In other instances, and so far as could be observed under similar conditions, the occurrence was intermittent but quite regular, holes 6 to 8 feet across having been formed to a depth of 2 and 3 feet. (See fig. 9.) These openings were spaced 25 to 35 feet apart and were repeated for several hundred feet along drifts and levels. The action may be slow and quiet, as shown in Figure 10, or violent,

![Figure 6](image_url)

**Figure 6.**—Spalling on convex face of pillar (Birmingham, Ala.)

as shown in Figure 9. Furthermore, certain levels may be more subject to disturbance than others. The two conditions—that is, occurrence at intervals along drifts and on given levels—would seem to indicate that the localizations of action might be due, in part at least, to strains rather than to more or less evenly distributed pressure of the hanging wall.
Aside from the effect of the character of the rock, the presence of fractures and jointing may have an important influence on rock bursts; jointed rock, though less subject to violent outbursts, will, when so affected, break up and be hurled farther than unjointed rock. The condition of the rock—that is, whether it is jointed or fractured—determines to a large extent the size of the fragments that result from rock bursts. Unjointed rock usually breaks coarser than jointed, although in hard, tough, blocky ground the reverse may be true. Bursts in coal beds usually produce much finely broken or powdered coal, which frequently fills adjacent workings.

Dr. W. F. Smeeth formerly held that there was a pronounced difference between the phenomena of rock bursts and quakes, the
latter being of greater magnitude and more serious than rock bursts; but with increased depth of workings rock bursts have become more severe, often equaling or approaching quakes in the extent of action and damage done; consequently the distinction has been largely lost. Similarly, the contention that there is a difference in the cause of the action—quakes resulting from movement and fracturing of large masses of hanging-wall rock while rock bursts are due more largely to intrinsic strains causing sudden and violent bursting of pillars—

is probably untenable. Doubtless the cause and effect are so intimately connected and merged that no distinction can safely be made. Sudden movement, even though slight, and the sudden checking of
movement of great masses of rock during readjustment of strains are enough to cause rock bursts and shocks, the only visible effect often being the bursting and collapse of pillars in the works, thus giving the impression that the outburst is the cause instead of the effect of the action, when it may be a mere incident to the greater disturbance. (See figs. 11 and 12.) Great masses of hanging wall may be involved, extending over wide areas; these will bend and set up strains and stresses until movement occurs, when the static load will change to a live load, crushing pillars near by or at considerable distance and setting up tremors that may be felt several miles away.

Evidently the action originates in the top rock or hanging-wall rock and is confined largely to the fractured portion or to the direct-pressure block that builds up in height as the failure of pillars progresses along the dip in the workings. The great mass of fractured rock rides upon the pillars and artificial supports in the workings and is therefore unstable, being subject to movement through failure of the pillars and breaking down of portions of the hanging wall, supported between pillars, due to local weaknesses.

**FAILURE OF HANGING-WALL ROCK**

The character of the hanging and foot walls has an important bearing upon their failure and that of the interposed pillars. With strong walls both may move without fracturing, the pillars alone failing; but with a strong, rigid footwall the live loads of the hanging wall, acting through the pillars, may punch them upward into the hanging wall, seriously fracturing it and often causing extensive falls. Should the hanging-wall rock be badly broken by
joints, its disintegration and failure through the punching action may be especially severe and pronounced. (See fig. 7, B.) Furthermore, the mass of rock included between the slips $b$, when forced into the hanging wall, loosens and permits portions of the pillar $c$ to fall. With weak footwall rock the punching action is prevented, as the footwall yields and heaves; the hanging wall also settles, with the result that both walls crowd into the workings, often without material damage to the pillars.

