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A REVIEW OF THE EFFECTS OF EARTHQUAKES ON UNDERGROUND MINES

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CONTENTS

ILLUSTRATIONS

Tables

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By Peter R. Stevens[1]

ABSTRACT

The nature and geography of earthquakes is summarized and the effects of earthquakes on underground structures, due both to the causative process, faulting, and the secondary process, shaking, primarily in the continental United States, is reviewed. The principal sources of information are eyewitness reports, as instrumentally derived seismological data have been available for only about 70 years. Reference is made to the results of instrumented studies in mines and data pertaining to mine bumps and rock bursts in mines. The perceptibility and physical effects of earthquakes in mines and underground workings deserve more systematic study than they have received. Severe damage is inevitable when a mine or tunnel intersects a fault along which movement occurs during an earthquake. Mines in the epicentral region of strong earthquakes, but not transected by fault movement, may suffer severe damage by shaking. Mines outside of the epicentral region are likely to suffer little or no damage from a strong earthquake. Other factors being equal, it appears reasonable that the severity of damage due to shaking would probably be least in a mine located in fresh, highly competent rock; somewhat greater

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damage would probably be expected in a mine in weathered or less competent rock; and the greatest damage would be expected in a mine located in loose unconsolidated or incompetent rock.

PURPOSE AND SCOPE

The purpose of this paper is to review the literature pertaining to the effects of earthquakes on underground mines, to determine whether or not underground mines have been damaged by seismic activity, and to record the nature and extent of such damage as may have been reported.

Requests for pertinent information were made to Federal, State, and Foreign agencies concerned with mining, geology, and seismology, and to several recognized authorities in these fields. This paper is primarily concerned with the continental United States. Effort was concentrated on the most seismically active areas. In the United States seismic activity is generally greatest in a narrow belt fronting on the Pacific Ocean and decreases eastward through the Basin and Range and Rocky Mountain Provinces.

Instrumentally derived seismological data have been available for only about 70 years. The principal sources of information for this study have been eyewitness reports which are subject to error, especially when the observations are made under conditions of surprise, mental stress, and fear. Such accounts are frequently difficult to appraise because pertinent details are often omitted. In the early days much of the country was unsettled, communication was difficult, and much of the information has been gathered from newspapers. It is quite possible that when the greatest earthquake intensity was in a remote and isolated area, no reports were received. Many mines are located in remote areas and unless significant damage occurred, it is quite possible that no report was made.

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NATURE AND GEOGRAPHY OF EARTHQUAKES

Earthquakes result from stresses which accumulate in rocks composing the outer 700-km of the earth's shell. The origins of these stresses are imperfectly understood as to the source of energy and the mechanism by which this energy is converted to strain. It is generally assumed the energy is of thermal origin (radioactivity, cooling of the earth, etc.) although gravitational forces may also be involved. Transfer of thermal energy into mechanical energy or elastic strain may be accomplished by the following mechanisms: 1) convection currents; 2) change of phase or state; 3) expansion; 4) contraction; 5) diffusion processes; and 6) possibly other as yet unknown mechanisms.

Earthquakes are generally believed to result from release of slowly accumulating strain in crustal rocks due to sudden rupture of the rock in accordance with the elastic rebound theory of Reid (1910). According to the elastic rebound theory, an earthquake is initiated at a point where the gradually accumulating elastic strain becomes equal to the strength of the rock and rupture occurs. The rupture surface is commonly called a fault. Two principal wave types are produced during an earthquake, longitudinal and transverse, which proceed with different speeds depending upon the physical properties of the rock. Longitudinal waves (P, compression waves) always travel faster than transverse waves (S, shear waves).

The energy is not propagated uniformly in all directions and the directional pattern of longitudinal waves is not the same as that of transverse waves. The directions of maximum radiation of transverse waves and minimum radiation of longitudinal waves lie parallel and perpendicular to the fault in the plane defined by the greatest and least compressive stress axes, whereas the longitudinal radiation pattern has minima in the direction of the fault plane and at right angles to it. In earthquakes the amplitudes and periods of the transverse waves are usually greater than the amplitudes and periods of the longitudinal waves. P and S waves travel through the interior of the earth.

There is another class of waves that travel along the surface only. These are surface waves and include the types known as Love waves and Rayleigh waves. In seismology, when an S wave is polarized so that all particles of the substance move horizontally during its passage, it is denoted SH; when the particles all move in vertical planes containing the direction of propagation, the wave is denoted SV. In most cases, the destruction produced by shear waves is greater than that produced by the other types of waves.

The point at depth where faulting is initiated is called the focus or hypocenter. The surface point vertically above the focus or hypocenter is called the epicenter. From the focus or hypocenter faulting proceeds along the fault surface in two dimensions. The direction of slip on the fault may be horizontal, vertical, or a combination of the two. Under favorable conditions the first motion of the ground recorded on a seismograph reflects the direction of slip on the fault. The intersection of the fault with the surface of the earth is the fault trace. The epicenter of an earthquake is usually not on the fault trace except when the fault surface is vertical.

The energy released in the greatest earthquakes is very roughly equivalent to 10,000 of the original atomic bombs, such as the one dropped on Hiroshima; the energy released in the smallest felt earthquakes is approximately equivalent to the energy released in the explosion of 1 lb (453.6 grams) of TNT. Because it is not simple to calculate the energy of earthquakes from generally available data, Richter (1935) devised a magnitude scale for classifying earthquakes by 'size' or 'strength' at the earthquake source on the basis of instrumental data. The scale is based on the maximum recorded amplitude of a standard torsion seismograph located at a distance of 100-km from the source for shallow earthquakes. The scale is logarithmic; thus a magnitude 8 earthquake represents recorded amplitudes 10 times larger than those of a magnitude 7 earthquake, 100 times larger than a shock of magnitude 6, etc. Empirical tables were constructed for calculation of the magnitude at all epicentral distances and for various focal depths and for several types of waves. Each whole unit increase in magnitude represents approximately a 30-fold increase in energy release.

Whereas magnitude is an instrumental measure of the size or strength of an earthquake, seismic intensity is a subjective measure of the violence of shaking at a given point. The scales of intensity, such as the modified Mercalli scale (table 1), are based on the effects of ground vibration on people, structures, and natural objects. Intensity varies from point to point depending on the distance from the source, the nature of the structures or objects involved, the density of the population, and the effects of ground conditions at the site and along the propagation path. In reference to the effects of ground conditions on intensity, Richter (1958, p. 143) states, "Isoseismals drawn from adequate data are rarely circular and often show elliptical elongation in the direction of the major structural trends." (Isoseismals, or lines of equal intensity, are commonly mapped as boundaries between areas of successive intensity ratings, such as IV and V.) "There is often a longer continuous extent of competent rocks along a structural trend than in the transverse direction; when the waves emerge from such rocks into alluvium or unconsolidated sediments there is considerable absorption, accompanied by increase of local intensity."

Table 1.--Modified Mercalli Intensity Scale of 1931 (Abridged)

I	Not felt except by a very few under especially favorable circumstances. (I Rossi-Forel Scale)
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to III Rossi-Forel Scale)
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale)
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V Rossi-Forel Scale)
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale)
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale)
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars. (VIII Rossi-Forel Scale)
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys factory stacks. columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII to IX Rossi-Forel Scale)

X Damage <u>considerable</u> in specially designed structures; well-designed frame structures thrown out of plumb; <u>great</u> in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel Scale)

X Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Land slides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale)

XI Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII Damage <u>total</u>. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward into the air.

