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Subsidence Potential in Shale and Crystalline Rocks

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Abstract

This report presents a statistical summary of worldwide subsidence experience in shale and crystalline rocks, and includes an expanded bibliography of the most significant references on mining-induced subsidence in these rocks. No measurements have been reported in the literature of subsidence in "massive" shale and crystalline rocks (potential host rocks for radioactive-waste (radwaste) repositories). Predictions of the subsidence response of massive rock based on information gained from less uniform rocks will be subject to unknown but possibly large error.

Subsidence is controlled by a complex combination of mining and geologic factors. For example, as the percentage of shale in the rock mass decreases and the amount of sandstone increases, the angle of draw (and the area of potential surface subsidence) decreases. When limestone is present in the overlying rock the angle of draw can be three times less than for an equivalent amount of sandstone. In fractured crystalline rocks the angle of draw and the resulting surface deformation appear to be controlled not only by properties of the rock substance, as in shale, but also by preexisting joints. Faulting can limit or enlarge the draw angle in any rock formation. The data show that gross errors may occur when applying a subsidence model developed at one mine in one geologic environment to a mine at another location.

Control of subsidence with backfilling has been highly successful. In one case the subsidence predicted without backfill was nearly 20 times greater than that actually measured with backfill.

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Introduction

Modern industrial society produces increasingly larger amounts of highly toxic, long-lived chemical and radioactive-waste products. The attractiveness of proposals to place these hazardous materials in deep, geologically stable, storage sites depends on the stability of both the near- and far-field geologic environment. It is unreasonable to assume that any series of rooms and pillars will remain stable for many thousands of years. It is essential, therefore, to be able to predict and prepare for the deformation and failure of those pillars and for the resulting subsidence of the surface. The possibility that delayed subsidence will breach such a containment facility and allow surface water to enter can only be evaluated by considering the much shorter historical record of mining-induced subsidence.

No rock type has all of the desirable attributes for waste containment. However, crystalline rocks and thick shale sequences have been suggested as prime storage sites. Shale, a relatively weak rock, would inhibit the migration of hazardous wastes because of its tendency to deform plastically rather than by fracture. Pillars excavated in shale will, however, remain stable for a shorter time than pillars excavated in much stronger crystalline rocks (mainly granite and gneiss). Joints in rock masses provide a potential avenue for ground-water movement. In deep mines the water that enters through such joint systems in crystalline rocks must be pumped out. It is common practice to excavate shallow (100-150 m) storage caverns for liquified petroleum gas (LPG--butane and propane) in shales because of their ability to contain LPG under moderate pressures, <0.7 MPa (<100 lbf/in^2).

It is desirable to place storage facilities for critical materials in massive formations because predicting long-term rock mass response, while not simple, should be easier in massive formations than in more complex geologic environments. Alternating beds of different flat-lying or folded sedimentary rocks or folded, fractured, and injected metamorphic rock masses represent complex geologic environments which generally should be avoided.

The purpose of this report is to summarize and interpret the most relevant published subsidence information and to suggest the degree to which this information may be applied to predictions of subsidence in massive shale and crystalline rocks.

Mining background information

It is not possible to find mines operating in massive shale and crystalline rocks because there is no economic incentive, that is, no coal or other economic product to extract. Measurements of surface response to mining below shale and crystalline rocks are, therefore, virtually absent from the technical literature.

There are numerous statements concerning the importance of geology in the development of damaging subsidence effects. For example, Sopworth (1898, p. 165) suggested the following classification for beds overlying British coal deposits:

1. "Measures consisting of fairly equal proportions of rocky and argillaceous beds, and containing thick beds of sandstone." (Rocky probably means sand-size and coarser sediments.)

2. "Measures including a small proportion of rocky beds, say 15 percent, and only thin beds of sandstone." (Eighty-five percent argillaceous, 15 percent sandstone.)

3. "Variations between these two."

In the first case, according to Sopworth (1898, p. 165-166), the edge of the subsidence trough will follow or lie over the excavation and in the second case it will lie over the solid coal. (See fig. 1 for nomenclature.) In the third case it will vary between (1) and (2). The same year, Cooper (1898, p. 134) called attention to the absence of an angle of draw where the overlying beds include strong thick layers of limestone. As recently as 1976, Dunrud (1976, p. 1) stated, "Knowledge of geologic, topographic and socioeconomic conditions in prospective mining areas is vital to planning safe and efficient mining activities * * * ."

While no subsidence information exists for massive shale or massive crystalline rocks considerable data are available in the technical literature for layered sedimentary rocks overlying coal mines and for geologically complex crystalline rock masses above metal mines. The typical sedimentary sequence in coal deposits involves a cyclic deposition of different rock types (cyclothem) in which only one of the rock types is shale, although shale is the most abundant rock type at many locations. The typical geologic environment of a metalliferous ore deposit in crystalline rock, if indeed there is a typical deposit, includes folded and fractured rock masses. Faults, or dikes of different igneous rocks, frequently disrupt the continuity of the enclosing crystalline rock masses. In addition, the mining of thick (mining height greater than one-tenth the depth), irregular-shaped metalliferous orebodies frequently results in a prominent, steep-walled collapse depression at the surface. Such a collapse depression, which can be as much as tens to hundreds of feet in depth, is easy to measure and the measurement does not have to be very precise. The failure of pillars in a horizontal waste storage facility would not produce a steep-walled collapse depression or pit, but only a broad shallow downwarp of the ground surface, that is, trough subsidence, because there is no reason to use mining heights of one-tenth the depth, or greater. With one notable exception, no effort has been made to measure the more subtle, local, downward deflection of the surface, that is, trough subsidence, adjacent to a prominent collapse depression (Thomas, 1971).

Massive shale overburden represents, in effect, one extreme of rock type in the case of sedimentary lithology. Coal-mining subsidence-monitoring results involve different sequences of varying lithologies. Shale is typically a major proportion of the overlying sequence of strata. Bell (1975, p. 28) stated, "Argillaceous rocks account for about three-quarters of the thickness of a sequence of coal-bearing strata" in England. Kapp (1973, p. 7-8) on the other hand stated that, "There is approximately 70 percent of sandstones in the strata over the Kemira longwall panels" near Wollongong in Australia.

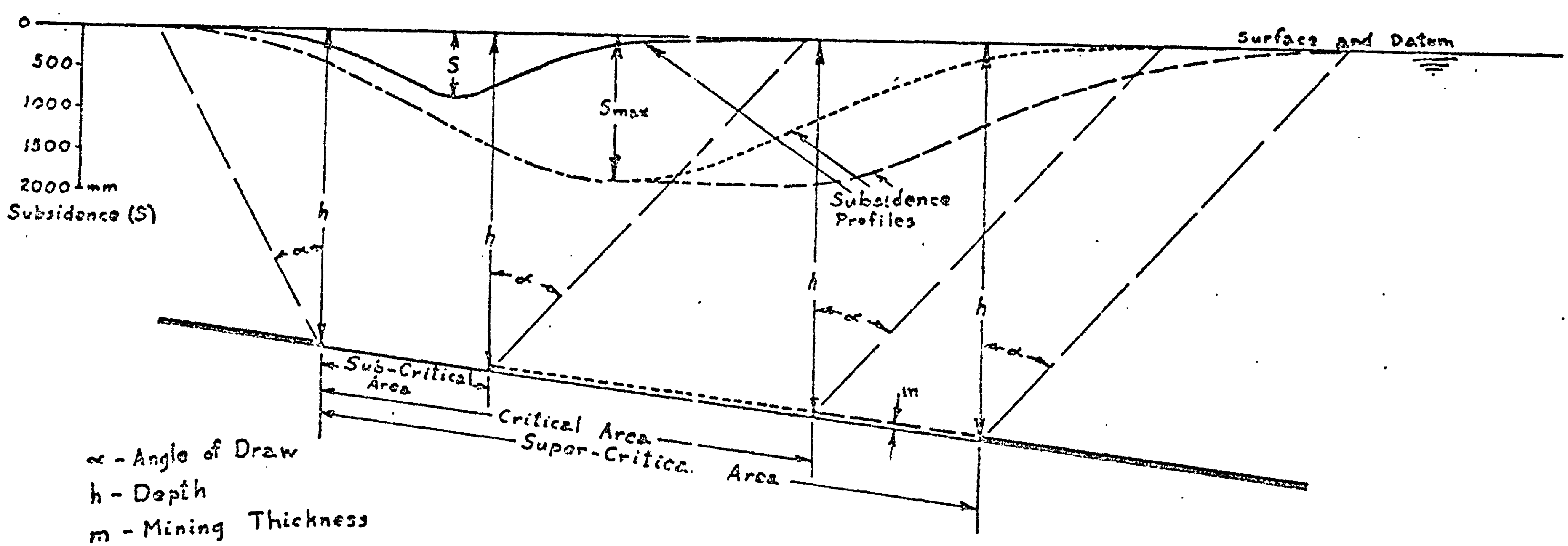

Figure 1.--Trough subsidence description. (Modified from National Coal Board, 1975.)

The limited number of subsidence-monitoring programs reported in the literature which also determined and reported the overlying lithology is indicated in table 1. It should not be assumed that lithology alone controls subsidence, nor for that matter that lithology is the only geologic factor that influences subsidence. Individual bed thickness, relative strength of the rock substance, and bedding cross-joint frequency probably have an effect on the amount of subsidence measured.

In regard to the prediction of subsidence, the extent of detectable subsidence outside the area of active mining is of as much interest as is depth of subsidence. The reach of subsidence effects outside the area of mining, generally referred to as the "angle of draw," appears to be highly variable. The angle of draw, the angle formed by the vertical line above the outer limit of mining and the lateral limit of detectable subsidence, has a special importance to land-use planning, because it indicates where the surface will be unaffected by mining-induced subsidence. The large variation in tabulated angles of draw is shown in table 2. The potential for error in applying an angle of draw measured from one country to another, or even within one country and (or) district is obviously considerable.

Subsidence over thin, tabular-bedded deposits

A tabular-bedded deposit can be considered thin when caving produced by collapse of the mine roof does not propagate to the surface and form a pitlike collapse depression. Schulte (1957, p. 193) reported on sinking a shaft from an upper coal seam to a fully extracted and caved longwall panel below. Schulte was unable to detect any damage to the rock exposed in the shaft walls more than nine seam thicknesses above the lower seam. He also found that the rubble from the collapsed roof had a height between three and four seam thicknesses above the former roof of the lower seam. Piggott and Eynon (1977, p. 763-765) mathematically examined the potential height of collapsed rock above rooms in room-and-pillar workings (figs. 2, 3). They concluded that the collapse height for a conservative 30-percent swell (bulking factor) for the rubble from the collapsed roof rock would result in a collapse height of 3.3-10 times the thickness of the mined seam. The smaller collapse height should develop in the case of rectangular (uniform) roof collapse and the larger collapse height in the case of adverse conical roof collapse, which occasionally develops above room intersections.

The subsidence effects resulting from failure of the pillars in a waste storage facility either in shale or in crystalline rock should be similar to that which would occur upon the extraction of a thin, tabular-bedded deposit. The surface depression that results is referred to as a subsidence trough. The standard symbols employed by the NCB (National Coal Board, 1975, p. 3) are presented in figure 1. The primary factors affecting the development of the trough in flat-lying tabular deposits like the Carboniferous coal measures of Great Britain are mining height and minimum mining width. Depth is a secondary factor, increasing the angle of draw distance, the extent of surface influence, and possibly the maximum subsidence. The similarity of subsidence measurements at different mines in Great Britain is indicated by the subsidence profiles in figure 4 (King and Whetton, 1957, p. 27).