The failure of the top rock or hanging wall is responsible for the formation of the direct-pressure block, being definitely limited by the angles of break determined by extensive observations and shown in
Figure 1. The position and shape of the pressure block are shown in Figure 2, the length of the block being determined by the lateral extent of workings. Evidently failure takes place more definitely and extensively on the top or up-dip side of the block than on the back and ends, because the action of gravity tends to separate the fractured rock while on the back the tendency is to hold the fractured rock in place. Ultimately the hanging wall breaks and falls through drag and failure of pillars; this is hastened by the action of live loads and thrust on layers parallel with the dip. (See fig. 13.) Furthermore, as a direct result of failure of pillars through rock bursts, probably permitting buckling to act, freeing thrust strains, the hanging wall often bursts out, forming cavities 15 to 20 feet in diameter and 8 to 10 feet deep, usually at the top of stopes and just below the arch pillar that collapsed through rock bursts. Figure 14 shows the result of thrust on hanging-wall rock. This condition has frequently been observed in the copper mines and is a further sign of localized pressure or strains.

The presence of a well-defined system of joints or slips is largely responsible for failure of hanging wall, particularly in the so-called natural stowing so common in the copper mines. The pronounced dip slips that occur in the hanging-wall traps are of special interest in this connection, in that they separate the rock into distinct layers and permit its ready breaking up.

FAILURE OF PILLARS AND OTHER SUPPORT

Pillars fail either through the application of live loads or through static pressure of the block. The latter is effective in two ways—as a normal component of the weight of the superincumbent rock
and as a pressure on the face or perimeter of the pillars through the support of the hanging wall. Throughout the workings the immediate hanging wall is supported by pillars with variable spans, depending upon the distance between pillars; with long spans the swing between pillars is great, and the bending or drag is correspondingly large, with increased pressure thrown upon the face of the pillars. (See fig. 15.) The effect of live loads is to cause rock bursts, while with static loads and particularly with pressure concentrated on the face of the pillars slow demolition of pillars results. The drag of the sagging hanging wall pulls away from the pillars, causing the tops to
overhang and gradually to assume a concave face from which fragments are broken by flaking and wedging. With shorter spans of hanging wall the pressure is more directly downward or normal to the plane of the lode, when spalling and wedging are the usual modes of failure, particularly marked when heave acts. (See figs. 16 and 17.)

![Image](image-url)

**Figure 15.—Pillar distorted by drag of hanging wall (Birmingham, Ala.)**

In the copper mines all degrees of action can be observed from quiet, slow, continuous movement to sudden and violent bursts, the fragments projected from the face ranging from fist size and smaller to masses weighing several hundred pounds. As previously intimated, there are slight grounds for considering that internal
stresses occur in the rock or that remnants of regional strains persist, yet local manifestations, such as the irregular occurrences of bursts on the walls of drifts, would seem to indicate that strains do exist. However, such localized action may be due to lines of weakness directing and concentrating pressure at certain points. The more or less orderly occurrence of bursts as noted may be connected with the more pronounced slips, which occur according to a definite system.

Pillars may fail through shear parallel with the dip, with the strike, or between them, that is, diagonal with the dip. They are caused by drag, thrust, or direct pressure, and all are affected by the presence of slips. (See figs. 18 and 19.) Stulls and posts fail by direct pressure, usually without lateral movement, the shortening being taken up to a certain extent by compression, beyond which the timber fails by brooming, splitting, and spreading out radially, umbrella wise, or by making an abrupt bend at one end. (See figs. 20, 21, and 22.)

When subjected to great pressure of the hanging wall following extensive failure of adjacent pillars by rock bursts large timbers 8 feet long have been observed to bend several inches out of line in the middle and constitute the only evidence that hanging or foot walls have moved, as no fracturing occurs.

WHERE ROCK BURSTS OCCUR IN MINES

Various parts of mines are particularly susceptible to rock bursts but depend largely upon the conditions and factors already set forth, such as the character of lode and wall rock, the dip of lodes or beds, the depth of workings, and the method of mining. Pillars and angu-
lar projections of stope walls in large worked-out areas are particularly subject to violent bursts, which may be classed as pressure bursts, while rock bursts in shafts, drifts, crosscuts, and all narrow work are in the nature of strain bursts, with the possible exception of some bursts in shafts. However, a condition that may affect the magni-

![Image](image-url)

**Figure 17.—Breaking down of pillar by wedging due to heave**

tude of the disturbance and partly account for the difference noted is the effect of blasting in large and narrow openings, the latter often being badly fractured. Furthermore, the natural lines of weakness, such as joints, slips, or crossings, affect the resistance of rock to failure more on a large free face than in small openings, all
factors that should be given due consideration in discussing the location of rock bursts in mine workings.