The increase of intensity on emergence from rock into alluvium is followed by relatively rapid falling off of intensity with distance in the alluvium but, even at a distance from basement rock, soft ground is especially subject to heavy shaking.

Often large earthquakes are preceded at intervals of hours or days by foreshocks, usually small. A foreshock increases the stress on the fault in its neighborhood and thereby may hasten the break of the main shock although the final increment of gradually accumulating stress may also be a result of some external force such as tidal stress or of some weakening mechanism in the rock such as increased pore fluid pressure. A large shallow earthquake is typically followed by thousands of aftershocks of smaller magnitude. The frequency of occurrence of aftershocks is greatest immediately following the principal shock and decreases rapidly with time so that the sequence usually ends within 1 or 2 years. A large earthquake sometimes is followed within a few hours, days, or months by another of similar or greater magnitude in the same area. Occasionally swarms of small earthquakes occur without any principal large shock.

The majority of earthquakes and those with the greatest energy occur in the upper 40-km of the earth's crust. Deeper earthquakes occur with decreasing frequency down to 250-km; below 250-km the frequency of occurrence per unit depth interval becomes about constant to a depth of 700-km.

Although earthquakes may occur anywhere on the earth, epicenters occur chiefly in a few narrow belts or zones. The great majority are concentrated in the circum-Pacific belt (figs. 1 and 2), which includes about 80 percent of the shallow shocks (i.e., focal depths less than 60-km), 90 percent of shocks occurring at depths between 60- and 300-km and nearly all of the deeper ones (Benioff and Gutenberg, 1955, p. 131). Nearly all of the remaining large shocks at intermediate and shallow depths occur in the Alpide belt. A smaller number of earthquakes including a few major shocks occur along the principal ridges of the Atlantic, Arctic, and Indian Oceans. The Pacific basin and the continental shields are relatively aseismic.

In the Americas, earthquakes occur most frequently in the arcs fronting westward on the Pacific basin; the Aleutian-Alaskan; the Californian; the Mexican; the Central American; and the Andean. Two arcs, one in the West Indies and one in the south Atlantic, front eastward on the Atlantic Ocean.

Figure 3 shows locations for all known historic earthquakes with intensities of V or greater in the United States through 1970. Earthquakes in California and western Nevada represent approximately 90 percent of the seismic activity of the continguous United States. Most of these shocks occur at shallow focal depths (16- to 24-km) and along known faults or fracture zones. In California, the major tectonic trend is roughly northwest-southeast; the faulting is primarily strike-slip in character and is dominated by a master fault system, the San Andreas.

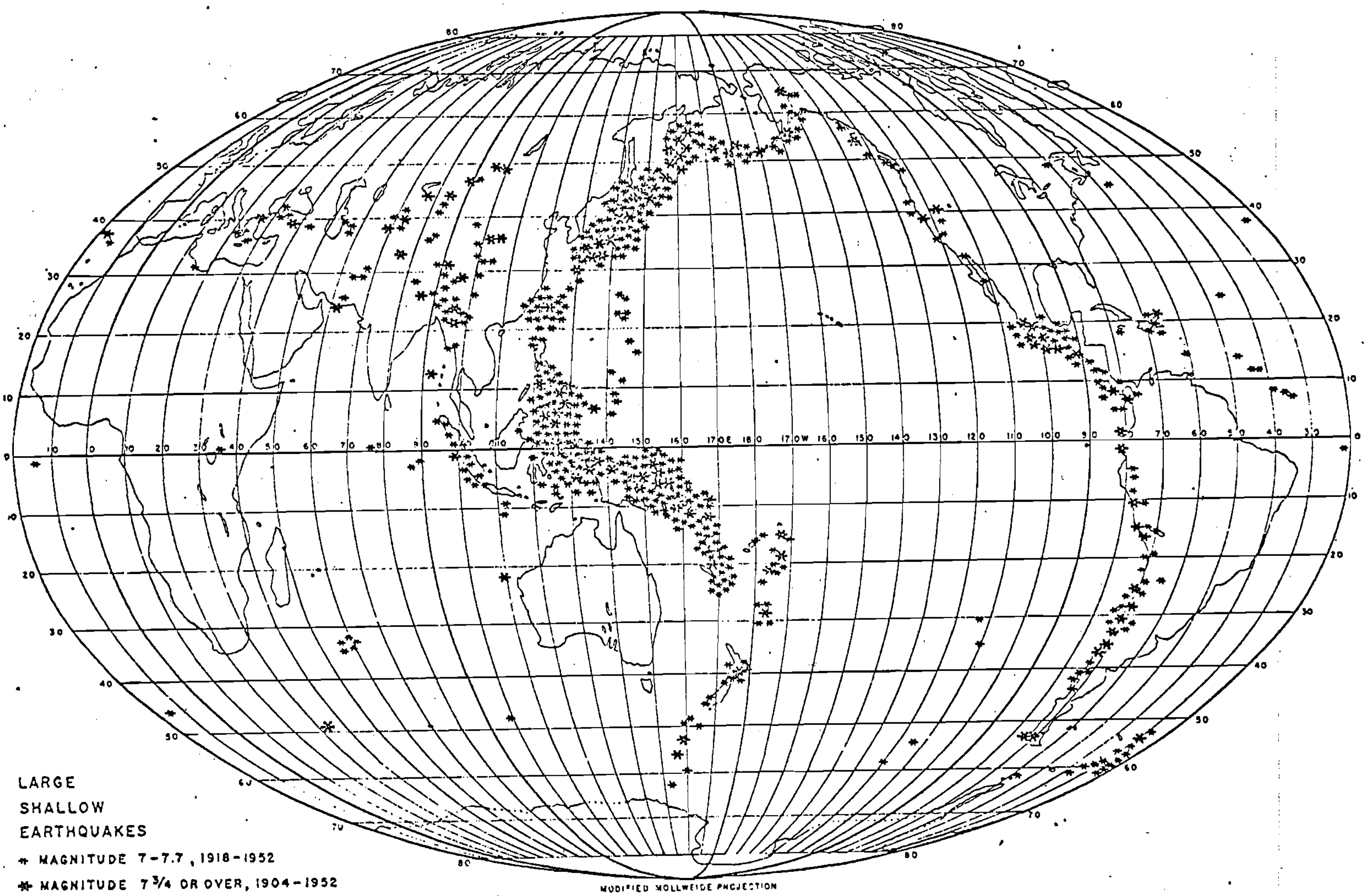

Figure 1. World map of shallow earthquakes.
After Gutenberg and Richter (1954).