Table 1.--Lithologies, mining conditions, and measured subsidence (supercritical condition)

Location and commodity	Lithologic percentages in overburden			Depth (m)	Mining height (m)	Extraction (percent)	Maximum subsidence (percent of mining height)	References
	Shale	Sandstone	Limestone					
Pennsylvania, coal.	50	22	28	98	1.7	83	40.0	Greenwald and others (1937).
Do----------	59	11	30	130	2.1	85	51.5	Maize and Greenwald (1939).
Do----------	78	13	9	108	1.6	90	50.0	Maize, Thomas, and Greenwald (1940).
Do----------	59	11	30	162	2.1	85	48.2	Maize, Thomas, and Greenwald (1941).
Do----------	59	11	30	91	2.1	85	46.3	Do.
New Mexico, coal.	63	37	0	104	3.0	100	69.0	Abel and Gentry (1978).
Great Britian, coal.	68	32	0	539	1.4	100	58.4	Sinclair (1950).
Do----------	63	29	8	793	1.8	100	65.2	Do.
Do----------	64	36	0	41	.6	100	84.0	Briggs and Ferguson (1933).
New Mexico, uranium.	86	14	0	152	3.0	36	7.0	C. H. Parrish (written commun., 1979).
California, borate.	17	83	0	118	42.1	100	73.9	Obert and Long (1962)1/.
Pennsylvania, coal.	48	52	0	60	1.8	86	57.9	Montz and Norris (1930).
Illinois, coal.	71	17	12	130	1.1	100	61.2	Herbert and Rutledge (1927).
Do----------	57	38	5	152	2.4	69	34.8	Do.
Illinois, shale.	64	4	32	119	7.6	51	15.2	Abel (1973); Fenix and Scisson, Inc. (1972).
New Mexico, potash.	40	(50 percent Salt Fm.)	10 2/	305	3.8	95	58.8	Miller and Pierson (1958).

1/ Possibly subcritical, but presence of flat-bottomed subsidence trough indicates supercritical area.

2/ Dolomite.

Table 2.--Angles of draw (from vertical) for coal mining in the United States and Europe

Country or district	Brauner (1973, p. 9)	Wardell (1959, p. 530)	Newhall and Plein (1934, p. 65)
Netherlands	35°-45°	35°-45°	-------------
Ruhr	30°-45°	-------------	-------------
Lower Rhine	-------------	29°-39°	-------------
France	35°	-------------	-------------
Great Britain	25°-35°	28°-40°	-------------
United States of America (Pennsylvania).	20°	-------------	20°-25°
Poland	-------------	19°-34°	-------------

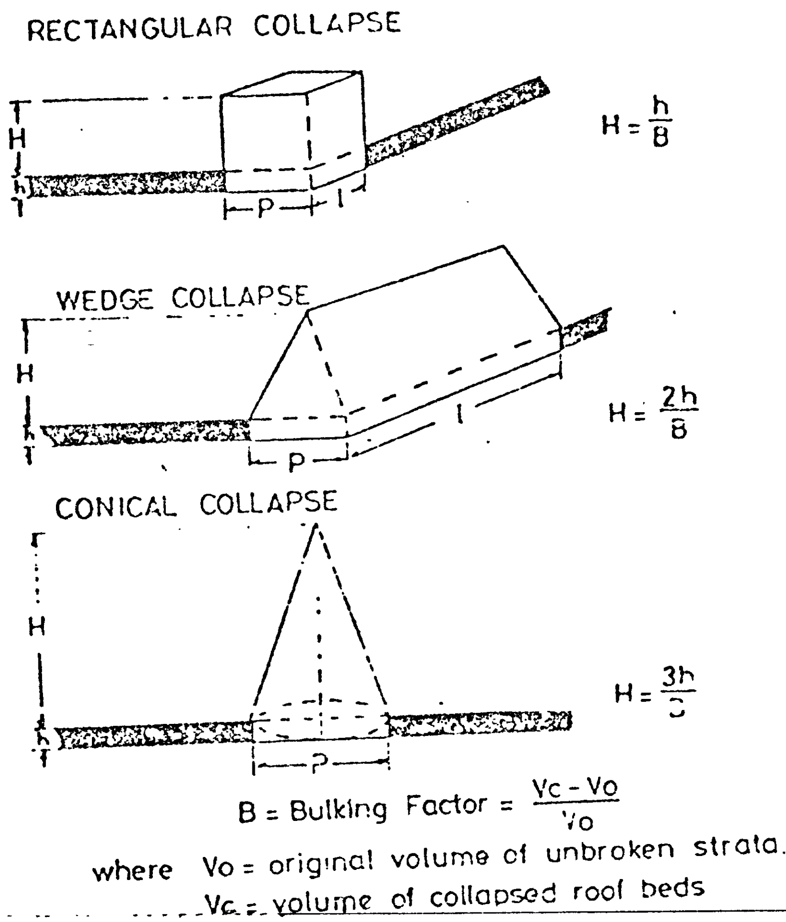

Figure 2.--Diagram showing notation for calculating maximum height of collapse (H) in relation to geometry of collapse. (Modified from Piggott and Eynon, 1977.)

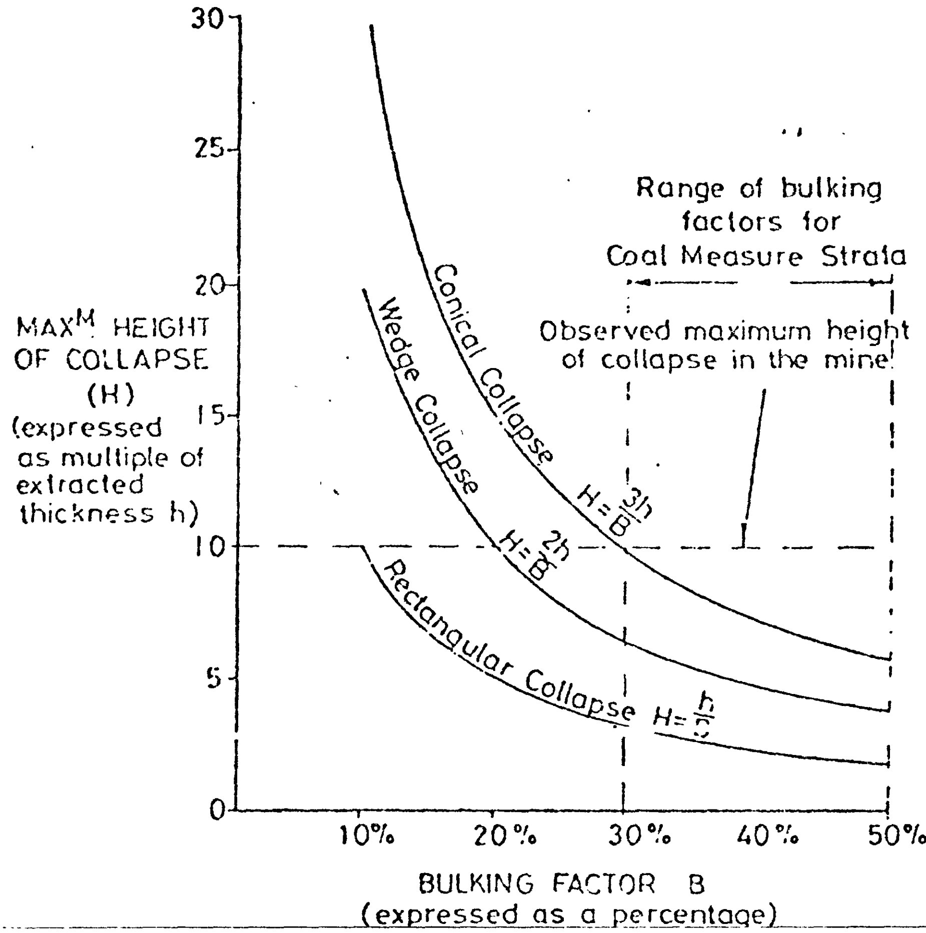

Figure 3.--Graph showing variation in maximum height of collapse for different modes of failure and bulking factors. (Modified from Piggott and Eynon, 1977.)

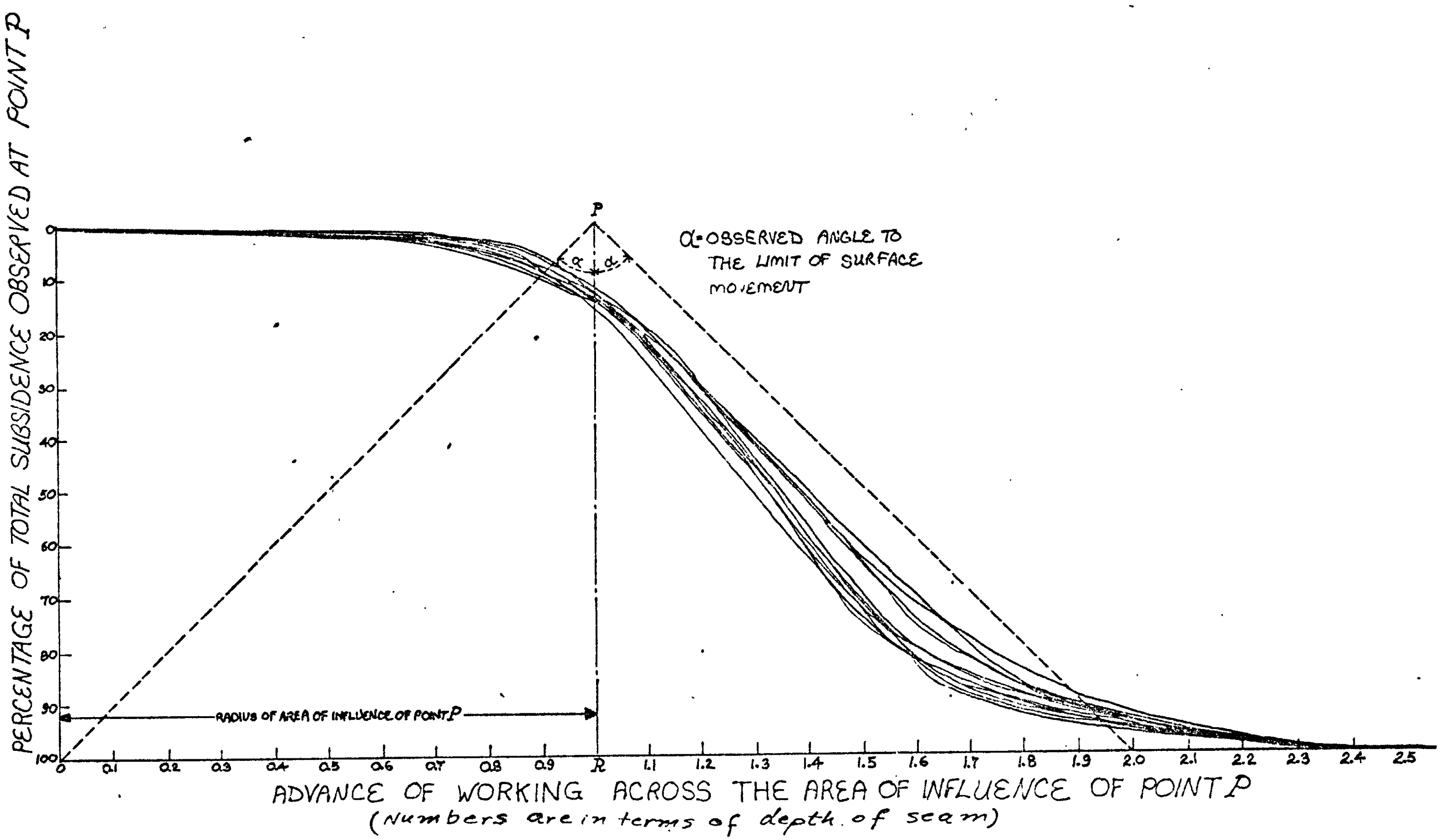

Figure 4.--A family of subsidence development curves from 11 British coal mines. (Modified from King and Whetton, 1957.)

