A MINERALOGIC STUDY OF SILICOSIS*

R. C. EMMONS AND RAY WILCOX
University of Wisconsin, Madison, Wisconsin.

ABSTRACT

Silicosis is caused by the presence of colloidal silica in the tissues of the lung. Such silica apparently destroys living tissues by collecting on cell walls. Its source is believed to be inhaled particles of quartz and silicates which remain in the lung long enough for the mildly alkaline lung fluids to attack them chemically. The removal of such dust particles from the lung is facilitated by the presence of other dust particles which serve as flocculating agents. It is recommended that if such protector dusts are not present in an environment where the silicosis hazard prevails, then they should be added as an economical and effective means of protection. The suggestion is also made, based on experimental data, that other minerals not yet recognized may create similar health hazards. A microscopic examination by a competent petrographer should be made to determine what protector dusts are needed in a given case.

The attention which has accrued to the silicosis problem, stimulated by humanitarian and scientific interest as well as by the commercial demand for prevention through control of conditions, is in a measure justification for the entrance of more petrographers into the field in a cooperative attempt to contribute to a solution. Since the materials which cause silicosis are mineralogic and petrographic in nature, and since experimental backing for a suggested preventive method involves the study and handling of mineralogic and petrographic materials and technique, it is proper to remove this part of the burden from the physiologist in the interest of efficiency and economy of time. The results of the study presented here were obtained after repeated consultations with Drs. Middleton, Bunting, and McCarter of the faculty of Medicine of the University of Wisconsin. We wish, also, to acknowledge the helpful cooperation of Professor E. Truog of the University of Wisconsin, Department of Soils, and of Professor E. B. Fred and J. L. Roberts for extending the use of the facilities of the Agricultural Bacteriology department.

The literature on the subject is so extensive and has been collected so effectively by others more competent to do so in the medical field, that no attempt is made here to do more than give occasional pertinent references.

Outstanding conclusions of others which should serve as a basis for further work are two: First, that silicosis is caused by the liberation in the lung of colloidal silica by minerals able to produce it in that specific

* Presented December 29, 1936, at the annual meeting of The Mineralogical Society of America held in Cincinnati, Ohio. This work was supported in part by a grant from the Wisconsin Alumni Research Foundation.

environment;[1,2] Second, that certain materials, notably shale, have been observed to exercise a protective influence in the lung on those exposed to the silicosis hazard.[3,4] It is logical, then, to direct further work along lines which connect these two conclusions. The thesis of this paper is that certain minerals, which are present in shale, and elsewhere, have a protective influence in an environment which is otherwise conducive to silicosis.

The theory adopted here for the cause of silicosis is briefly as follows: A mineral particle in the lung is submerged in a mildly alkaline solution which slowly dissolves any particle of the nature of quartz, which is susceptible to alkaline attack. Since considerable time may elapse before such a particle may be expelled from the lung, the chemical attack, especially for some minerals, becomes quite effective. The silica thus liberated is either in true solution or in a colloidal suspension, probably both. This silica is dispersed radially outward and collects on the walls of nearby cells, which become "smothered" by the adhering silica film. Their function is destroyed and the cell dies. This dead cell tissue is then replaced by connective tissue which constitutes the silicotic nodule. Since the dispersed silica radiates outward from the mineral source the immediately adjacent cells are the first to be destroyed. Until the adjacent cells collect their quota of liberated silica, more remote cells are unaffected. Therefore, the nodular growth forms from the center outward, in surface layers much like the skins of an onion. These constitute the whorls commonly seen.

On the basis of this theory the immediately noxious substance is the dispersed colloidal silica, and not the foreign particle which is the source of it. It is obvious that any mineral which is susceptible to attack by the mildly alkaline solutions in the lung, with the liberation of silicic acid, is also capable of causing silicosis unless the dispersion of the liberated silicic acid can be prevented. Let us first view another aspect of the problem.