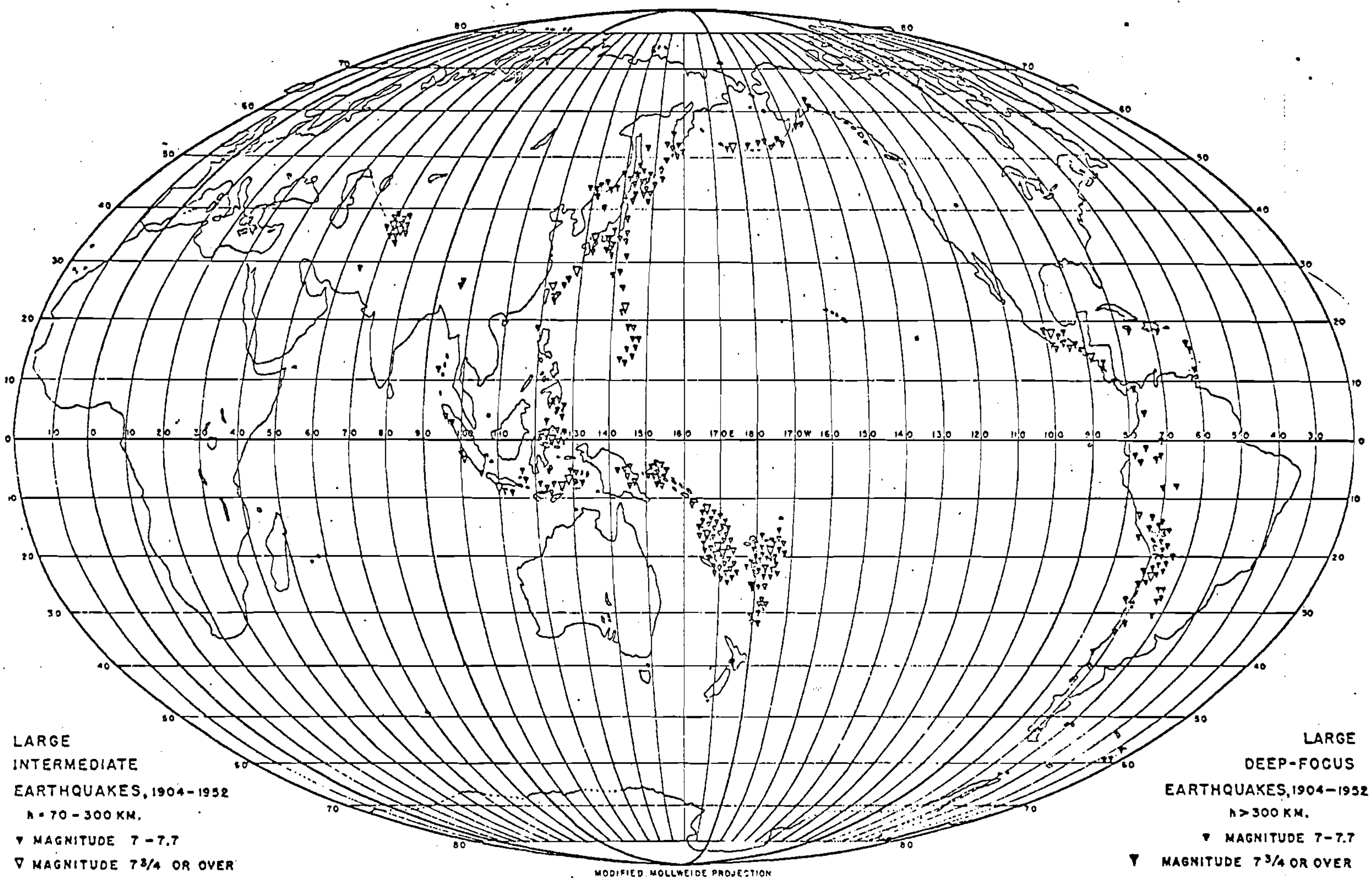

Figure 2. World map of deep-focus earthquakes; all known shocks of magnitude 7 and over, 1905-1952.
After Gutenberg and Richter (1954).

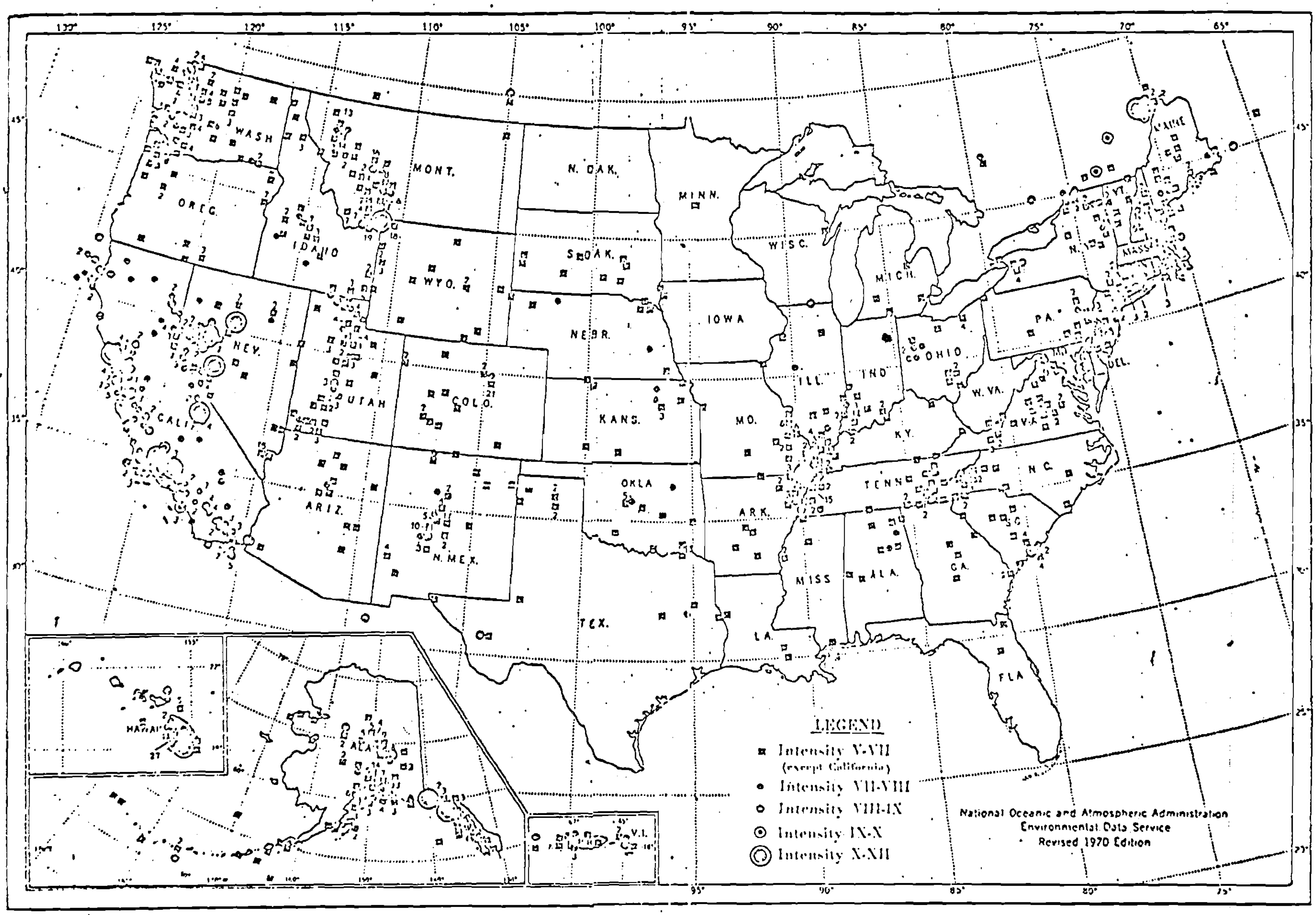

Figure 3. Earthquakes (intensity V and above) in the United States through 1970.