The simplest mining geometry is produced by longwall extraction. In longwall coal mining the coal seam is completely extracted as a rectangular panel with a width of about 200 m and even a greater length. Leaving a portion of the coal seam as pillars, in the case of room-and-pillar mining, reduces the magnitude of subsidence, but does not change the general shape of the subsidence trough. The effect of pillars and (or) backfill on subsidence is discussed in a later section of this report.

Many investigators have assumed that the subsidence measured above one coal mine can be used to accurately predict subsidence that will result from mining at other locations. This is only grossly true (tables 1, 2). Obviously, geometric similarity among flat-lying tabular-bedded deposits is not the only control either on maximum subsidence or on angle of draw.

Data were collected from the literature to investigate the relationship between angle of draw and lithology, expressed in terms of the percentage of shale, sandstone, and limestone in the overlying strata. The data are presented in table 3. The proportions of the various lithologies, where not specifically reported, were calculated from drill hole logs. The percent of shale, sandstone, or limestone is by itself a relatively poor predictor of the angle of draw as shown in figures 5, 6, and 7. The statistical confidence that the angle of draw increases as the percent of shale in the overlying rock increases is only slightly better than 90 percent (fig. 5). Much lower confidence can be placed in the statement that the angle of draw decreases with increases either in sandstone (70 percent) or in limestone (65 percent) in the overlying rock (figs. 6, 7). However, a multiple linear regression evaluation of the sandstone and limestone percentages in the overlying strata indicates 98-percent confidence that the more complex relationship indicated in figure 8 is true. The indication is that limestone in the overlying rock causes as much as a threefold decrease in the angle of draw in comparison to an equivalent percentage of sandstone in the overburden. The student "t" statistical test for "goodness of fit" was used to determine these relationships.

More precise predictions of the complex interrelationship of geology and angle of draw require a more precise definition of the lithology, probably including bed thickness and jointing as well as rock type.

The dependence of maximum measured surface subsidence (S_{max}) on reported lithologies and mining conditions (table 1) is more complex than is the angle of draw relationship to lithologies alone. The assumed independent variables extracted from the literature were percent shale, percent sandstone, percent limestone, mining depth, mining height, and percent extraction.

The apparent dependence of maximum measured surface subsidence, as a percent of the mining height, on the lithologic percentages of shale, sandstone, and limestone is presented in figures 9-11. The calculated level of statistical confidence in an interrelationship, again using the student "t" test, between maximum subsidence and: (1) percent shale is 88 percent, (2) percent sandstone is 97 percent, and (3) percent limestone is 85 percent.

Table 3.--Angles of draw (from vertical) for mines in flat-bedded sedimentary rocks with respect to lithology of overburden

Location and commodity	Lithologic percentages in overburden			Angle of draw (degrees)	References
	Shale[1/]	Sandstone	Limestone		
Pennsylvania, coal.	50	22	28	18.0	Greenwald and others (1937).
Do-------------	78	13	9	24.0	Maize, Thomas, and Greenwald (1940).
Do-------------	59	11	30	9.0	Maize and Greenwald (1939).
Great Britain, coal.	12	88	0	0.0	English (1940).
New Mexico, coal.	63	37	0	15.0	Abel and Gentry (1978).
Great Britain, coal.	68	32	0	17.0	Sinclair (1950).
Do-------------	63	29	8	12.0	Do.
Do-------------	64	36	0	29.0	Briggs and Ferguson (1933).
New Mexico, uranium.	86	14	0	40.0	C. H. Parrish (written commun., 1979).
California, borate.	17	83	0	8.0 (avg.)	Obert and Long (1962).
Pennsylvania, coal.	48	52	0	18.0	Montz and Norris (1930).
India, coal------	25	75	0	13.0	Kumar and Singh (1973).
Do-------------	23	77	0	21.0	Do.
Do-------------	57	43	0	28.0	Do.
Do-------------	37	63	0	18.0	Do.
Do-------------	35	65	0	17.0	Do.
Do-------------	35	65	0	17.0	Do.
Do-------------	23	77	0	17.0	Do.
Do-------------	32	68	0	27.0	Do.
Illinois, coal---	71	17	12	8.5	Herbert and Rutledge (1927).
Do-------------	57	38	5	0.0	Do.
Arizona, copper--	0	0	100	12.0	Trischka (1934)[2/].

1/Includes all argillaceous rocks.

2/Fault bounded on all four sides. Therefore, not employed in statistical analysis.

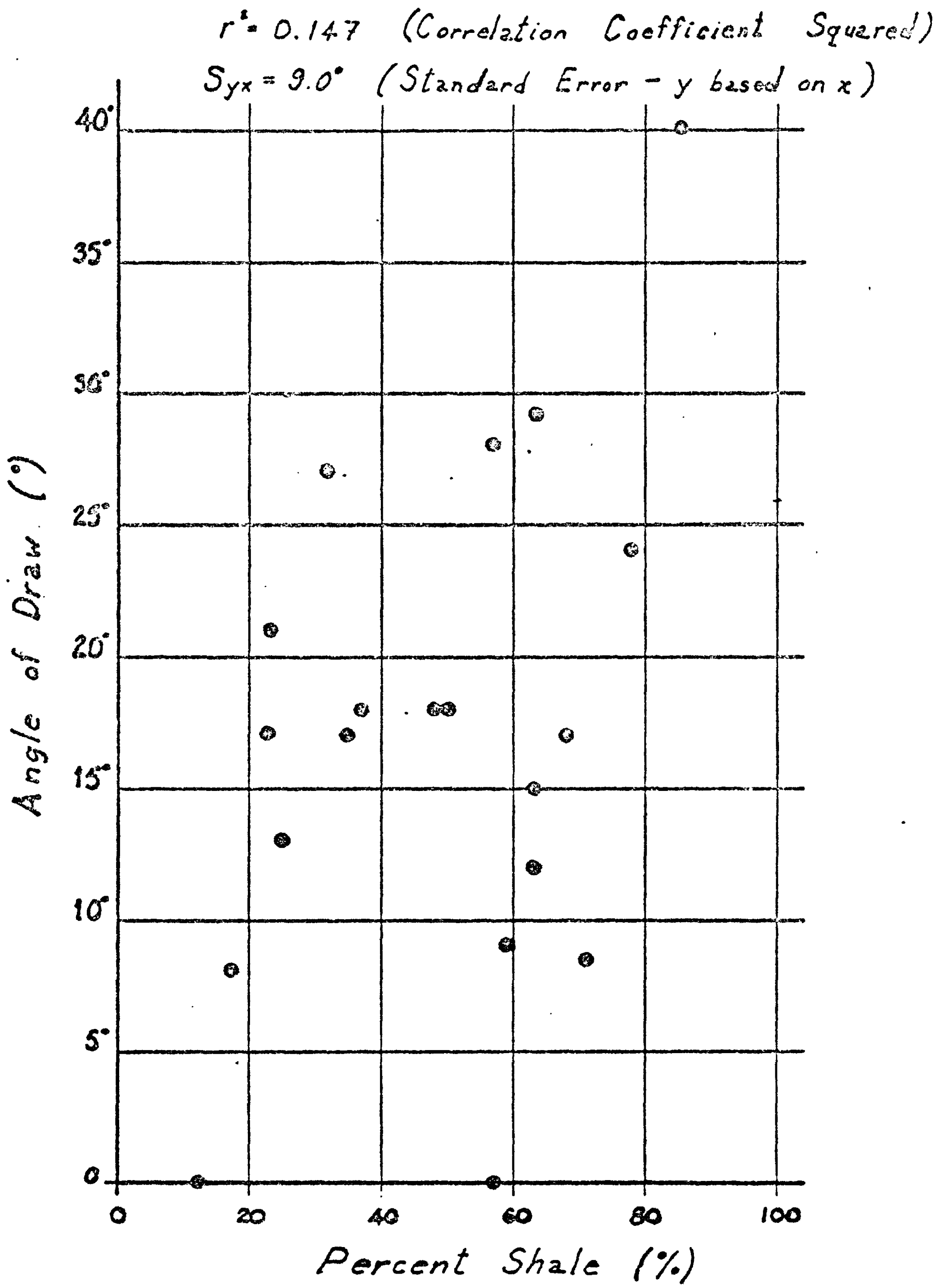

Figure 5. Reported angle of draw versus percent shale.

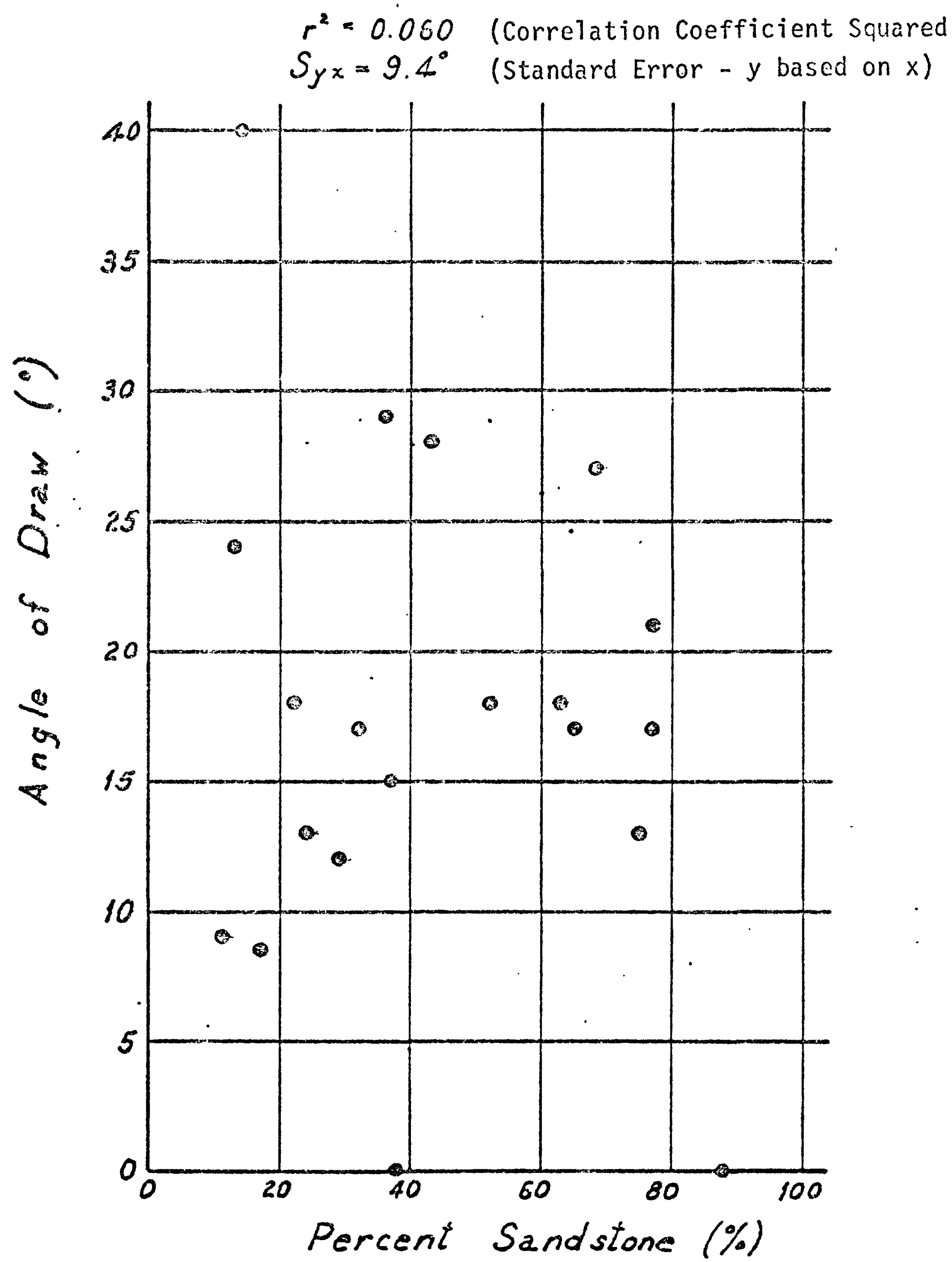

Figure 6. Reported angle of draw versus percent sandstone.