The lung is equipped with means of eliminating foreign bodies which reach even the remote air sacs beyond the bronchioles. This means consists of amoeboid scavenger cells known as phagocytes which engulf such bodies and then convey them from the lung. This phagocytosis functions variously on different materials. If it functions properly there is inadequate time ordinarily for the effective chemical attack on the foreign body. This kind of protection is then to be emphasized especially.

Haldane and his associates[4] have demonstrated that the lung does not eliminate all mineral materials with equal ease. Pure minerals are eliminated with difficulty; certain mixtures are eliminated much more easily.

Pure lamp black ("flue dust"), "pure china clay," and pure quartz are difficultly eliminated. On the other hand, most coals are relatively easily eliminated, as are mineral mixtures which include shale. Haldane has called attention to the influence of shale as a protector against silicosis. Mavrogordato[5] used coal dust as an "antidote" for silica dust in guinea pigs. Haldane, with his wealth of experience states,[4] "There seems to be little doubt that when a mineral which, owing to the presence of much quartz, gives a naturally dangerous dust, is mined with country rock of another character which has to be worked simultaneously, the danger from the quartz may be almost abolished."

There seems to be ample reason to believe, therefore, that protector minerals exist. If a sound explanation can be found, then the protector minerals may be identified. By way of explanation Haldane stated in 1917.[3] "It can well be imagined that insoluble dust particles are attractive to dust cells in proportion to the soluble substances adsorbed in the dust particles, and that the particles containing little of these substances will be correspondingly unstimulating." Again in 1929[4] Haldane stated, "Why then do some kinds of dust stimulate the dust cells? It must be, I think, because they are either themselves soluble or contain something soluble and thus capable of acting as a stimulant." This explanation is as Haldane says, "still more or less obscure."

Doubtless there are many factors which control phagocytosis. It seems reasonable that if one dust, such as shale dust, is stimulating to a phagocyte then that dust should be selectively removed and the unattractive quartz dust left behind. But in presence of such a protector dust, *both* dusts are removed. The following explanation, therefore, is suggested as the factor of paramount importance.

Cataphoresis runs have been made on many such substances as those discussed here and were repeated for this study. It is known that silica in a dilute sodium chloride water solution carries a negative charge. Other substances, similarly, carry a positive charge, notably carbon as carbon black, iron oxide as hematite, and the alkaline earth carbonates. In the presence of these oppositely charged materials the whole is aggregated by virtue of this attraction and thus loses its disperse state. (It has been reported that both quartz and carbon, and possibly other such substances are reversed in charge by the adsorption of proteins in the lung fluids. The principle still holds.) Koppenhofer calls attention to the similarly neutralizing effect of aluminum hydroxide sol on colloidal silica.[6]

The inhalation of pure mineral materials, whether carrying a positive or a negative charge, leads to disperse distribution,—masses of particles,

mutually repellent and in a state of open packing. The forces which hold such particles apart are not commonly appreciated for their full worth—they are real forces. In a purely mechanical way, phagocytosis of such disperse material is difficult. The carrying capacity of individual phagocytes is thus cut down, and we say the lung cannot eliminate such pure material. On the other hand, mixed minerals of positive and negative charges form flocculated aggregates—particles in a state of close packing, many more of which may be handled by one phagocyte, since a given volume contains more particles.

The following simple experiment illustrates the flocculating action. To three settling tubes of freshly prepared serum (beef serum was used by us) add three powders of suitably fine size. To one add quartz powder, to the second add carbon black which has been rendered oil free by washing with alcohol, acetone or a similar oil solvent, and to the third add a mixture of the two. Each powder should be previously wetted with water under partial vacuum to eliminate air bubbles and films. Two or three hours after mixing the wet powders and serum, the mixed powders will be found to have settled much farther than the others.

Since shale is a rock and not a mineral, but an assemblage of minerals, and since one prominent constituent of shale is quartz, then on this basis shale is a very inefficient protector to add to noxious dust. Some of the constituents of shale are harmful, some are protectors. The protectors are, we believe, those which carry the opposite charge in lung fluids to that carried by quartz. These protector minerals if added alone to noxious dust should, therefore, be much more effective than shale.