Many earthquakes of intensity V or greater have occurred in Washington and Oregon; others occurring either offshore, in British Columbia, or in adjacent states have been felt. Most of the shocks occurred in the western part of the area; the strongest shocks have been in the Puget Sound area.

Alaska and the Aleutian Islands are part of the circum-Pacific seismic belt and earthquake activity is greater here than in any other state. Two principal seismic zones are present; one extends from Fairbanks through the Kenai Peninsula and along the Aleutian Islands; the second zone extends from north of Yakutat Bay southeastward to the west coast of Vancouver Island. Two of the notable earthquakes of the last century, including one accompanied by the greatest known vertical deformation of the ground, have occurred along the second zone.

Much earthquake activity has occurred in the Rocky Mountain and intermountain areas to the west. Many of the earthquakes have occurred in sparsely populated regions and accounts have been inadequate although some of the shocks have been of considerable severity.

Seismic activity in the non-mountainous central region of the United States is generally low except for the upper Mississippi and Ohio Valley areas where earthquakes are relatively frequent. In 1811-12, three of the great earthquakes of known history occurred near New Madrid, Mo., in the Upper Mississippi Valley.

A moderate amount of low-level seismic activity is associated with the Appalachian Mountains in the eastern part of the United States. In addition, major earthquakes such as the Charleston, S.C., earthquake have occurred along or off the Atlantic coast. New England and New York contain zones of relatively high seismic activity and are also affected by large earthquakes originating in the Laurentian trough and St. Lawrence River Valley.

EFFECTS OF EARTHQUAKES UNDERGROUND

Effects Due to Faulting

Earthquake effects may be classified as primary, due to the causative process, such as faulting, or secondary, due to the passage of elastic waves generated by the primary process.

Displacement along a fault involves forces which are virtually irresistible so far as man-made structures or excavations are concerned. Some man-made excavations and structures have been so unfortunately located as to be damaged in this manner.

In the San Francisco earthquake of 1906, two tunnels on the narrow gage Southern Pacific Railroad were damaged. The 213.97-m deep, 1,863-m tunnel (Wrights No. 1, Santa Cruz Mts.) at Wright Station was offset 1.37-m transverse horizontal where it crossed the San Andreas fault. Other damage consisted of the caving of rock from the roof and sides, the breaking in flexure of upright timbers, and the upward heaving of rails and breaking of ties. The 1,737-m tunnel, 206.65-m deep (Wrights No. 2, near Glenwood) directly to the south did not cross the fault and was somewhat less damaged from shaking; timbers were broken and the roof caved blocking the tunnel at several points. The Morrell house, which stood above the No. 1 tunnel and was on the San Andreas fault, was torn in two.

The Izu earthquakes in Japan in 1930 occurred along the Tanna fault which intersected one of the drain tunnels which extended ahead of the Tanna Tunnel connecting Atami and Mishima and which was under construction during the earthquake. At a distance of about 0.61-m beyond the main tunnel heading, faulting resulted in transverse horizontal offset of 2.29-m. The only damage to the main tunnel was a few cracks in the walls. In Karuizawa, 160-m above the tunnel, 55 percent of the dwellings were thrown down and at Tanna and Hata, nearby villages in the Tanna basin, 40 percent of the houses were destroyed. Surface displacements along the fault occurred over a distance of 24-km. The Tanna basin consists of about 40-m of unconsolidated lakebeds of sandy clay and boulders overlying andesite and agglomerate through which the tunnel passes.

During the Imperial Valley, California, earthquake in 1940, an abode structure astride the fault trace was demolished and Southern Pacific Railroad was broken by strike-slip faulting, both at Cocapah. Direct breaking and offset of roads, canals, and irrigation ditches by faulting also occurred during this earthquake.

Four tunnels on the route of the Southern Pacific Railroad between Bealville and Tehachapi cross the White Wolf fault zone and were greatly damaged by the Kern County earthquakes of 1952. Tunnel No. 3 was heavily damaged at its Tehachapi end and 61-m of its original 213-m length was daylighted after the quake. An active fault crossing the tunnel was found during daylighting. At one place, the buckled rail extended under the concrete wall, indicating the wall had raised sufficiently to permit this. No. 4 tunnel was badly shattered and subsequently daylighted for its full length. Tunnel No. 5 was badly damaged. Cracks and holes were formed in the ground above, and rock and soil flowed through these openings into the tunnel. The roof collapsed in several places, but the tunnel was reconstructed without daylighting. Tunnel No. 6 suffered transverse displacement along a fault and was subsequently daylighted.

Blanchard and Laverty (1966) report three cracks in the Claremont Water tunnel at its intersection with the Hayward fault zone near Berkeley, California. The cracks, which were not present in 1950, occur near station 172+00 where the tunnel is about 45.7-m beneath the surface. In 1966, a resurvey of the alignment of the tunnel showed right lateral offset across the zone of fracture to be 168-mm since its construction in 1929, measured from the original tangential alignment. Of this amount, only 48-mm (south wall) or 20-mm (north wall) can be accounted for as displacement due to fracture of the lining. The remaining 119. to 147.-mm are accounted for as flexture of the lining. The offset takes place in a segment of the tunnel less than 30-m in length. Except for buckling of the invert in the zone of fracture, no indication of vertical displacement was found. Displacement in this tunnel is not known to be associated with any seismic event and probably reflects cumulative displacement by gradual creep along the Hayward fault zone.

Bonilla (1967) has summarized historic surface faulting that has occurred in the United States and adjacent parts of Mexico. Reports of damage to mines as a direct result of faulting are conspicuous by their absence. However, a mine intersecting a fault would inevitably suffer damage should slippage occur along the fault.

In at least two instances, subsurface faulting has been less evident on the surface: 1) The November 26, 1930, earthquake on the Izu Peninsula, Japan: "The principal macro-seismic event was displacement on the Tanna fault, which had been known since 1924, when it was encountered in excavating a railway tunnel. The evidence of faulting during the earthquake was greatest in the tunnel, with left-hand strike-slip of 2.4 metres (7 feet 10 inches) and a westward down throw of 60 centimetres (not quite 2 feet). On the surface above the tunnel the displacements were 'much less' (strike-slip at one point was 70 centimetres)", (Richter, 1958, p. 580). 2) The July 21, 1952, earthquake in Kern County, California: "Cracking and other evidence indicated less displacement at the surface immediately above the tunnels", (Richter, 1958, p. 528).

Effects Due to Shaking

Most reports of mine damage suggest the damage is probably due to secondary effects of earthquakes--the passage of elastic waves generated by the primary process.

The literature contains scattered statements that the effects of earthquake shaking are less in mines or caverns than at the surface. Most mines are located in solid rock which is a good transmitter and the wave energy is passed on through the rock with minimum decrease in speed and the smallest displacement possible. However, porous rock and unconsolidated materials are more compressible, and upon entering such materials the speed of the wave is reduced. With decreasing speed, the kinetic energy flux in the wave is maintained by increasing amplitude which gives rise to increased shaking and increased intensity. To explain the decrease in shaking with depth, there is also the consideration that the surface amplitude for a normally incident SH-wave is twice the amplitude of the incident wave. Hence, if the dimensions of the mine excavation are considerably smaller than the wave length of an incident SH wave, the amplitude of the surface motion will be about twice that measured at depth in the mine.