$r^2 = 0.049$ (Correlation Coefficient Squared)
$S_{yx} = 9.5°$ (Standard Error - y based on x)

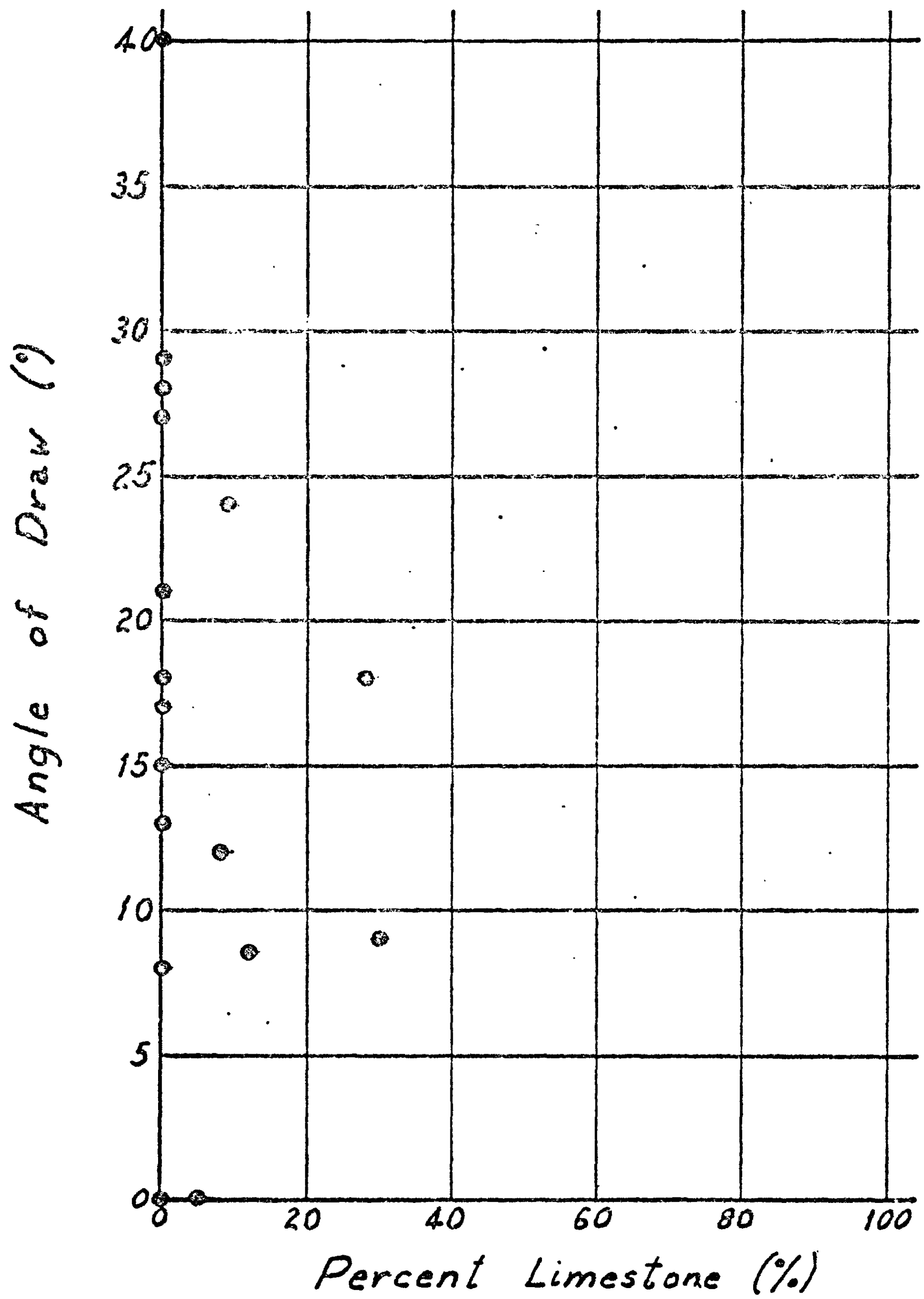

Figure 7. Reported angle of draw versus percent limestone.

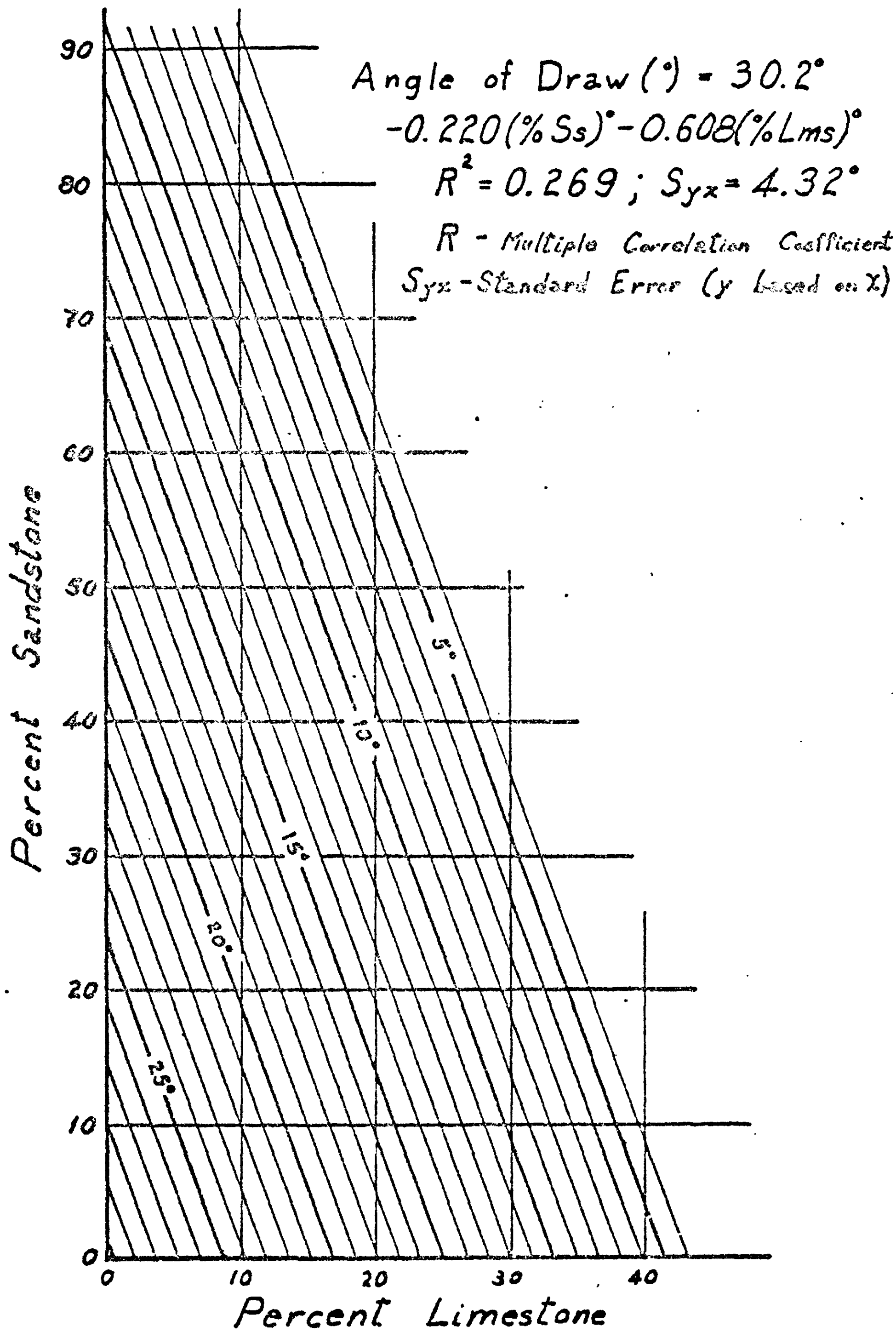

Figure 8. Reported angle of draw versus percent sandstone and limestone.

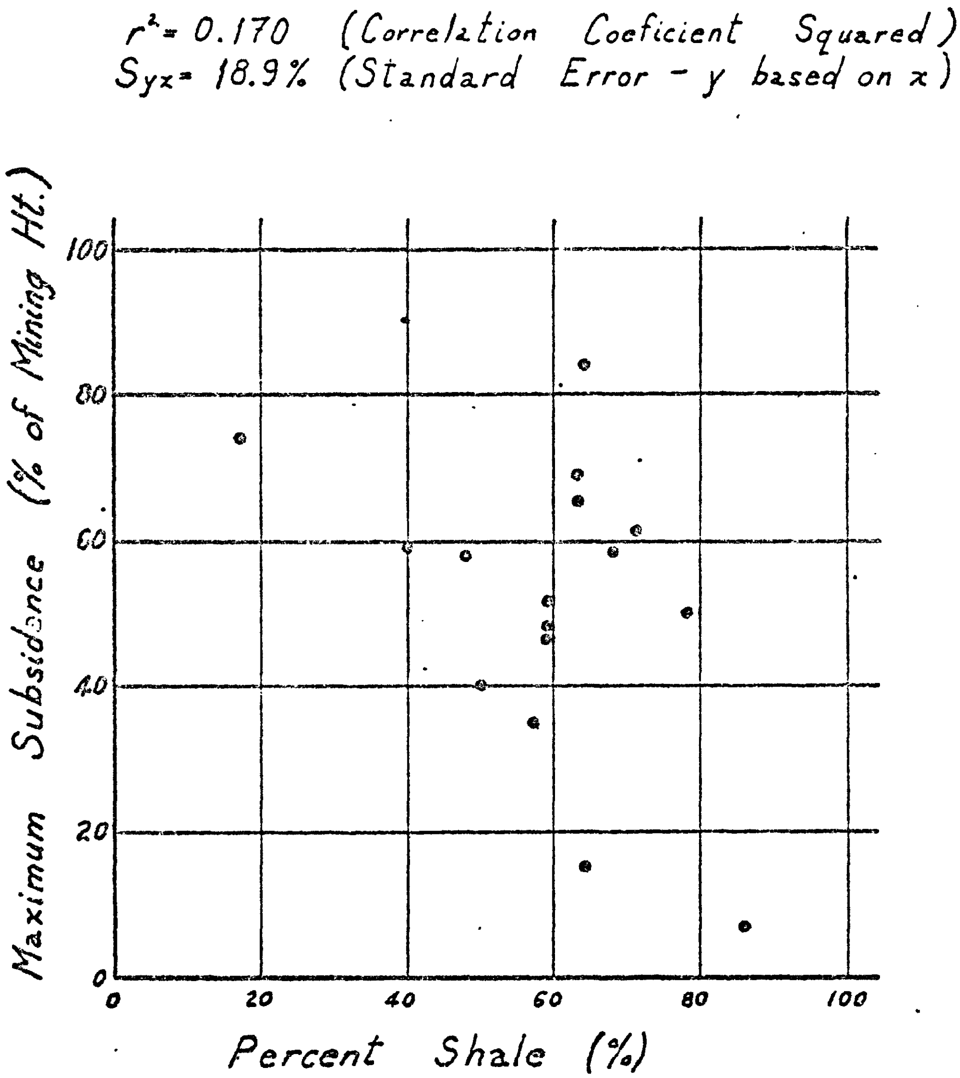

Figure 9. Reported maximum subsidence versus percent shale.