It is probably safe to say that narrow openings, such as drifts and crosscuts, are subject to the most violent bursts, although, as they are more confined, the effect may appear to be greater than similar occurrences in open stopes. Violent bursts probably occur most frequently in the arch pillars, "bottoms," or "bridges" of ground when being removed, particularly as the levels are approached. Angular projections of ground or "spurs" are also very susceptible to concentrations of pressure and often suffer severely from bursts. Shafts and stopes are often badly damaged or de-
molished by violent bursts from the walls. Drift and stope pillars are particularly subject to the less violent forms of failure, such as spalling and wedging. (See figs. 3 and 5.) Drifts and crosscuts may have the whole perimeter affected by a burst, which has been

![Figure 20.—Stulls falling under pressure of hanging wall](image)

responsible for the theory of the rock pressures or strains acting hydrostatically. (See fig. 23.) On the other hand, the walls of all openings, large or small, may show an effect resembling a blast with a slow-acting explosive, in that large masses of rock are broken

![Figure 21.—Stulls falling and spreading under pressure](image)

and separated from the face, rather than the violent shattering action of a high explosive. (See figs. 24 and 25.) In shafts the action may be confined to the sides or ends of the sections, probably the most pronounced action being on the sides; slower failure occurs on
the ends. Shaft pillars may fail through bursts on the shaft or stope sides, due to concentration of pressure from workings. The hanging wall is not ordinarily subject to bursts, although several pronounced occurrences have been observed that were not the result of failure and collapse of hanging wall but definite bursts, crater-like cavities being formed. Bands of sandstone in the conglomerate copper lode may cause the hanging wall to fail, the sandstone breaking out and exposing considerable areas of hanging trap; under such conditions the failure is not in the nature of a rock burst, although the trap may be fractured and weakened by the outburst in the conglomerate and sandstone.

Barren ground is more susceptible to rock bursts than mineralized rock; consequently remnants of the lode rock left as pillars, being
nonpay rock, are more prone to bursts than are pillars formed of pay rock.

Rock bursts have occurred in all parts of the copper mines mentioned, very severe bursts having occurred in shafts, levels, and stopes. The ends of the sections have been hurled into the shafts, accompanied by falls of wall rock, the top falling and the bottom heaving. Violent failure has occurred on both sides of shaft pillars in the conglomerate lode, due to concentration of pressure as the stopes approached the shafts. Next to shafts as points where rock bursts occur the removal of arch pillars or "bottoms" has proved
dangerous. Numerous violent bursts have occurred both in the usual operation of cutting out the arches and in removing them by a second or robbing operation. There has been extensive failure of levels by the breaking down of pillars on the hanging-wall side, thus permit-

![Figure 26.—Failure of hanging wall accompanying rock burst](image)

ting the hanging wall to fall, crushing the timbers at the bottoms of the stopes. (See figs. 26 and 27.)

The heaving of the footwall rock has a marked influence upon disturbances in levels and probably contributes very materially to their cause and effect. Heave may be slow or sudden and violent. Under the former conditions the levels may be ultimately filled with small-size broken rock; in the latter instance masses of footwall rock are often forced upward, filling the level from the footwall side. (See

![Figure 27.—Hanging wall fallen through weakening by rock burst](image)
figs. 28, 29, and 30.) The former action may be brought about by pressure transmitted through the pillars, while the more violent action is probably the result of live loads acting as bumps. The live loads may be transmitted through both hanging and foot walls, the combined action setting up rock bursts in the intervening pillars. Bumps have been particularly severe at times, as when extensive failure was occurring in the abandoned and caving stope, the effects of the live loads being felt in levels considerable distances from the origin of the action. Men have been hurled off their feet; heavy bodies, such as engines, cars, and pumps, have been bounced from the levels some distance into the stopes above; and masses of ore have been thrown about.
AIR BLASTS IN MINES