Richter (1958, p. 147) cites the following examples of the reduced effects of earthquakes underground, "there were many reports of this nature for the Japanese earthquake of 1923. A thoughtful description of similar observations in Arizona for the Sonora earthquake of 1887 has been given by Staunton (1917, p. 25-27). On August 22, 1952, the strong aftershock of the Kern County earthquake series, destructive at Bakersfield, was felt generally in the Giant Forest area of Sequoia National Park, and caused some anxiety for the safety of a party being conducted through Crystal Cave; however, no one in the party noticed the earthquake."

Alan Ryall (written commun., October 30, 1974) provides the following information, "In the June 8, 1887, issue of the Walker Lake Bulletin, an earthquake was reported felt 1,500 feet (457-m) underground at Virginia City, which shows that the town was either very near to the center of disturbance or that the quake was a very deeply seated one." In the Esmeralda Union of June 6, 1868, an earthquake was reported at Virginia City and the report states: "What seems almost miraculous is that the great mines at Virginia and Gold Hill were not caved in or otherwise injured. In some of the Virginia mines the flow of water was greatly increased, while in Gold Hill, it was generally diminished."

The following is quoted from the text of a talk by R. W. Lemke, presented to the Colorado Scientific Society following his examination of the effects of the 1960 Chilean earthquake. "One interesting observation concerning the lack of reactivation of faults due to the earthquake was made by Dr. Watanobi, a Japanese geologist. He went down into some coal mines that extend under the ocean for a distance of three miles (4.8-km) just south of the epicenter. Here he observed several old faults in the mines but he saw no new movement that could be attributed to the earthquake. In fact, there was practically no damage whatsoever. The miners had heard some strange noises during the quakes but otherwise felt no effects of the quake--fortunately for them."

Pardee (1927, p. 9) reporting on the effects upon mines of the Montana earthquake of June 27, 1925, states, "Contrary to a rather widespread apprehension, the workings of mines were not damaged by the earthquake, and in fact, the shock was not generally noticed by the miners who were underground at the time. At Barker, a group of miners who were at work in a stope at a depth of 250 feet (76-m) did not feel the shock, though it was generally noticed in that neighborhood by persons at the surface. So far as learned, the thousands of miners at Butte who were underground at the time were generally unaware that an earthquake had occurred. In view of the fact that mine workings are generally constructed so as to withstand the jars from blasting, it is not surprising that they would resist damage by the less violent vibrations of this earthquake. Owing to the common occurrence of the jars caused by blasting, miners at work would not be likely to notice especially the somewhat similar vibrations of seismic origin. Furthermore, as these vibrations are less destructive in areas of solid rock than in loose materials, they would be less noticeable underground than at the surface."

Staunton (1917, p. 25-27) reports on the effect of the Sonora earthquake on a mine at Tombstone, Arizona:

> "Evidence regarding the degree to which earthquake vibrations are perceptible below the surface of the ground and the physical effects of such vibrations seems to be meager. This is doubtless due to the fact that people

who have had such experiences seldom take the trouble to record them. The writer has been told by persons who have been in mines during earthquakes of quite marked surface intensity that nothing was felt underground; while others, in other mines, have reported that they were plainly felt. It is possible that both are right, and that the varying testimony is due to differences in rock structure, the neighboring rocks in one case transmitting the vibrations readily and in the other absorbing and deadening them, or possibly they are locally cut off by intervening cushions of inelastic material such as decomposed dikes. It is conceivable also that wave interference may locally cause stationary spots, or there may be nodes. Such phenomena are understood to be recognized by seismologists regarding the surface effects."

"The writer has had the experience of being in a mine during an earthquake and it is to record a few observations regarding this experience that these notes are made."

"In May, 1887, there was a succession of earthquake shocks felt pretty generally throughout the southwest, but in more pronounced degree in southeastern Arizona, and to a still greater extent in northern Sonora, Mexico, where considerable damage was done, and where it would have been very great if there had been many large structures in that locality. It was found later that the center of the disturbance was in Sonora, over 100 miles (161-km) south of the international boundary line. A committee of investigation was sent down to report on the effects of the earthquake, and, as I remember, found a very extensive fracture, open in places, and with vertical displacements of many feet in the walls at intervals. Doubtless the report of the committee can be found in the papers of that time. An account was printed in the Engineering and Mining Journal of June 11, 1887, covering surface effects in southern Arizona."

"It appears to be well established that the vibrations were of sufficient intensity to constitute a fair working test of what earthquake vibrations might be expected to do to mine workings in their paths. At that time the mines of Bisbee and Tombstone were very extensively opened, and there were many miles of underground workings, including many large cavernous open stopes in the limestone, with little timbering. Notwithstanding these conditions, the actual damage underground was only trifling, while on the surface the shocks were sufficient to cause plaster to fall, to throw down chimneys, and disarrange foundations so as to require the resetting of engines."

"Up to that time I had always understood that earthquake vibrations were not very perceptible far underground, but I found this to be a great mistake in some cases. In company with an assistant I was engaged on some survey work in a mine at Tombstone in a large inclined open stope about 150 feet (45.7-m) below the surface. The first warning was a heavy roaring noise, followed almost immediately by the beginning of vibration which seemed to culminate in a very pronounced jolt. The first impression was that there had been an explosion of some kind, but I quickly recognized the vibrations for what they really were, as I had felt earthquakes before. The loosened rocks from the hanging wall crashed down with much noise, striking sparks as they came in contact with the hard footwall, and for a few moments our situation was one of considerable danger and such as to leave a vivid mental impression."

"At another mine where men were working at a depth of 500 feet (152.4-m), cutting out a chamber in hard limestone about a hundred feet from the shaft, they dropped their tools and rushed for the station, where they needed no urging to come up. They said they thought the mine was caving in, as everything seemed to be moving. One of the men told me that he was standing in a drift in hard white limestone; that he felt impelled to brace himself against the walls to maintain equilibrium and that he distinctly saw a wave of deflection in the solid rock approach and pass him. He is not an imaginative person, and he has repeated this statement to me within the past few days, as he lives in Los Angeles, and I sought him to question him again about his experiences and sensations."

"A man went to find a miner who was working alone in a very soft raise being put up from the 500-foot (152-m) level, but strange to say, he had noticed nothing unusual and took the warning called up to him as a joke, refusing to come down. The vibrations so apparent in the hard rock seemed to have been absorbed by the softer, spongy rock."

"So far as the writer's experience goes, it seems to show that, while earthquake vibrations extend at times to depths of several hundred feet in a very pronounced degree, there is little to be feared in the way of material damage to mines from them even when of considerable intensity."

Other reports on the effects of earthquakes on mines include the following:

Cedar Mountain, 1932: "An earthquake of magnitude 7.3 originated in West-Central Nevada on December 20, 1932 (December 21, 06:10:05 G.C.T.). It was felt over the whole of Nevada (intensity VI at Reno) and in adjacent states, as far as San Francisco, Los Angeles, and Salt Lake City (fig. 28-16). The meizoseismal area was in one of the graben-type valleys of the Great Basin, flanked by fault-block mountains. It is one of the least inhabited parts of the United States; at the time of the earthquake hardly a dozen persons were in the region. A stone cabin was demolished, a mill at one mine was considerably damaged, and there was some underground sloughing in various mine workings" (Richter, 1958, p. 507).