Sometimes a lung builds a wall ("capsule") around masses of foreign particles. Such isolated masses will not be affected by the addition of a protector dust. Thus Mavrogordato says,[5] "If silica dust be given to an animal who has previously inhaled coal dust, the presence of the coal does not stop the arrest of the silica. If coal dust be given to an animal who has previously inhaled silica dust, the coal does not fetch out the silica. For beneficial results the silica and 'antidote' must be inhaled simultaneously."

Let us separate the fact from the theory. That protecting elements exist is, we believe, definitely recognized. Though shale is one of them, it helps but little since shale is itself a mixture of noxious and protector elements, and, further, no two shales are identical in composition. Some shales which the senior writer has studied for their silicosis hazards he believes would offer no protection whatever, in fact they contain almost exclusively noxious minerals. Calcareous shales, on the other hand, we believe are real, but not efficient, protectors. It has been demonstrated

experimentally that certain *pure* minerals are *not* readily eliminated from the lung. It has also been demonstrated experimentally that certain *mixtures are* readily eliminated from the lung. The theoretical explanation offered here is that flocculated, or aggregated foreign bodies may be eliminated by phagocytosis while disperse bodies may not. Our aim is to accomplish the aggregated state by mixing suitable dusts with noxious dust to facilitate the elimination process. We define suitable dusts as those which carry in the lung fluids a charge which is opposite to that carried by noxious dusts. There are experimental and other reasons to believe that the protector dust functions best when inhaled *with* the noxious dust. Next we shall indicate our further belief that there is some benefit from the delayed inhalation of protector dusts.

On the assumption that the dispersion of silica is the immediate cause of the formation of a silicotic nodule, it is reasonable to believe that if the liberated silica can be conveyed from the lung there will be no harmful effect. But we think of phagocytosis as a process primarily to eliminate sizeable foreign bodies rather than material of colloidal dimensions. If, however, the colloidal material is flocculated to form aggregated masses or adsorbed films on solid bodies, then it constitutes a tangible mass on which the phagocyte may function. In other words, the phagocytosis of colloidal or dissolved silica seems not to take place unaided. Furthermore, the noxious element, colloidal silica, is robbed of its potency while flocculated.

How then may the silica liberated from minerals which the lung has not been able to eliminate, be prevented from spreading? There are many circumstances, of course, when such prevention cannot be accomplished. If, however, any of the protector dust particles are near the source of colloidal silica they constitute a strong attraction for the free silica just as they do for the coarser dust particles. They may be expected, therefore, to serve as collectors for at least some of this liberated silica, retaining it as a discrete unit. Mavrogordato has shown that "silica-stricken" areas of animals' lungs selectively arrest inhaled carbon dust.[5] It is obvious that such protector dust particles will be of greater protection the closer they are to the source of silica being liberated. Hence the double advantage of inhaling protector dusts along with noxious dust. Such protector dust is itself a sort of scavenger to free colloidal silica and as such, doubtless yields some benefit, even though not inhaled along with the noxious dust.

Coal is not a reliable carbonaceous dust to add. The charge carried by a coal particle depends upon the customarily recognized factors, but also upon its ash content. This is the apparent reason that coal is usually

eliminated from the lung. A pure coal, if such there is, like carbon black would doubtless be retained by the lung.

Haldane has cited Cripple Creek, Colorado, where calcite is a constituent of the ores, as a locality where silicosis is not a serious problem despite the silica content of the ore. We point to the calcite as a protector mineral.

At Mysore, India, where the ore is high in ferromagnesian minerals, silicosis is not so serious as expected, though there is some doubt cast on these statistics. The Geological Survey reports of India indicate the presence of carbonates as well as ferromagnesian minerals which may serve as protectors.