The term "air blast" was formerly employed to designate all phenomena relative to violent failure of pillars in mine workings, accompanied by more or less violent movement of air. As experience and information accumulated and broadened, it was recognized that not all violent bursts were in the nature of air blasts or rushes of air, and a division or classification separating the two types of phenomena was made. Air blasts occur, but not all rock bursts are air blasts; in fact, the vast majority of rock bursts are not accompanied by violent movement of air. However, evidence is conflicting, and it is probable that considerable movement of air occurs with the more violent outbursts of rock.

![Figure 30.—Masses of footwall thrust upward because of heave](image)

In the copper mines there have been extensive rock bursts with a movement of air no greater than would be produced by moderate blasting; on the other hand, the bursting of the end of a small pillar in a stope has hurled men 15 to 25 feet up the stope if they were in such a position as to be protected from flying rock. In other instances men and cars have been hurled considerable distances along drifts, and timbers have been displaced and thrown about.

Actual air blasts have occurred in at least two mines in the district, the Atlantic and the Wolverine; in both of these mines large blocks of ground collapsed suddenly because of inadequate support and closed large areas of open stopes. The air being expelled violently from the workings through the shafts caused much damage underground and forced out of the mine great volumes of air charged with dust, dirt, and small fragments of rocks, sticks, and other débris, which rose 150 feet or more in dense columns, the
larger pieces of rock, sticks, clothing, and débris falling back at a height of 50 to 60 feet. The air was so filled with dirt and small particles of ore that they obstructed the view and cut the face and hands like a sandstorm. Furthermore, everything in the mine was covered with a thick layer of dust, so thick, in fact, that it was difficult to distinguish the bodies of men killed in the blast from rock and timber.

The source of the fine particles and dust that cover the rock and timbers following a rock burst is the grinding action of the fragments during the fracturing and outburst of the rock, while in dry workings much may come from the workings themselves when stirred up and swept along by the force of the outburst. Rock bursts accompany the fall of blocks of ground but are the result rather than the cause of the air blasts.

**MISCELLANEOUS INFORMATION**

Rock bursts occur in groups or series, rarely singly, that is, throughout periods of days, weeks, or months. Usually they build up in strength or magnitude to a maximum, then diminish in intensity and fade out. In the South African gold mines, where seismographs have been installed to permit study of rock bursts, the shocks ranged from 13,000 to 17,000 per annum, but only 10 per cent were considered heavy. They occurred with the greatest frequency in these mines during June and February, the largest number occurring in June. In the copper mines more than 300 have occurred in a day, but probably 10 to 20 is a more usual number. Although they have occurred throughout the year, the last and probably most pronounced series of rock bursts began in November, 1927, reached the maximum in the latter part of December, and died out in June of the following year. The time of day seems to be unimportant, but if a distinction could be made they occurred more in the daytime, particularly in the forenoon.

As a rule, considerable noise accompanies a rock burst, ranging from a grating, grinding sound to reports of a wide range of intensity, often resembling explosions of powder or having a sound like a clap of thunder. Although some sound practically always accompanies tremors felt on the surface, it is seldom loud, being a grating, rumbling noise.

Tremors have been felt 12 to 15 miles away, but 3 or 4 miles is more common. In the copper mines of Michigan shocks have been distinctly felt up to 6 and 8 miles. Furthermore, rock bursts have occurred simultaneously in mines 15 and 20 miles apart, coupled with an unstable condition in stopes in certain parts of the mines, small pieces of rock falling continuously. What common condition,
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if any, existed is not known and is problematic. As a rule, shocks and tremors are more severe on the surface than underground, except locally where the outbursts occur.

Fracturing of the surface, even the formation of fairly wide cracks, often results from rock bursts and air blasts, the effect of the former being more extensive than the latter. The surface may be affected by rock bursts one-half to a mile or more from the outcrop, while the effect of air blasts is usually confined to an area 100 to 200 feet from the outcrop.