Excelsior Mountains earthquake sequence, 1934: "This earthquake provided an opportunity to obtain data on the relative perception of shocks on the surface of the ground and underground in mines. As the principal shock occurred during the noon hour when most of the miners were at the surface, no data on it are available. The miners were all agreed, however, that such shocks as they felt were stronger at the surface than underground. Miners in a tunnel at Marietta reported that they felt obliged to steady themselves during the strong foreshock but were less concerned about the shock and heard less noise than persons at the surface. Miners at Silver Dike scarcely noticed shocks underground that were acutely perceptible to those at the surface. It seems probable that the difference in perception of shocks between the surface and underground may be related to a decrease in amplitude of surface earthquake waves with depth much as the amplitude of water waves decreases from the surface downward" (Callaghan and Gianella, 1935). Concerning this earthquake, Alan Ryall (written commun., Oct. 30, 1974) states, "....there is considerable damage to the workings of the Quailey Mine, on the northwest side of the Excelsior Mountains, and this was said by the owner to have occurred during the 1934 earthquake." The following report is taken from Ulrich (1946, p. 31-34):

May 9, 1944, "A sharp local earthquake, reaching intensity of at least VI, was reported from Mullan and Burke, Idaho. The following is quoted from a press report: "The shock caused a staging to fall in a stope off the 4,450-foot (1,345-m) level in the Morning Mine at Mullan, and one worker was buried in the muck to his knees, causing body bruises, two broken ribs, and possible internal injuries. Three other Morning Mine workers were peppered by flying rock when the slippage broke timbers and knocked out headings in another section of the mine. Morning Mine officials said this morning that no cave-in occurred and no ground was lost although the tremor was felt throughout the workings."

From seismological notes (October, 1945, p. 195): "Lone Pine, California, August 24, 1945. An earthquake "distinctly rough" in character set windows rattling at 1:27 p.m., P.W.T. No damage was reported throughout Inyo and Mono Counties, but mine officials in Upper Pine Creek said that it was accompanied by a roar that "drowned out" blasting going on in the Canyon."

Additional evidence pertaining to the degree to which earthquake vibrations are perceptible underground and the physical effects of such vibrations is presented in tables 2, 3, and 4. The available records range from reports of earthquakes being felt or not felt in mines to reports of flooding of mines, spalling of rock in mine workings, and collapse of mine workings and tunnels. Seldom do the reports contain sufficient detail to appraise the extent of the damage or its immediate cause. Thus in the reports of flooding of mines, no details are given as to the cause of the flooding or whether one or several levels or the entire mine was flooded. One can only speculate that the earthquake may have resulted in renewed movement along existing fractures or that fracturing of the rock resulted from the earthquake and provided avenues of water movement into the mine.

Similarly, reports of falling rock seldom specify the extent of damage or the immediate cause, such as spalling of loose roof pendants, collapse of walls or roof due to renewed movement along old fractures, etc. Also, reports of mine tunnels that cave in do not specify the extent, although it is improbable all of the workings collapsed, or the immediate cause of the collapse, whether due to renewed movement along old faults or joints, destruction of roof-supporting structures, etc.

Instrumented Studies in Mines

The most detailed information on the perceptibility of earthquakes and their physical effects underground is that obtained by instrumented studies in mines.

Carder (1950, p. 13-14) reporting on the operation of seismographs at the surface and at the 5,000-foot (1,524-m) level in the Homestake Mine, South Dakota, found that the records at 5,000 feet (1,524-m) showed no significant difference from those at the surface, except for the lack of minor local and superficial disturbances at the 5,000-foot level. In a later study, P-waves of 1-second period were recorded at a depth of 300 feet (91.4-m) with twice the amplitude recorded at 5,000-foot (1,524-m) depth.

Kanai and Tanaka (1951, p. 107-113) compared in detail the seismograms from instruments operated simultaneously at the surface and at depths of 150, 300, and 400 metres (492, 984, and 1,312 ft) in the Hatachi Mine; the differences were not large. Subsequently seismographs operated at the surface and at depths of 150, 300, and 450, and 600 metres (492, 984, 1,476, and 1,969 ft) in a copper mine in Hatachi recorded a very large number of small earthquakes. The ratio of maximum surface displacement to displacement at 300-metres (984-ft) deep was about 6 at the mine and 10 at a school resting on alluvium 6-kilometres (3.7-mi) away. Earthquakes with an average period of incoming waves close to the free period of the surface layer caused the maximum ratios, but in many earthquakes the ratios were as small as one third of the above. The period of the short-period waves (ripples) recorded on surface seismograms but not underground, corresponds to the predominant period of the surface layer; ripples dominate the surface record when the incoming waves included components with period equal to that of the ripples.--See Kanai, Osada, and Yoshizawa, 1953, 1954.

Concerning the depth factor in the effects of earthquakes on tunnels, and citing the above data on seismograms from mines, Duke and Leeds (1959, p. 308-309) state: "Qualitatively, these researches demonstrate experimentally the following effects at depth:

1. At short periods, surface displacements are larger than underground displacements.
2. The ratio of surface to underground displacement depends on the type of ground. It is greater for alluvium than for weathered rock. It may reach a value of at least 10.
3. For wave periods over one second, the ratio becomes comparatively small, approaching unity as the period increases.
4. There is a particular average period of incoming waves for which a given type of ground will provide a maximum ratio of surface to underground displacement. If the average period of incoming waves is not approximately equal to this particular period, the ratio will be materially smaller."

Mine Bumps and Rock Bursts in Mines

Phenomena closely related to earthquakes are "mine bumps" and "rock bursts" in mines. Mine bumps are violent, spontaneous disruptions of rock faces and ribs in mines and are a hazard to life and property in the mines in which they occur. Mine bumps and rock bursts in mines are due to failure of the rock under stresses resulting from removal of material. Commonly such failures occur gradually as mining proceeds; however, in competent and structurally resistant rock, the stresses may accumulate to high levels before failure. The energy released when failure does occur produces true seismic waves which have been recorded on distant seismographs. Because the location of the origin is known, these features have been the subject of special seismological investigations in the United States, South Africa, Canada, Europe, and elsewhere. The U.S. Geological Survey instrumented studies of these features in coal mines in Central Utah in 1967 and 1968 and at the Somerset Coal Mine in Colorado in 1969. The results of these investigations are contained in two reports: Osterwald and others, 1971, 1972. Concerning these studies, Frank W. Osterwald (written commun., June 5, 1974) states: "Some earthquakes in the surrounding regions have been followed within a short time by large bumps (rock bursts) in the mine, other earthquakes have produced no effects, so no valid conclusions can be drawn. We can't really say that bumps following immediately after earthquakes are caused by the earthquakes."

N. G. W. Cook, Director, Mining Research, Chamber of Mines (written commun., August 25, 1974) provides the following summary of investigations in South Africa.

> "All the evidence indicates that earth tremors, rock bursts, and bumps arose in the Witwatersrand as a result of mining and have followed the pattern of mining in terms of frequency of incidents and epicentral position and focal depth."