$r^2 = 0.312$ (Correlation Coefficient Squared

$S_{yx} = 17.2\%$ (Standard Error - y based on

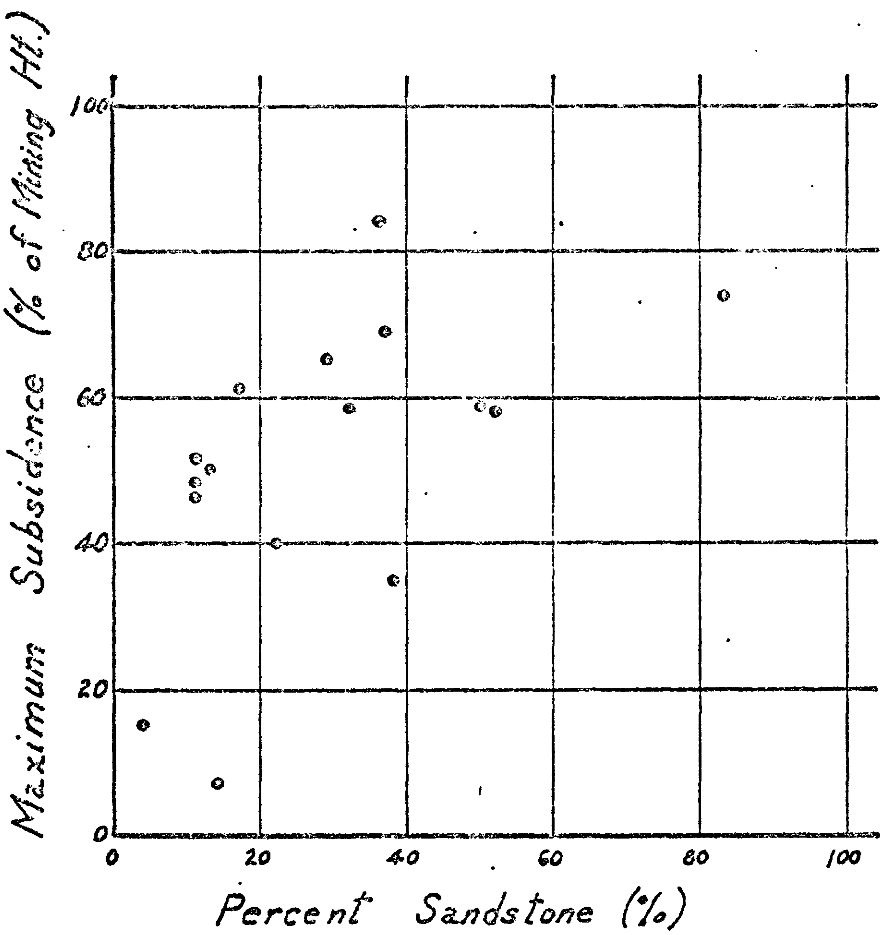

Figure 10. Reported maximum subsidence versus percent sandstone.

$r^2 = 0.146$ (Correlation Coefficient Squared)

$S_{yx} = 19.2\%$ (Standard Error - y based on x)

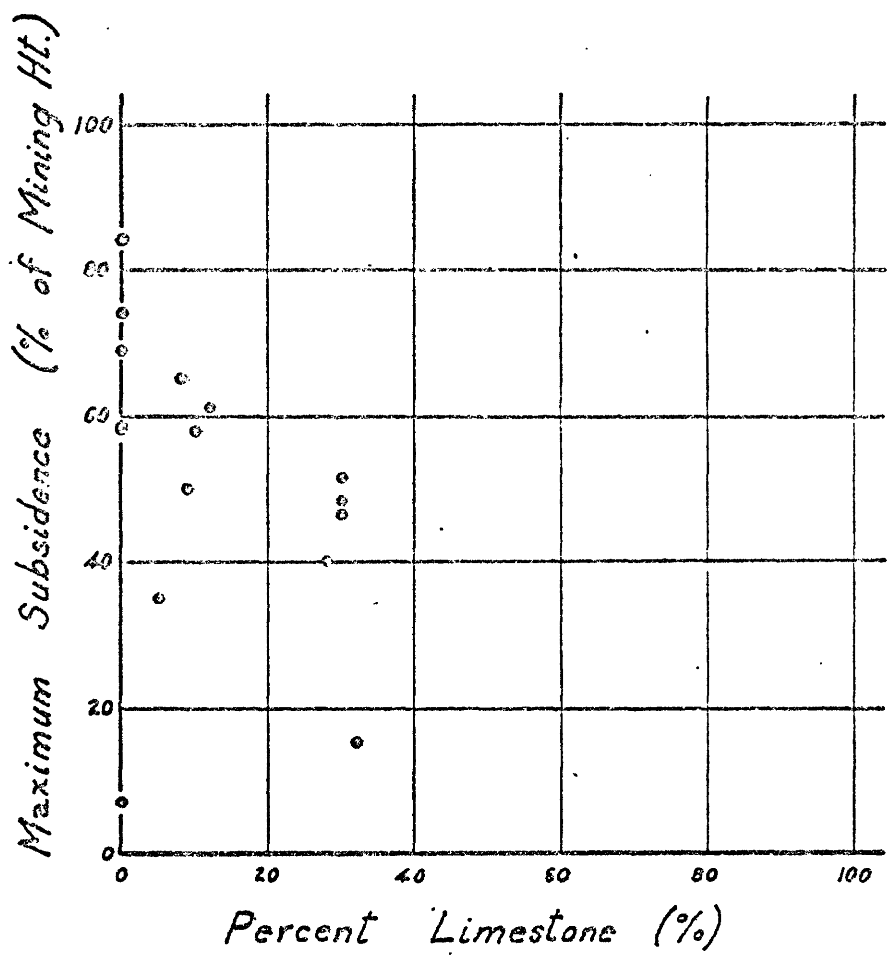

Figure 11. Reported maximum subsidence versus percent limestone.

The reported data on mining conditions indicate that there is probably no relationship between depth of mining and maximum measured subsidence (fig. 12). In fact, the calculated confidence level of about 40 percent is less than that for flipping a coin. The relationship between mining height and maximum measured subsidence involves one extreme outlying value (fig. 13), the results of which were reported by Obert and Long (1962) for a 42-m-high block of borate. This block was blasted down as a plug, which could make its inclusion in the statistical analysis questionable. Dropping the outlying value (fig. 14) increases the level of confidence in an interrelationship from 55 to 98 percent. The highest level of confidence, greater than 99 percent, of a relationship quite reasonably exists between the percent extraction and the maximum measured subsidence (fig. 15).

Subsidence over crystalline rocks

The crystalline rocks above many metalliferous orebodies are not ordinarily massive because they are commonly jointed and faulted. In addition, the typical igneous rock mass varies in rock composition, and may contain dikes, sills, and inclusions of country rock. These features generally would be undesirable in sites for underground storage or disposal of hazardous waste. Metalliferous orebodies generally have irregular geometries, varying in lateral and vertical dimensions. The thickness of ore withdrawn during mining in crystalline rocks is frequently sufficiently great to result in collapse of the surface. MacLennan (1929, p. 169) reported that a block cave stope broke through overlying massive Precambrian schist to the surface after 12.6 percent of the thickness of rock between the extraction level and the surface was removed. Thomas (1971, p. 5) reported that the upper surface of the monzonite rocks overlying one orebody was breached when 11 percent of the rock column had been withdrawn. Thomas (1971, p. 54) reported that withdrawal of about 10 percent of the same rock column above another orebody at a nearby location produced a similar breach.

The subsidence mechanism in the case of mineral extraction in crystalline rock is roughly as follows:

1. Collapse of rock progresses upward from the mining horizon (undercut level) as ore is withdrawn from below. The resulting column of caved and broken rock is confined above the area of extraction.

2. The ground surface does not begin to measurably subside until the collapse has so thinned the overlying intact rock that it cannot transfer the load of the overlying rock to the adjacent solid rock ribs. The overlying solid rock will then begin to deflect downward toward the collapsed rock below. Lateral movement of adjacent rock into the collapsed rubble column is resisted by the active pressure of the rubble (broken rock). In extreme cases, where the adjacent solid rock begins to move laterally into the rubble column, it is resisted by the passive pressure (resistance) exerted by the broken rock.

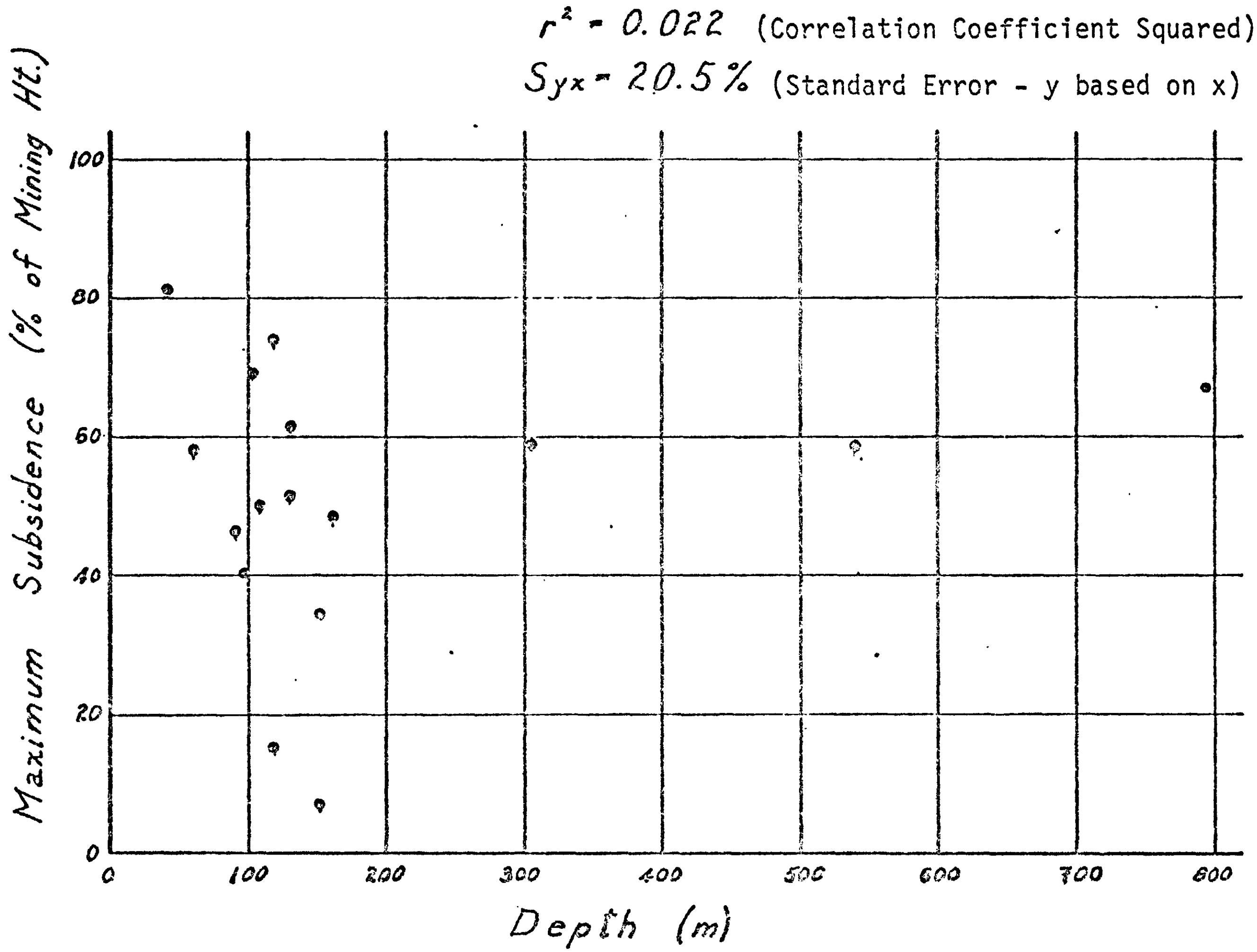

Figure 12. Reported maximum subsidence versus depth.