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The terms “pressure” and “strain” bursts indicate the cause of rock bursts and in a general way the character and magnitude of the effect. The former are usually slower in action, although they cover a wide range of action and effect, whereas the latter are localized and usually sudden and violent. Furthermore, pressure bursts are probably responsible for rock bursts in large openings, such as stopes, and produce ground movement accompanied by tremors or quakes, while strain bursts occur in narrow workings, often causing considerable damage and loss of life.

Pressure bursts are due to the load of the overlying rock masses concentrated on pillars in workings through the direct weight of a mass known as the arch block or direct-pressure block and the removal of considerable areas of the lode rock. Strain bursts are explained by strains and stresses set up in the rocks by the folding of beds, cooling of igneous rocks, and thrusts along the dip. The change from static to dynamic pressure may contribute very materially to both pressure and strain bursts; the resulting action being designated as bumps may have a very destructive effect upon workings.

The phenomena associated with pressure bursts range from a slow action, such as flaking, spalling, and wedging, to the extensive crushing of pillars and breaking and collapse of top and hanging-wall rock. Levels and the adjacent stopes are closed by crushed pillars and caved hanging wall, and tremors may be set up by the resulting vibrations that are felt over large areas. Strain bursts are violent, breaking down the walls of shafts, drifts, and crosscuts and filling them with fragments of broken rock from the pillars and rock fallen from the hanging wall; however, little or no hanging-wall rock falls except locally where the rock is weak and may be affected by sudden release of support through failure of the pillars. The most visible effect of bumps is on the footwall side of levels and drifts, where the bottom rock is heaved, timbers crushed, etc. (See fig. 30.)
Violent movement or rushes of air may accompany rock bursts, but such action is the exception rather than the rule; however, air blasts are not uncommon but are due to the fall of large masses or blocks of ground after an extensive failure of support in stopes. Air ejected from such openings if escaping through small openings may attain high velocities, with possible damage to workings and loss of life.

With increased depth of mining and the higher rock pressures that follow, rock bursts have increased in magnitude and intensity, leaving little reason for doubt that the weight of the overlying rock is the direct cause. Their prevention and abatement are, then, problems of deep mining whose solution is becoming increasingly important.

PREVENTION AND CONTROL OF ROCK BURSTS

It has been said that "while nature is primarily responsible for the condition of unstable equilibrium, the immediate agent is man, who interferes with forces beyond his control." It is possible, however, to control in part the occurrence of rock bursts by employing mining methods particularly adapted to that end. As in all other phases of mining, economy of operation is the controlling factor, and all proposals advanced must be subject to the acid test of costs; consequently suggestions that involve increased cost of development, working, support, or handling, either directly or indirectly through reduced extraction of pay rock, can not be seriously considered.

The control or subsequent diminution in effect of rock bursts would seem to be the most desirable end sought rather than prevention, which involves a careful investigation of conditions affecting their occurrence and elimination or easement thereof. Of prime interest in this connection is the gathering of information on the character of the forces acting to produce outbreaks. That is, is it pressure alone or do strains exist? What is the relative importance of static and dynamic loads? Although it can not be expected that more than approximate estimates can be made, both positive and relative information are important. Without such information forces that might act must be considered as probably effective, and all must be considered; therefore, static and live loads and strains constitute the forces that must be given consideration.

SUGGESTIONS ON THE PREVENTION OF ROCK BURSTS

The weight of the overlying rock mass, within definite limits, is the static load, and for its control the following means have been suggested and employed:
1. Small pillars that are expected to crush and cushion settlement of hanging wall can be left systematically arranged. If pillars can be formed of poor rock, their use might be permissible; but pillars so formed are very likely to be arranged so irregularly as to defeat the end sought.

2. Rock-filled cribs, also employed to cushion settlement of the hanging wall, can be built. Their use has proved their value.

3. The hanging wall can be blasted down after the stopes are cleared.

4. Block mining can be employed, leaving 50 per cent of the lode to be removed following the filling of stopes with caved rock.