Since rock drilling is rarely done in uniform material, it is both difficult and hazardous to state that a given case has resulted from a given dust. Irregular occurrences of silicosis, where the rock seems safe, need explanation. Stewart and Faulds recent report on pulmonary fibrosis of hematite miners[7] is such an example. Possibly the relative strength of charges is the controlling factor at times. It is inevitable that the phosphate content of some hematite ores, a recognized adsorption phenomenon, modifies the quantity if not the quality of the charge the mineral will carry. And a natural corollary of the views expressed here is that a reversal of the charge of the protector mineral by any unforeseen factor renders its part detrimental rather than beneficial. It is impossible yet to evaluate other factors which may easily control in a given instance. Of fundamental importance, however, are experiments such as those of Mavrogordato who showed that flint dust was retained in animals' lungs whereas mixtures of flint and coal dust were not so retained. More such work is needed to learn what other influences may enter to prevent this flocculating action of apparently suitable mineral mixtures.

Solubility of Silicates

At the suggestion of Dr. W. S. Middleton, and with these ideas in mind, an experiment was formulated to test the susceptibility of minerals to attack by such solutions. A group of fourteen commonly occurring silicate substances was treated with blood serum over a period of two months. The underlying assumption is that any mineral which may liberate silica under such conditions may do so if introduced into the lung. The details of the experiment follow.

Pure mineral materials were first obtained when possible. Impure minerals were purified in order that any results obtained could be attributed to one material alone. The mineral was first crushed, then ground in a mechanical steel mortar. The ground material was sized by

allowing it to settle in distilled water a suitable period of time. The material in suspension was then decanted and the solid material mainly centrifuged out, and oven dried at 100°C. This was examined under the microscope to check the size. Resizing was done when necessary to limit all to a size range of 1μ–10μ. In the case of platy and fibrous minerals one dimension is commonly greater than 10μ but the thickness of such flakes is near 1μ–3μ. The time and speed of centrifuging were controlled to eliminate material below 1μ in the final product. By repeating the centrifuge procedure a number of times it was possible to get a powder virtually free from particles less than one micron in diameter.

This sized material, if hard, invariably contained iron from the mortar, which had to be removed. This was done in two ways. In one method the iron was dissolved by use of strong HCl and the resulting $FeCl_3$ rinsed out by repeated centrifuging. From those minerals which are more susceptible to attack by strong HCl, the iron was removed by bubbling H_2S gas through the suspension and then dissolving the FeS with N/20 HCl according to the procedure of Drosdoff and Truog.[8]

Minerals which were impure, notably the sericite used, were purified gravimetrically. This consists in floating off the lighter constituent with a heavy liquid. The procedure is as follows:

The dried powder is placed in a flask and the flask evacuated. Bromoform, diluted with acetone, is introduced under vacuum after which air is admitted. This gives thorough wetting and thereby enables each particle to behave as a discrete grain, and not as a member of an aggregate. The gravity of the liquid is adjusted to lie between the specific gravities of the minerals to be separated. The suspension is then centrifuged—one constituent floats and one sinks. The floating cake is decanted. Microscope examination was used to check the purity. It was sometimes necessary to go through the procedure twice. The gravimetric purification was done on the crushed powder before fine grinding. Only purified material was ground, with the exception of augite, which contains a little chlorite, a very common alteration product which was not removed.

The purified, ground, and sized material was next placed in pyrex flasks for treatment with serum. As an added precaution to insulate the inside of the flasks from possible solvent action of the serum, they were previously coated with a film of "gelva," a commercial resin. To accomplish this a syrupy solution of gelva in acetone was prepared and applied to the inside of the flasks. This dried for several hours, was baked at 110°C. for several hours more and finally roasted carefully over a gas burner to a light brown color. The resulting film, though not completely successful, remained intact on most of the flasks throughout the experiment. In the flasks containing quartz (2), biotite, talc (1), microcline

and sillimanite, the film broke sufficiently to expose some of the glass during the last week or two of the run. We feel that the glass surface thus exposed is negligible compared to the surface exposed on the mineral powder, and that the influence on the final results is small.