> "Measurements of the virgin state of stress in sediments of the Witwatersrand system have shown that the vertical component is due to the weight of the overburden and that the horizontal component has a magnitude about half that of the vertical component. Even though the Witwatersrand sediments are faulted and intruded by dykes, stress differences should not be great enough to mobilize these discontinuities in the absence of the disturbances created by mining. As a result of mining, which progresses at a rate of about 30 km^2 year (3.23×10^5 ft^2/yr), the weight of the overburden results in stress concentrations around the perimeter of the mine excavations. Stresses in this vicinity may reach values of

up to 10 kilobars (1.02×10^7 kg/m^2 or 1.45×10^5 psi) and a regular pattern of rock fracture adjacent to the mine excavation is formed. There is evidence to indicate that the pattern is affected by geological disturbances, which have the effect, broadly, of concentrating the energy and causing more seismic activity than would be present in their absence. On the Far West Rand in the Klerksdorp area, post-Witwatersrand normal faults of shallow dip are extensive. We believe that the stress changes caused by mining here mobilized these faults resulting in minor earthquakes, but this matter is still being studied. The seismic activity caused by mining seems to follow many of the patterns of earthquake seismic activity, including a linear relationship between the logarithm of the number of events and their magnitude. However, there is no obvious relationship between the amount of damage caused by large rock bursts and their intensity."

CONCLUSIONS

The perceptibility and physical effects of earthquakes in mines and underground workings deserve more systematic study than they have received.

The following generalizations are consistent with the available data:

1. Severe damage is inevitable when a mine or tunnel intersects a fault along which movement occurs during an earthquake. Possible damage includes offset of the workings on either side of the fault, destruction of timbering, collapse of roof and walls of workings, and flooding of the mine--all of which could have disastrous consequences in a mine.
2. Mines in the epicentral region of strong earthquakes, but not transected by fault movement, may suffer severe damage by shaking. Timbering may fail and collapse of roof or walls and mine shafts or their linings may occur. Flooding of mine workings by enlargement and interconnection of joints or old fractures is possible.
3. Mines outside of the epicentral region are likely to suffer little or no damage from a strong earthquake. Some spalling of rock, falling of loose or weakened roof pendants, or some shaking are the only effects to be expected and in many cases the earthquake is not even noticed in mines so located.

Other factors being equal, it appears reasonable that the severity of damage due to shaking would probably be least when the mine is located in highly competent, unweathered rock; somewhat greater damage would probably be expected in a mine in weathered or less competent rock; and greatest damage would be expected in a mine located in loose unconsolidated or incompetent rock. However, comparative data on this are inadequate.

The intensity of shaking below ground is commonly less severe than on the surface due seemingly to rock type. In general the progression of rock type upward from depth is from highly competent unweathered rock, through weathered rock, to loose unconsolidated rock.

Table 2.--Observations Pertaining to the Effects of Earthquakes on Mines appearing in Holden's Catalogue (Holden, 1898, 253 p.)

Jan. 7, 1869 "Two sharp shocks near the Newton Copper Mine, Amador? County, Cal." No mention is made of effects or damage in the mine.

Mar. 26, 1872 "Cerro Gordo and Eclipse Mines, Inyo County, Cal. The rocking motion was distinctly observed, especially in the timbering, and the miners went to the surface but soon resumed work." This was the great Owens Valley earthquake. Commenting on this report, Dr. C. F. Richter, written communication, Aug. 12, 1974, states "The report is odd because the time of occurrence was about 2:30 am."

Mar. 26, 1872 "Geyser Gulch near headwaters of the San Joaquin River. Miners cabins in this vicinity were thrown to the ground with violence. This place is 40 or 50 miles (64 or 80-km) from Independence, Inyo County." No mention is made of effects of earthquakes in the mines.

May 3, 1887 "I have no record of this shock at Fort Yuma, but I assume it to have been felt there. In Science, 1887, May 20, p. 483, under the heading, "The Sonora Earthquake, is a good account by G. E. Goodfellow, of the shock at Tombstone, Arizona. At this place, there were loud detonations. The severe shaking lasted 10 seconds, the moderately severe about 20, and tremors a little over one minute. No building of any stability was damaged, and no person was injured. The railroad track of the A.T. and St. F.R.R. at a point where it ran east and west, was thrown 4 1/2 inches (11.4-cm) out of line, the convexity looking south. The bend was 300 feet (91.4-m) long. For 48 hours after the shock there were tremors. Miners 600 feet (183-m) below the surface felt the shock severely and some became sick. Miners at 150 feet (46-m) noticed the shock less. The area of disturbance is estimated at 1,200 by 600 miles (1,930 by 965-km). In Fronteras Valley, Sonora, old Mexico, and the neighborhood, the shock was destructive to houses and to human life. Fissures north and south were produced. The center is probably south of Fronteras. At San Bernadino Ranch, 90 miles (145-km) southeast of Tombstone, all the houses were thrown down. There are extinct craters at this place."

Table 2.--(Continued)

April 28, 1888 "Reno (Nevada), a smart shock: three waves in 3 sec., followed by a general trembling for 10 sec. The time of the third and severest shock was 8 h. 48 m. 38 s. p.m., direction S. to N. (letter from U.S. Surveyor - General Irish). Two other observers say W. to E.--Grass Valley: felt in the Idaho mine below the 1,600 ft (468 m) level. Alta, May 2d. Very heavy, lasting 5 sec., from E. to W. Chronicle, April 30--Grass Valley: the Orleans mine was flooded. The shock was at 8:45 pm and very heavy (VII). It was proceded by a loud noise. The duration was about 5 sec. and the wave was E. to W......"

May 19, 1889 "Central Calfornia: at the Lick Observatory, nobody was awakened, although the motion registered by the seismographs was considerable. This is probably owing to the long period of the vibrations. The time recorded by the earthquake clock was 3:96 am."--"Forest Hill: in the Mayflower mine, no sign of an earthquake at 600 or 800 feet (183 or 244-m) underground. Directly over the mine the shock was strong enough to rattle a washbowl against a pitcher."

Table 3.--Reports Pertaining to the Effects of Earthquakes on Mines. Taken from the Catalogue of Townley and Allen (Townley and Allen, 1939, 297 p.)

Dec. 19, 1869 Several shocks in Mariposa, California, and in the mines of Virginia City, Nevada. Also A.M. December 20.--Fuchs. In the A.M., several shocks at Mariposa.--Perry. It is very probable that these shocks were felt at the Mariposa Mill, Virginia City, Nevada, and not at Mariposa, California--Townley and Allen.

July 31, 1900 Utah and Juab Counties, Utah. At Goshen, Utah Co., dishes were broken, plaster fell from walls, and a chimney was broken. At Santaquin, Utah Co., an adobe house was split in two, and people thrown from beds. Miners underground at Tintic, Juab Co., came to the surface, frightened; the deep shaft of the Mammoth mine was so twisted that the cage could not be lowered to the bottom--Salt Lake Tribune, Nov. 14, 1901.

July 9, 1871 Kern County, California. Severe shock felt in the Joe Walker mine, which almost instantly was filled with water.--Los Angeles News, July 16, 1871.

April 28, 1888 Nevada City, California. Walls of courthouse cracked. Two severe shocks, proceded by a deep rumbling sound. Direction north, Grass Valley. Felt in the Idaho mine below the 1,600 foot (483-m) level. Alta, May 2. Very heavy, lasting five seconds, from east to west.--Chronicle, April 30. The Orleans mine was flooded.

Oct. 28, 1909 "The miners at the Bully Hill mine at Delamar, Shasta County (Cal.) were so badly frightened by the rumbling and shaking of the earth that they started to come to the surface. In Redding, several persons occupying rooms on the upper floors of brick buildings rushed into the streets. The clock in the dome of the courthouse stopped at 10:45 pm. Reports generally agree that the duration of the earthquake was thirty seconds. There were three sharp shocks, but the vibrations were continuous."--Santa Rosa Press Democrat, October 30, 1909.