5. Stopes can be filled with waste rock that must be disposed of or obtained from old stopes adjacent to the workings.

6. Longwall faces should be worked if possible, the working face being run "end on," that is, parallel with the slips rather than across them. The faces should be as long as possible.

7. Rapid work is essential even to the employment of concentration methods, but care should be taken that the areas so worked are well distributed and balance other unworked areas.

8. Leaving isolated areas should be avoided, but if they are necessary, as when poor ground is penetrated, they can be offset by artificial supports, such as rock-filled cribs.

9. Rock-filled cribs are preferable to pillars, and they should be used even where it is evident that they will be inadequate as final supports.

10. In working parallel beds or lodes the pillars or supports in the separate workings should not be superimposed. The same is true of working faces; the upper lode should be mined first.

11. The retreating system of mining can be employed. This may be the cut-and-fill, shrinkage, or any other method that may prove most satisfactory, according to occurrence of lode, dip, etc.

Methods of working based upon the above suggestions relative to practice have under certain conditions proved satisfactory; under other conditions of occurrence of lode and wall rock they have not been so desirable; but, as a whole, they have improved conditions, acting as a control if not a preventive of rock bursts.

If pillars are to be employed they should be considered as temporary support only, and there should be a direct relation between the mined and unmined areas. The ratio will vary with depth, 1 to 5 up to 1 to 2 or 1½ per 1,000 and 5,000 feet, respectively, or, stated otherwise, 20 up to 50 or 66 per cent, which would be prohibitive if the pillars were formed of pay rock, as they would probably have to be regularly arranged.
Rock-filled cribs come the nearest to rigid support of the various forms of artificial constructions, but they are expensive to build and can not be extensively employed. (See fig. 31.)

The use of caved rock to support the hanging wall has decided advantages, not the least of which is that of economy. The value of loose rock as a support for walls of pillars and stopes is well known, and while it is far from rigid will relieve the pressure on pillars by preventing the sag and drag of the hanging-wall rock and by the cushioning effect will permit the weight of the overlying rock mass to be distributed rather than concentrated on the pillars. Furthermore, the fractured hanging wall will be made more stable and therefore more easily supported, shocks and vibration of whatever nature will be dampened, and their effect will be diminished.

![Figure 31—Rock-filled cribs on hanging-wall side of drift](image)

The chief advantage of block mining is that of safety throughout the entire work of mining, but reduced extraction may result from caving of the hanging wall in the last stages or robbing of the remaining block inclosed by caved ground.

Stopes filled with waste rock will not prevent rock bursts but may so diminish their effect as to render them innocuous. Nothing short of rigid support will take the place of pillars and prevent movement that usually results in rock bursts. Filling brought into the mines is too expensive and can not be considered in this connection.

The employment of longwall faces in mining, particularly when they are worked to take advantage of such lines of weakness as slips, may sacrifice ease and economy of breaking ore to safety from rock bursts.
Continuous if not rapid work is essential to freedom from outbursts in drifts and stopes, except that once rock bursts start work should cease promptly until the trouble is past.

Irregular and isolated areas, as well as angular projections in workings, should be avoided, as they are potential sources of failure, usually of a violent nature. A few well-placed rock-filled cribs are more satisfactory than a larger number of irregularly placed pillars of ore or poor rock.

Application of the retreating system to a wide range in character, width, and dip of lodes has demonstrated its adaptability to change and modification. It has, furthermore, had a modifying and minimizing effect on the disastrous results of rock bursts, although it does not prevent their occurrence.

Various suggestions have been made relative to the protection of shafts from the effect of rock bursts. These include the following:

1. Give the shaft ample clearance to permit removal of broken timbers and rock and ease pressure on the walls.

2. For shafts in the lode stope out 50 to 100 feet on either side and fill with waste rock, not rigid support.

3. Leave no pillars above shafts placed in the footwall; the weight will then come on the pillars at the ends of the shafts.