A weighed amount of each mineral powder was placed in the coated flask, stoppered with cotton and sterilized in an autoclave for an hour. The serum used in the experiment was obtained from beef and human blood in the following manner: The warm blood was exposed to the air momentarily to cause clotting, and then covered and placed in the refrigerator for a period varying from several hours to twenty-four hours. The clear serum was poured off, and before its introduction into the flask, a sample was taken upon which the *p*H was determined with the glass electrode.

Serum was introduced into the sterilized flask by filtration through a bacteria-proof filter, which had been sterilized in the autoclave and transferred to the flask over a strong flame in a steamed room with the customary precautions against bacterial contamination. The serum was then drawn through the filter into the flask and when the desired quantity had been introduced, the filter was removed and a sterilized coated cork introduced into the mouth of the flask and sealed with beeswax.

The sealed flasks were placed in a water bath where the temperature was held at 37.5°C. $\pm$ 0.5°C. The flasks were attached to a central rod, adjusted to oscillate back and forth 100 times per minute, and were kept in the water bath for a period of two months.

After removal from the bath at the end of two months the flask was opened and a sample taken to determine the *p*H of the serum. The remainder was centrifuged at 3500 RPM for 15 minutes to throw down the mineral particles. The supernatant liquid was poured off and analyzed for silica.

The procedure of the analysis was as follows:

About 10 cc. of concentrated $Mg(NO_3)_2$ solution was thoroughly mixed with 100 cc. of the serum in a platinum evaporating dish and placed on a hot plate at about 70°C. for 12 hours. It was then heated slowly over a burner till the nitric oxide fumes had been completely driven off, after which it was ignited at high temperature. The resulting fluffy powder was treated with concentrated HCl and diluted with water before filtering. The filtrate was evaporated on the hot plate and dehydrated in the oven at 110°C. for one and one-half hours. The dehydrated mass was again treated with concentrated HCl and water to dissolve the chlorides, and then filtered through a new filter paper. The two filter papers, washed with warm 1% solution of HCl, were combined and ignited in a platinum crucible.

The crucible and contents were weighed, and then treated with HF and H_2SO_4 acids and placed on the hot plate to evaporate. After ignition the crucible was again weighed and the difference in weights taken to be the weight of SiO_2.

In the analysis of the serum the sample was usually split into two aliquot parts, and each part analyzed separately.

Mineral	Size range (microns)	Sample weight (gms.)	Vol. of serum (cc.)	Type of serum	*p*H at 25°C. before run	*p*H at 25°C. after run	SiO_2 dissolved (%)
Quartz (1)	1–12	10.041	200	Human	7.60	6.90	0.100
Quartz (2)	1–12	10.463	200		7.55	7.14	0.080
Opal	1–10	10.434	120		7.72	7.21	0.100
Sericite	2–15	10.029	140		7.88	6.71	0.195
Asbestos (amphibole)	1–15	9.438	140		7.56	7.31	0.120
Cristobalite	1–10	10.738	200		7.35	7.10	0.076
Sericite	2–15	8.962	180		7.60	7.05	0.185
Biotite	2–20	8.142	200		7.62	7.30	0.123
Asbestos (amphibole)	1–20	10.735	150		7.40	7.04	0.105
Glass (optical)	1–12	10.803	250		7.59	7.20	0.085
Talc (1)	2–20	8.912	190		7.65	7.31	0.104
Talc (2)	2–20	10.410	200	Beef	7.52	7.45	0.091
Microcline	1–10	10.772	220		7.48	6.72	0.045
Bytownite	1–10	11.888	190		7.53	6.92	0.060
Garnet (almandite)	1–10	10.156	150		7.62	7.41	0.052
Augite	1–10	9.856	220		7.56	7.39	0.055
Tourmaline	1–10	8.475	150		7.60	7.02	0.069
Sillimanite	1–10	6.722	200		7.62	7.21	0.065

To give a measure of the amount of colloidal SiO_2 liberated from each mineral, the weight of dissolved SiO_2 was compared with the original weight of the mineral sample and the percentage of dissolved SiO_2 calculated.