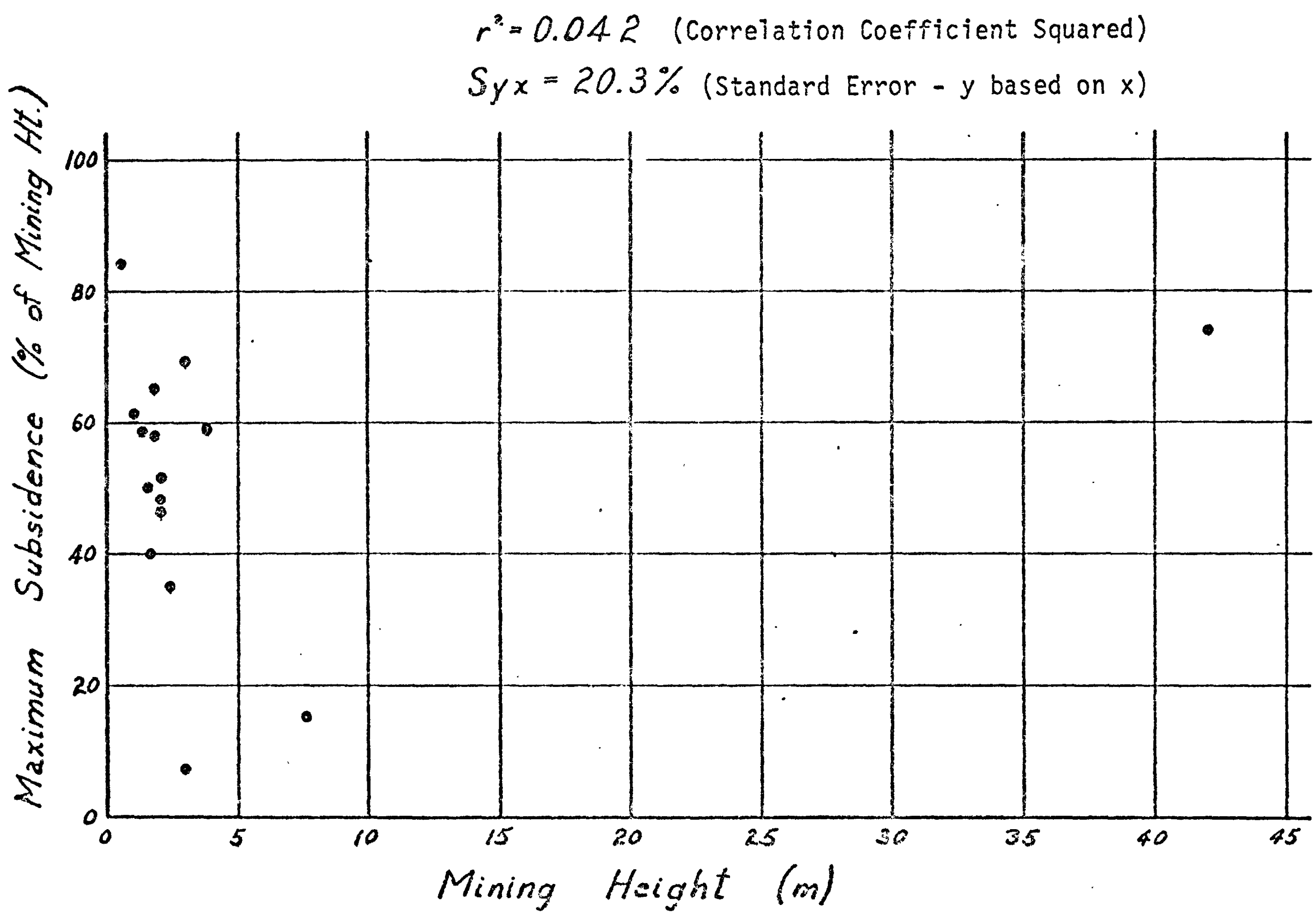

Figure 13. Reported maximum subsidence versus mining height (all data).

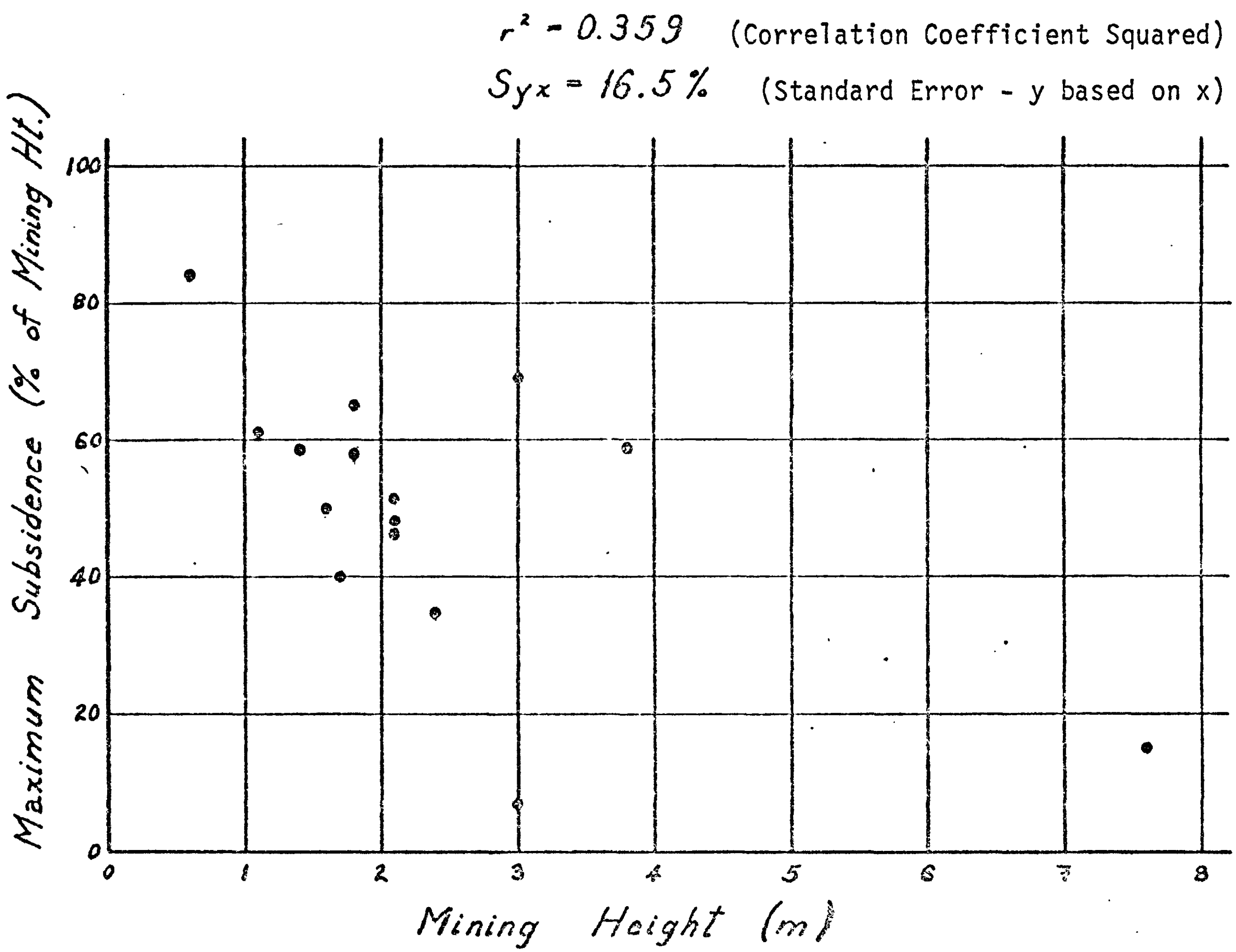

Figure 14. Reported maximum subsidence versus mining height (data outlier removed).

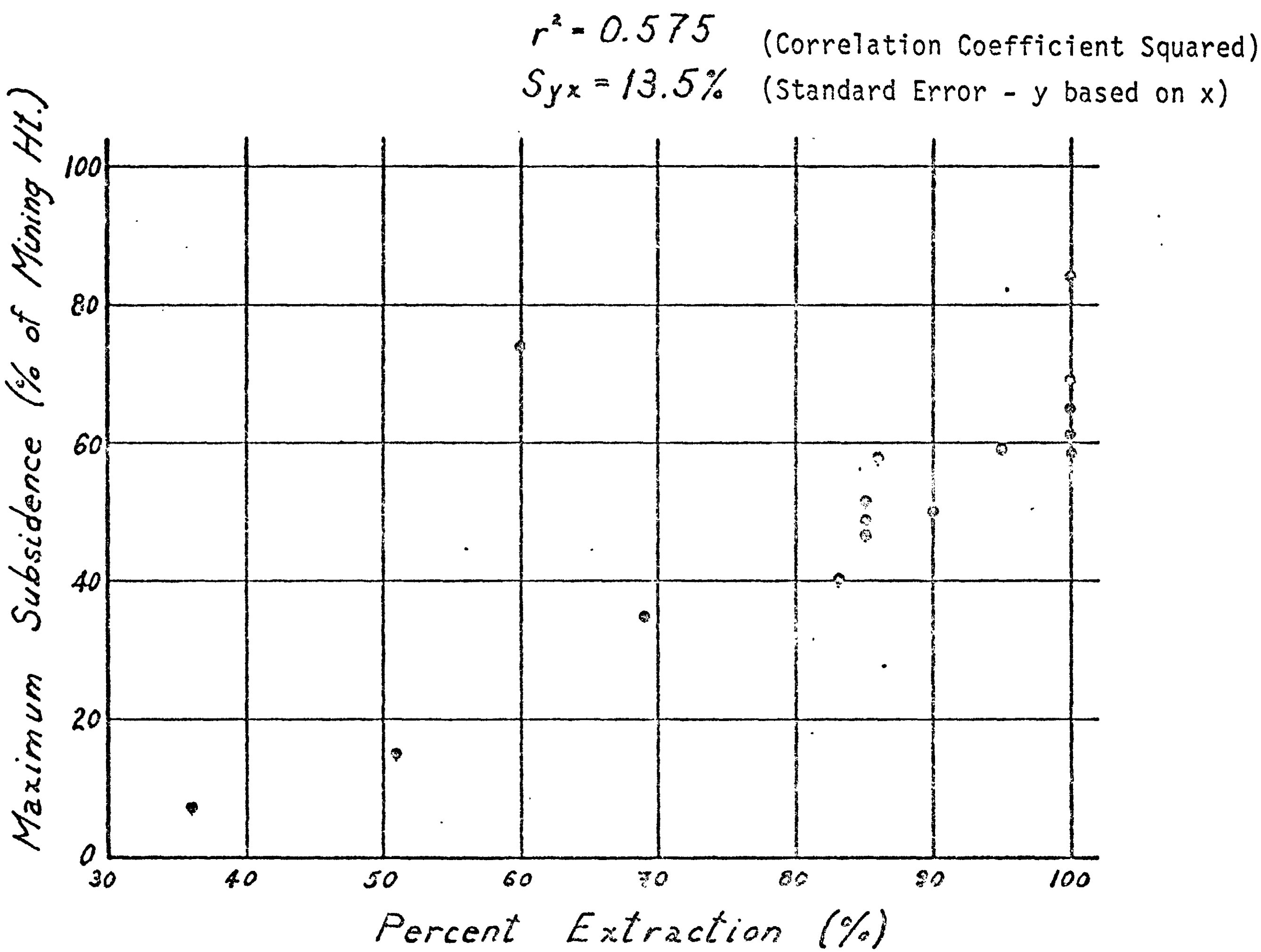

Figure 15. Reported maximum subsidence versus percent extraction.