4. If a shaft is in the hanging wall above the lode, leave pillars that extend back of it and to the sides, or, if it is stoped out, place as rigid support as possible.

5. Leave pillars large enough to prevent fracturing in the vicinity of shafts.

6. Place shafts in the footwall 100 feet or more from the lode.

Drifts and crosscuts may be protected by forming the tops when driven according to the angle of break of rock, but such "arched" tops can not be conveniently supported with timbers if use of the latter becomes necessary. Levels should not have pillars left directly above them, but if support is necessary rock-filled cribs should be used.

Other measures have been suggested and employed, more to protect the miners than to prevent rock bursts. The following are among the more important: The use of squeeze blocks, forming a capping to posts and stalls; the employment of facing boards at the working face; the drilling of "stab holes" in the face to a depth of 3 or 4 feet in which small charges are fired fracturing the pillars; and the use of temporary supports as props to check movement and give warning of increasing pressure. Where outbursts can be anticipated, adequate support should be provided, such as small pillars that are expected to fail and give warning of concentrations of pressure of the hanging wall.
In general, it may be said that timber, regardless of how it is placed and the amount used, can not take the place of solid pillars in the support of workings. Unless filling is rigid, a practically impossible condition, it will not prevent but may materially reduce and minimize the effect of rock bursts and by distributing pressure may prevent its concentration. These results may also be obtained by employing mining methods particularly suited to existing conditions and evident susceptibility to rock bursts. With great depth of mining artificial support can not and will not prevent outbursts of rock due to pressure, as it is greatly inferior to the natural rock as a supporting medium. The movement of rock masses will and must take place, and it is only by control thereof that mining can be made possible. Failure of support can not be prevented and when it occurs results in a corresponding failure of the remaining natural supports as pillars.

**COMMENTS AND SUGGESTIONS ON PREVENTION OF ROCK BURSTS IN COPPER MINES**

In view of the conditions affecting working that exist in Michigan copper mines and as a result of observations therein, the following comments and suggestions are made to supplement those already discussed: Rock bursts are due to pressure that acts in different ways but is induced by the weight of overlying rock masses. The load directly overhead and acting vertically is of the most importance and is resolved into normal and parallel components, with a remnant of the vertical load acting. The weight of beds or layers in the hanging wall acting on the line of dip produces a thrust that increases the magnitude of the normal component and the action of live loads, resulting in bumps effective in both hanging and foot walls. Observation in the mines indicates the presence of strains and stresses that are thrust rather than regional strains; the irregularly localized action in the pillars and hanging-wall rock is evidently produced by strains.

Heave in the footwall rock is due to both static and dynamic loads. The former causes a slow filling of levels and stopes by pressure transmitted through pillars; the latter causes sudden and violent upthrusts of the rock, often in large fragments. (See figs. 28 and 30.)

Numerous observations taken in abandoned stopes on angles of break of hanging-wall rock have shown that there are final or ultimate angles of break beyond which failure is due to ground movement on a large scale rather than to the normal process of failure under the action of gravity. (See fig. 1.) The application of the ultimate angles of break to the tops or backs of drifts and crosscuts will go far toward making them permanent and eliminating timber as
support. The same condition applies to all openings and should be
given due consideration in the development of mines, particularly
when susceptible to extensive failure, either slow or rapid, for rock
under stable equilibrium is much easier to support than when prone
to fall through the drag of gravity.

Thrust strains may be largely overcome by caved stopes that break
the continuity of the layers of rock in the hanging wall, thus sub-
stituting broken for solid rock. The regular and systematic caving
of the hanging wall should materially relieve strains that contribute
to rock bursts, but unless the caved ground extends considerable
distances vertically it may be overridden and a distinct but
diminished effect will result.

As fractured rock is not subject to violent outbursts ground reg-
ularly and systematically fractured may prevent such disturbances.
The extension of the practice of drilling short stab holes to longer
holes placed in pillars where outbursts are liable to occur, with or
without small charges, might serve a useful purpose, and as pre-
viously indicated a similar practice could be applied to the hanging
wall.

**BIBLIOGRAPHY**