No allowances were made for the factors involving variations in *p*H, or the size frequence distribution of the particles within the set limits. The influence of the first factor is not wholly known, but that of the latter is probably appreciable.

The results of these experiments are given in the table and graphically in figure 1. Although these results are not infallible and the method by which they were obtained somewhat arbitrary, they indicate certain things. All the materials which yielded a greater percentage than .075% of silica, with the exception of biotite, have been suspected of producing silicosis. Biotite is in some ways similar to talc and sericite,

which throws suspicion on minerals of the mica type. Outstanding of course is sericite, and the attention given to this mineral as a cause of silicosis is supported by this work. To many of us who regarded the mere presence of sericite in the lung on incineration as evidence that it was

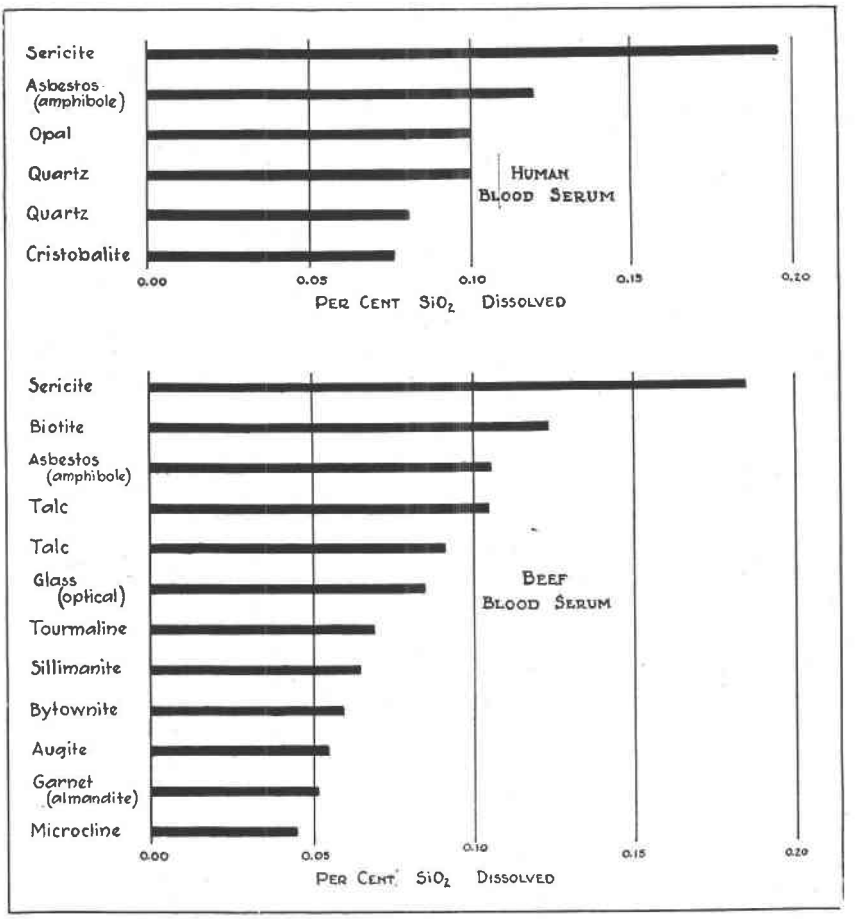

FIG. 1. The length of the line opposite a mineral name indicates the amount of silica dissolved by the blood serum, the mineral being powdered and the mixture agitated at body temperature for two months.

harmless (otherwise it would have been consumed), its silica yield here is most arresting. At the present time we cannot say more. In general these results indicate the desirability of further experiments of this general type to learn what other minerals may release colloidal silica in body fluids.