3. Further extraction of caved ore from below results in increased sag (subsidence) of the ground surface above and adjacent to the area of extraction. The overlying intact rock is progressively thinned by the further upward migration of the broken rock, which causes intact rock to deflect onto the caved rock. The initial trough subsidence is similar in shape to the trough subsidence observed above coal mining (Thomas, 1971, p. 6, 16).

4. Continued extraction of ore will result in breaching of the surface. The initial breach is typically in the form of a circular pit, commonly referred to as a chimney. The chimney is roughly centered over the mining area, but may be offset a minor distance. Such an offset is probably the result of preferential collapse along geologic weaknesses in the rock mass.

5. If ore extraction continues, the surface breach will grow laterally near the surface where the broken rock, and the restraint it provides, has moved down the chimney. The rock adjacent to the subsided chimney either slides along geologic weaknesses, such as joints or faults, or topples into the evacuated upper part of the chimney.

6. The final, or ultimate, angle of draw is determined either by the place where the lowest angle of geologic weakness intersects both the ground surface and the mining horizon or by the place where the angle of repose of the broken rock mass is reached, whichever has the lower angle.

The presence of a fault in crystalline or sedimentary rock can terminate the angle of draw short of its normal value. In the case of crystalline rock a steeply dipping fault which lies outside the collapsing rock column can terminate the gradual increase of the angle of draw at the surface outcrop of the fault. In the case of trough subsidence and sedimentary rock (Lee, 1966) the subsidence curve is usually truncated by such a steeply dipping fault. In both cases, the ground surface abruptly drops across the fault, with the downthrown side toward the chimney or toward the center of the trough.

If a gently dipping fault intersects the collapsing rock column the lateral extent of surface subsidence can increase outward to the place where the fault intersects the ground surface. Whether or not this takes place depends primarily on the shear strength of the fault zone. Thomas (1971, p. 38-45) indicated the lateral extension of the subsidence pit to be about 1,000 ft along the San Manuel fault and beyond the draw limits measured on the other sides of the pit.

It is common practice to report both an initial and a final angle of draw for caving subsidence. The initial angle of draw is the extent of subsidence effects at the time the surface is breached. The final angle of draw includes the limit of measurable subsidence effects after mining has ceased. A negative initial angle of draw, that is, it extends inside the mining area, is frequently reported if precise survey measurements are not made. Such a negative angle of draw is the angle between the vertical and a line connecting the side of the chimney to the nearest side of the mining level. Reported initial and final angles of draw which breached the surface above metalliferous mines in crystalline rocks are tabulated in table 4. No information was found for initial angles of draw for trough subsidence where the extraction of thickness was limited and the surface was not breached by caving.

The progression of surface subsidence described above will end at any stage if extraction of rock from below stops, except where long-term consolidation of the collapsed rock has occurred. The ultimate extent of subsidence is controlled by "bedding and jointing which constitute the principal lines of weakness universally present in rock formations" and "may be considered the controlling factors in ground movement" (Crane, 1929, p. 6). "When rock formations are broken due to the removal of underground support, the movement occurs upon existing planes of weakness and not upon fresh breaks across the formations" (Crane, 1931, p. 3).

Both subsidence troughs and chimneys can occur either in crystalline or in sedimentary rocks and either above shallow coal mines or above shallow or deep metal mines. The differences are generally related to the lateral extent of surface subsidence effects. Lateral subsidence above crystalline rocks can extend farther because the dip of the joints can be flatter than the angle of draw observed for trough subsidence above bedded sediments. Typical bedding cross-joints are approximately perpendicular to the bedding planes. In flat-lying sediments, the bedding cross-joints do not define the extent of subsidence. In this case it is the flexure of the beds that determines the extent of subsidence. Typical subsidence in bedded sediments which are sufficiently deep that no collapsed chimneys result (about 10 times extraction thickness), does not extend beyond step 2 above.

Subsidence associated with pillar failure in room-and-pillar mining

Room-and-pillar mining is frequently used in areas where the surface must be protected from the effects of subsidence. In Pennsylvania this provision has been codified into law (Bituminous Mine Subsidence and Land Conservation Act, 1966). The assumption that subsidence can be eliminated by leaving pillars of sufficient size, however, is erroneous. The extraction of part of a tabular deposit, in this case coal in Pennsylvania, will increase the vertical stress in the remaining pillars. The pillars will shorten in response to the increase in stress. This pillar shortening will be transmitted to the surface, but its effect is normally so small as to be negligible and frequently undetectable. Prediction of the long-term stability of the pillars is a major problem for room-and-pillar mining. Pillar failures leading to sudden surface subsidence have occurred as long as 100 years after mining (Thornburn and Reid, 1977, p. 90).

Table 4.--Angles of draw (from vertical) reported for mines in crystalline rocks

Location and commodity	Angle of draw Initial	Angle of draw Final	Remarks	References
Missouri, iron---	--------	54°	Jasper and slates, joint and foliation controlled.	Crane (1929).
Do-------------	--------	10°	Jasper "master joint" controlled.	Do.
Do-------------	--------	≤65°	Slates, foliation, and joint controlled.	Do.
Missouri, copper.	4°	24°	Joint (slip) influenced-------	Do.
Arizona, copper--	15°	40°	Porphyry and chlorite shist---	Mills (1934).
Do-------------	--------	≤55°	Porphyry, joint controlled----	Do.
Do-------------	--------	≤43°	Diorite, joint controlled-----	Do.
Colorado, molybdenum.	-2°-14°	≤30°	Granite gneiss host, residual stress.	Vanderwilt (1949).
Arizona, copper.	-5°-32°	24°-45°	Porphyry host rock, joint and fault controlled.	Kantner (1934).
Do-------------	14°-40°	44°-48°	Schist and massive conglomerate, limited fault control.	Fletcher (1960).
Do-------------	17°		Monzonite porphyry 69 percent, gila conglomerate 31 percent.	Thomas (1971).
Do-------------	--------	5°-24°	Joint and fault controlled----	Do.
British Columbia, copper.	0°-5°	23°-36°	Joint with minor fault control, volcanics, and hanging wall gabbro.	Nelson and Fahrni (1950).

The monitoring of the surface above room-and-pillar mining operations is rarely undertaken; however, data are available from the few surface subsidence-monitoring programs over failed pillars (table 5). The subsidence reported is much less than that predicted by the widely used NCB (1975) model for longwall mining--the uniform extraction of a thickness of coal across a wide and long area. Knothe (1957, p. 214) reported a reduction of maximum subsidences to as little as one-thirty-fifth of the NCB longwall subsidence prediction for 50-percent extraction by room-and-pillar mining. This, no doubt, results from the fact that when pillars fail they crush and expand but do not flatten out uniformly. The shortened crushed pillars increase in load-carrying capacity in some proportion to their increase in cross-sectional area. Wilson (1972, p. 413) reported placing 166 MPa (24,000 lbf/in^2) on a cylinder of coal fragments whose width was 20 times its height. Likewise, solid coal pillars could never carry such a stress unless their width/height ratio was similarly large. The data presented in table 5 and shown graphically in figure 16 permit a statistical analysis based on the method presented by Wardell and Eynon (1968).

Backfill has been placed in room-and-pillar workings in some mines to reduce subsidence. This method has been highly successful as indicated by the results reported by Kumar and Singh (1973, p. 6-2, 6-3) and by the results in table 5 for the Jharia mine in India. The predicted percent of subsidence without backfill is nearly 20 times greater than that measured with backfill (fig. 17).

Accurate prediction of the reduction in subsidence effects resulting from backfilling around pillars commonly is not possible because uncontrolled or unreported factors, such as the completeness of filling and the compressibility of the fill are not accurately known. It is also necessary to determine the percent of swell of the failing pillar as it interacts against the fill material. Subsidence effects can be greatly reduced by backfilling, but subsidence cannot be eliminated.

Rate of subsidence

The time factor in mining-induced subsidence has been investigated in the past, mainly as it applies to coal mining. Young and Stoek (1916), for example, reached only one general conclusion: the deeper the seam the longer the duration of surface movement. Although this is a widely accepted finding the reasons behind it still are not completely understood.

Table 5.--Subsidence measured above room-and-pillar and partial extraction workings following pillar squeeze or failure

Location	Mining height (H) (m)	Pillar width (W) (m)	Extraction (R) (percent)	Depth (D) (m)	Average pillar stress (L_{max}) (MPa)	L_{max} (H/W)	Subsidence (H) (percent)	References
N. Staffs., G.B.	1.30	3.1	70	79	5.98	2.54	13.8	Wardell (1969).
Do-------	1.30	13.4	51	101	4.21	.41	2.2	Do.
Do-------	1.37	9.0	41	137/274	5.26/10.52	0.786/1.57	10.5	Wardell and Eynon (1968).
Cannock, G.B.	2.13	15.0	31	265	8.70	1.22	9.6	Do.
Franklin, Ill.	2.44	5.0	69	152	11.2	5.56	34.8	Herbert and Rutledge (1927).
Lick Creek, Ill.	7.62	12.0	51	122	5.63	3.15	15.2	Warm (1973).
J.J. No. 1, N. Mex.	3.1	12.0	36	152	5.38	1.34	6.9	C. H. Parrish (written commun., 1979).
Montoar 10, Pa. 1/	1.7	2.3	83	98	13.03	9.59	40.0	Greenwald and others (1937).
Crucible, Pa. 1/	2.1	1.5	85	129	19.51	26.6	51.5	Maize and Greenwald (1939).
Gibson, Pa. 1/	1.6	1.5	90	108	24.47	26.1	50.0	Maize, Thomas, and Greenwald (1940).
Crucible, Pa. 1/	2.1	1.5	85	162	24.47	33.2	48.2	Maize, Thomas, and Greenwald (1941).
Nemacolin, Pa. 1/	2.1	1.5	85	91	13.65	18.6	46.3	Do.
Carlsbad N. Mex.	3.89	5.5	95	305	137.88	97.7	58.8	Miller and Pierson (1958).
Jharia, India. 2/	10.5	61.0	57	165	8.67	1.49	.56	Kumar and Singh (1973).

1/Data partly determined from plans and sections presented.
2/Not used in statistical analysis because of hydraulic sand backfilling (stowing).