Table 3.--(Continued)

March 21, 1917 Bishop, Inyo County, California. Rapid trembling, north to south, duration twenty-five seconds, felt by many. Felt also at the Crooked Creek Camp of the Los Angeles Power Bureau, twenty-four miles northwest of Bishop, as two shocks, each of fifteen seconds duration. The shocks were noticeable in the tunnel which was being driven at that point. Reports stated that the shock dislodged rocks on mountain sides west of Bishop. At other places in the mountains the shocks were light. The disturbance was not reported from Laws or Benton, nor from points south of Bishop.

Sept. 4, 1917 Owens Valley, Inyo County, California. Slight shock, felt by one at rest at Reward Gold Mine, nine miles southeast of Independence.

Nov. 7, 1939 "An earthquake, accompanied by a report resembling an explosion, rocked Grass Valley at 7:25 pm, causing doors to fly open, dishes to fall from shelves, and bricks from chimneys. The shock excited special remark because it was felt underground to a depth of 4,500 ft (312-m) or more as well as on the surface, and because early reports credited the cause of the shock to the collapse of underground workings. USCGSSF" from Seismological Soc. America Bull., v. 30, no. I, p. 88.

Table 4.--Reports of the Effects of Earthquakes on Mines, Taken from: Earthquake History of the United States, Revised Edition (through 1970).

July 9, 1871 "Kern County. Severe shock felt in the Joe Walker Mine, which was filled almost instantly with water."

April 28, 1888 "Nevada City. Walls of courthouse cracked. At Grass Valley, tops of chimneys fell. Orleans mine flooded; felt in Idaho mine below 1,600 foot (488-m) level. At Briggs, Idaho, plaster cracked. Felt from San Francisco northeastward into Nevada."

June 8, 1894 "Fish Springs, Utah. People ran outside at Emma Mine; dishes were thrown down at Utah Mine. Rumbling sounds."

Aug. 1, 1900 "Utah. Deep shafts of mine twisted so that cage could not be operated. Dishes were thrown from shelves. Plaster fell, dishes broke, and a chimney was damaged at Goshen. At Santaquin, an adobe house split in two; people were thrown from their beds."

July 26, 1905 "Calumet, Mich. An earthquake, which was apparently associated with the pecularily unstable conditions brought about by mining operations, was felt all over the Keweenaw Peninsula, Mich. It was heaviest at Calumet. There was a terrific explosion, chimneys fell with a crash, and plate glass windows broke. The explosion was heard far down in the mine. Felt at Marquette, Mich."

May 26, 1906 "Keweenaw Peninsula, Mich. At the Atlantic Mine, the effects were such as might be produced by a great earthquake. Rails were twisted, and there was notable sinking of the earth above the workings. Such effects were not noted elsewhere. The area affected was about 30 or 40 miles (48 or 64-km) in diameter."

Oct. 28, 1909 "Humbolt County (Cal.) All chimneys were thrown down and concrete structures were wrecked at Rohnerville. At Upper Mattole, chimneys were wrecked and cemetary monuments were thrown down. The shock was severe throughout Shasta County, but damage was moderate. Miners were badly frightened in a mine at Delamar. The shock was felt in Southwestern Oregon as far as Marshfield and Grants Pass, northeast from its epicenter to beyond Redding, southeast to Nevada City and Grass Valley, and south to Okiah. The shock was felt on board a ship 25 miles (40-km) southwest of Cape Mendocino. Magnitude 6+."

Table 4.--(Continued)

Oct. 2, 1915 "Time of occurrence.--22:54.
Epicenter.--Pleasant Valley, Nevada.
Area affected.--Approximately 500,000 square miles (12.9 x 10" m^2)
Intensity.--X at epicenter.
Magnitude.--7-3/4
Description.--This earthquake occurred along a fault on the eastern side of Pleasant Valley, which lies south of Winnemucca. While felt over a larger area than the California earthquake of 1906, it did little damage because of few structures and people. There were two shocks scarcely felt outside Nevada, one at 15:40 and another at 17:49. At Kennedy, there was a roar and people had trouble remaining on their feet; the shock was intensity V at Reno. At Kennedy, the motion continued until the main shock at 22:54. At this time, there was a great roar, people were thrown from their beds, and some were thrown to the floor. Adobe houses were destroyed. Concrete mine foundations cracked and mine tunnels caved in. As usual, effects were greater where materials were unconsolidated. In such cases, ground cracks appeared for considerable distances. At Winnemucca, damage was moderate and was confined to that part of the city on low ground. At Lovelock, large water tanks were thrown down and cracks appeared in the road. There was a great increase in flow of water, so much so that applications were filed for new water rights. A rift was formed with a fresh vertical scarp 5 to 15 feet (1.5 to 4.6-m) high and 22 miles (85-km) long, parallel to the base of the Sonoma Mountains. It was felt from Baker, Oregon, to San Diego, California, and from the Pacific Coast to beyond Salt Lake City, Utah."

Nov. 27, 1926 "Idaho near Rathdrum. Two distinct shocks. Felt at 1,000-foot (300-m) level in Hecla Mine, but not at 2,000-feet (310-m). Strongly felt at Wallace. Vertical jar noted. Slight damage at Kellogg. Felt area extended to Thompson Falls, Montana."

July 21, 1952 Kern County Earthquake
"Time of occurrence.--03:52
Epicenter.--35.0°N., 119.0°W, south of Bakersfield.
Area affected.--160,000 square miles (4 x 10" m^2)
Magnitude.--7.7
Intensity.--XI
Description.--This was the main shock of the Kern County series and the largest earthquake in the United States since 1906. Damage to property was estimated at $50 million. Intensity XI

Table 4.--(Continued)

effects were observed in a very small area on the Southern Pacific Railroad near Bealville. Reinforced concrete tunnels with walls 18 inches (45.7-cm) thick were cracked, twisted, and caved in. The distance between portals of two tunnels was shortened about 8 feet (2.4-m) in 300 feet (91-m). Rails were shifted and bent into S-shaped curves. Urban intensities, however, did not exceed VIII...."

Dec. 18, 1957 "Wallace, Idaho. Extensive damage at Galena Silver Mine (1 mile (1.6-km) west of Wallace). Timber fell and walls caved in, frightening miners 3,400 feet (1,036-m) underground. Awakened all and frightened many at Wallace. Also felt at Osburn and Mullan."

July 13, 1969 "Eastern Tennessee. Felt in Tennessee, North Carolina, Virginia, Kentucky, and Georgia. Slight damage occurred at Jefferson City, Tenn., where a few bricks loosened on chimneys and some rocks fell in zinc mines. At Knoxville plaster and concrete cracked, houses shook strongly, and furniture jumped up and down. Plaster cracked at Seymour and small objects fell from shelves. No damage occurred outside Tennessee. Magnitude 3.5".

Dr. Allan R. Sanford (written commun., July 26, 1972) provides the following information, "A mine in Socorro Mountain where we have seismic instruments has had slip of a few millimeters along a fault since the tunnel was driven. However, we have no idea whether this movement was caused by slow creep, vibrations from a strong nearby earthquake, or by sudden release of strain energy along the fault."

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