Koppenhofer[6] cites animal experiments by Giese in which injected kaolin suspension led to no harmful effects on the animals, and suggests that the aluminum hydroxide, set free simultaneously with the silicic acid and oppositely charged, renders the silicic acid harmless. Somewhat the same process may take place with sericite and other silicates containing aluminum, for Lemon and Higgins,[9] and Fallon and Banting[10] injected sericite suspensions into animals with little or no harmful results. Feil[11] has noted the absence of silicosis in slate quarry men exposed to a high concentration of sericite dust. If, together with the large amount of silicic acid released from sericite, as shown in the above solubility experiment, a correspondingly large amount of oppositely charged aluminum hydroxide were liberated, the two might act as mutual flocculating agents and enable the silicic acid to be removed.

Summary

Three substances are selected here as suitable protectors—carbon black, iron oxide (hematite), and alkaline earth carbonates. We believe that they are able, first, to render silica dust more easily eliminated by the lung, and, second, to protect the lung from the effect of colloidal silica liberated by proximate minerals which the lung has not been able to eliminate.

The idea here advocated is to add to a noxious siliceous dust one or more of these protector minerals, as a dust for an effective and economical means of rendering the noxious dust harmless. The question of grain size of the added dust immediately arises. The object is to maintain an adequate amount of the finer sizes (less than 10μ) since only these are effective. If we may use the reported effect of shale as a measure, then 20% of the protector mineral is adequate, but this refers only to the finer sizes, which means that less than 20% addition to the whole original dust is needed. The proper procedure seems to be a careful microscope examination of the dust in question to learn size-distribution and mineral content. This should dictate the kind and amount of protector dust to add. It should be borne in mind that the finer dusts are being re-supplied from the coarser ones ordinarily and are also being blown away. Experiment and experience will teach the details of the quantity of protectors needed.

References

1. Gye, W. E., and Purdy, W. J., The poisonous properties of colloidal silica: I. *Brit. Journ. Exper. Path.*, vol. **3**, p. 75, 1922; II. *ibid.*, p. 86; III. *ibid.*, vol. **5**, p. 238, 1924.
2. Beger, P. I., Injurious factors in asbestosis and silicosis: *Med. Klin.*, pp. 1222–1227 and 1258–1261, Sept. 14, 1934.

3. Haldane, J. S., The effects of dust inhalation: *Trans. Inst. Min. Engr.*, vol. **55**, p. 264, 1918.
4. Haldane, J. S., The avoidance of silicosis with dry methods of mining: *J. Chem. Met. and Min. Soc. South Africa*, vol. **30**, p. 54, 1929.
5. Mavrogordato, A., Some immediate and remote responses to the invasion of the living tissues by dust: *J. Chem. Met. and Min. Soc. South Africa*, vol. **30**, p. 64, 1929.
6. Koppenhofer, G. F., Studies on the pathogenesis of silicotic changes. IV. On the tissue changes after experimental introduction of colloidal silicic acid: *Virchow's Archives*, vol. **297**, p. 271–304, 1936.
7. Stewart, M. J., and Faulds, J. S., The pulmonary fibrosis of haematite miners: *J. Path. and Bact.*, vol. **39**, p. 233, 1934.
8. Drosdoff, M., and Truog, E., A method for removing iron oxide coatings from minerals: *Am. Mineral.*, vol. **20**, p. 669, 1935.
9. Lemon, W. S., and Higgins, G. M., Tissue reactions of lungs to intratracheal injection of particulate sericite: *Am. Rev. of Tuberc.*, vol. **32**, p. 243, 1935.
10. Fallon, J. T., and Banting, F. G., Tissue reaction to sericite: *Canadian Med. Assoc. Journal*, vol. **33**, p. 407, Oct. 1935.
11. Feil, A., Is there a pneumoconiosis of slate workers? Findings from an investigation at slate quarries: *Bull. Acad. Med.*, p. 105, Jan. 22, 1935.