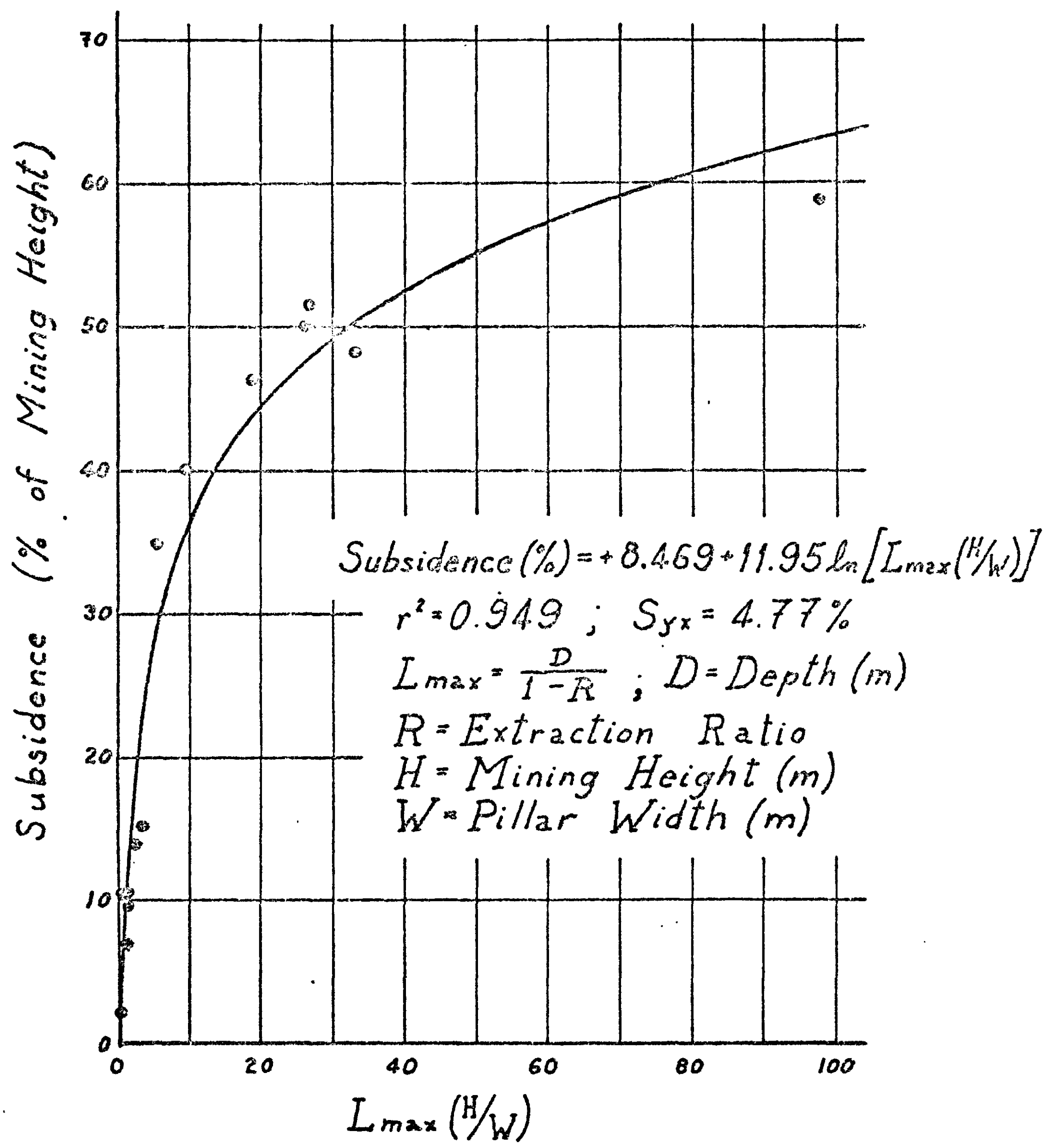

Figure 16.--Subsidence above room-and-pillar partial extraction workings following pillar squeeze or failure.

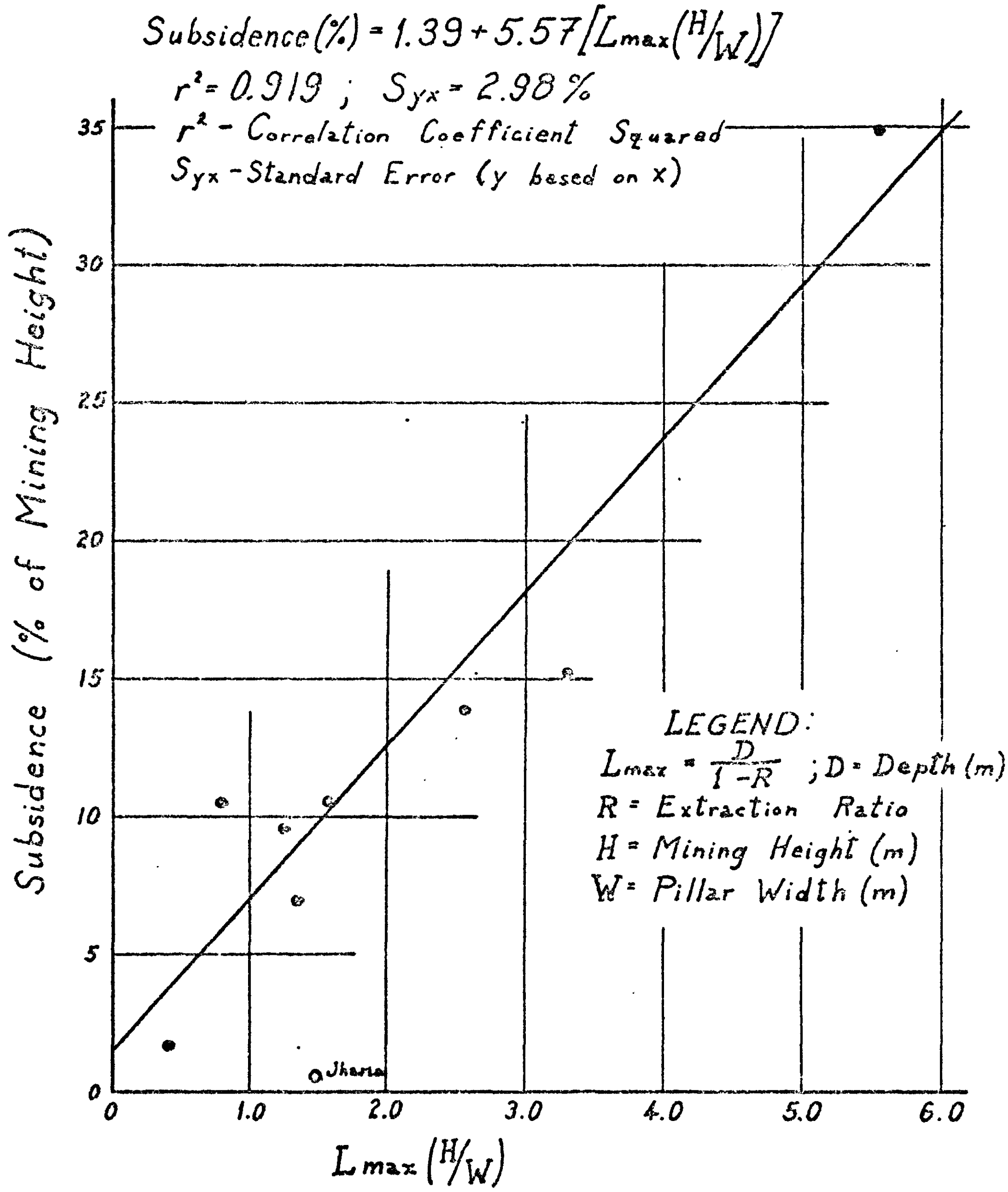

Figure 17.--Room-and-pillar subsidence accompanying pillar failure at low extraction.

Wardell (1953) showed that the subsidence of a point at the surface theoretically begins when a longwall face enters the "critical area" (fig. 3) and ceases when the face leaves the critical area. However, Wardell further showed that the surface point continues to subside (residual subsidence) for a variable period, perhaps months, but that on the average, 95 percent of the total subsidence occurs while the face is within the critical area. Most investigators suggest that rate of advance and depth of mining are the factors governing the rate of surface subsidence. In addition, a "development factor" which includes depth, mining height, and percent extraction (Orchard and Allen, 1974) has been proposed for mining-geometry influences. As stated earlier, in respect to the areal limits of subsidence, geological and geomechanical properties influence strain rates and modes of deformation. Orchard and Allen (1974) reported that, when the face advances out of the "critical area," further ground movements occur due to complex time-dependent stress redistribution processes in the overlying rocks.

The influence of depth of mining and face position on time-dependent subsidence becomes more important in the event of pillar failure in room-and-pillar mining than that in longwall mining. Pillar failure can be delayed, progressive, or sporadic.

Residual or delayed subsidence

Orchard and Allen (1974) noted that 9 percent of the total subsidence occurred during the 6 years after a 166-m-deep longwall face advance stopped at Peterlee, England. A thick dolomitic limestone apparently caused a delay and reduced the amount of subsidence. The same authors mention that a residual surface subsidence of 16 mm occurred 3 months after longwall mining of a 105-m-deep coal seam stopped in north Durham, England. Then, after a pause of 5 months during which there was no subsidence, a subsidence of 17 mm took place over the next 3 years. The delayed subsidence was 6.8 percent of the 3-year total. At this mine a 23-m-thick bed of sandstone apparently delayed surface deformation. A gradual lowering of the rock mass is associated with weak beds whereas violent, often delayed, collapse is associated with the sudden failure of strong roof rocks. According to Piggott and Eynon (1977), if there is at least one competent rock layer, which has a thickness of at least 1.75 times the appropriate opening span width, between the mine workings and the surface, the collapse process will be stopped by that competent bed.

Subsidence may be delayed either when the extraction percentage is decreased and pillars are left, or when backfilling is used. Similarly, Whetton and King (1961) found that the area of the underground workings also controls the timing and vertical extent of surface subsidence. Thus, roof deflection is proportional to roof span width and span width is proportional to surface subsidence; the greater the span width the more rapidly deformation will reach the surface.

Many accounts are recorded of severe surface deformations that occurred, often abruptly, long after mining ceased. With only a few exceptions, most of which are controlled by geological conditions such as those previously mentioned, the notable delayed residual subsidence has taken place in room-and-pillar mined areas rather than in longwall mined regions. In the former County of Lanark (Scotland) mining had been completed 118 years when a sudden collapse of sandstone beds occurred above workings only 16 m deep. At the surface structural damage to apartment buildings was so severe that the tenants were evacuated and several blocks of buildings were demolished (Thornburn and Reid, 1977). At Farmington, W. Va., intermittent episodes of subsidence occurred when 2- to 3-m-high coal pillars punched into the weak claystone mine floor (Gray, Bruhn, and Turka, 1977). Surface deformation that damaged dozens of homes and buildings began while the mine (85 m below the surface) was active. Subsidence movements continued for more than 4 years after mining stopped until the mine was backfilled with coal waste.

Summary and conclusions

Subsidence is the downward sinking of the ground surface due to the collapse of underground cavities, in the present case, mined cavities. The surface extent of subsidence is greater than the cavity length and width. Vertical movements predominate but lateral movements of both expansion and contraction also take place. In many areas maximum vertical subsidence is less than 50 percent of the mining height. Subsidence is a time-dependent deformation that may result from mine roof collapse, pillar failure, pillar punching, or various combinations of these mechanisms. Subsidence may be detected through rupture of utility pipelines, foundation displacements, or changed drainage patterns, more than 100 years after mining has ceased. Subsidence induced by longwall mining is much easier to predict and monitor than subsidence induced by partial extraction methods. The information presented here does, however, demonstrate that subsidence is controlled by the complex interaction of mining and geologic conditions and is time dependent, particularly in the case of room-and-pillar workings.

No measurements of subsidence effects have been made above room-and-pillar workings in massive shale and crystalline rocks. Therefore, predictions of subsidence from room-and-pillar excavation for waste storage facilities in these rocks based on information gained from less, perhaps much less, massive rocks will be subject to unknown error. Measurements in massive rocks will be needed to verify extrapolation of available subsidence measurements, mechanisms, and effects.

Perhaps reasonably accurate subsidence predictions can be made for deep waste storage chambers in more massive and less complex rock masses using one or more of the existing subsidence-prediction models for coal measure rocks. Accurate determination of geologic and excavation conditions, adequate monitoring, and careful analysis are required for a meaningful validation of such extrapolations.

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