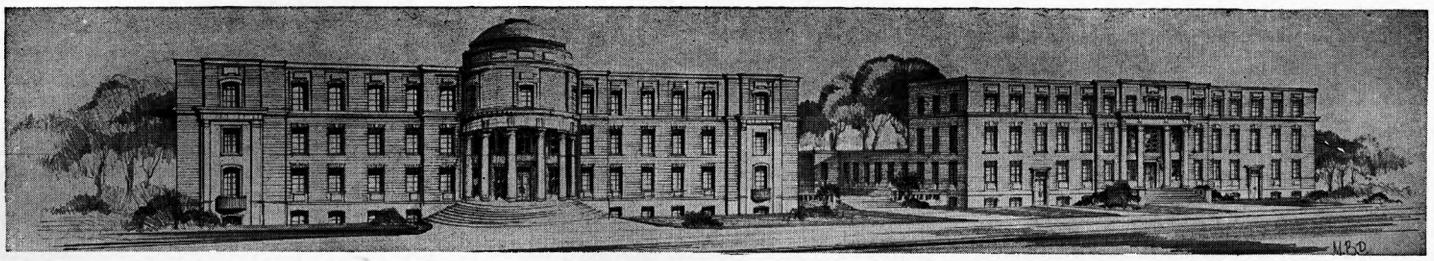
Mineral Industries



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ROCK MECHANICS
Its Scope and Potential

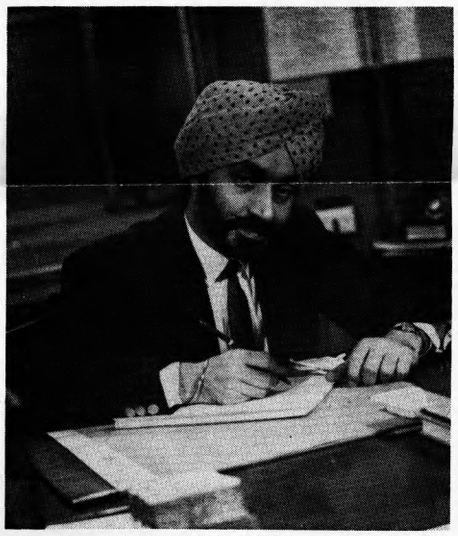
MADAN M. SINGH*

I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the state of Science, whatever the matter may be.

Lord Kelvin

By this criterion or by any other standard, rock mechanics is an embryonic science. But in spite of its infancy, it must be recognized as a science nevertheless. Since time immemorial rocks have played an unparalleled role in the history of human civilization. Consequently, man has often pondered on the behavior characteristics of rock when subjected to loads. Perhaps even the cave man gave thought to the stability of the roof over his head, and the stone-age man tried to conjecture as to optimum places to strike when carving tools. The varying strengths of rocks have certainly been recognized since prehistoric times. And everyone is familiar with the parable of the man who built his house on sand, with disastrous consequences!

Although the parable has been quoted often for spiritual reasons, it does not seem to have inspired anyone to an evaluation of rock properties in the more literal sense until recent times. Only in 1773 did Coulomb publish his discussion on earth pressure. In 1846



Dr. Madan M. Singh

Alexandre Collin's book entitled *Landslides in Clays* appeared with the words "mechanique terrestre" printed on the title page, perhaps quite significantly. Then in 1857 Rankine developed a theory of equilibrium of earth masses and applied it to some elementary problems of foundation engineering. Fayol conducted some experiments in 1885 and demonstrated the existence of a pressure arch around underground openings. Terzaghi's book *Erdbaumechanik auf bodenphysikalisher Grundlage* became available in 1925. In the United States pioneering work must be credited to Bucky (1931) who employed models in the study of excavations in rock and coined the term "barodynamics." In 1936 Harvard University held its first conference on soils and laid the foundation stone for the emergence of "soil mechanics" as a science.

Tennyson said, "Science moves, but slowly, slowly, creeping on from point to point." Nothing could be more true of rock mechanics. In spite of its inception in the late eighteenth century, it is only during the last decade that the subject has received more than individual consideration. Perhaps the general attitude of neglect was prompted by the complexity of the problems. Now, with more sophisticated mathematical techniques, rapid means of analysis and computation, and precise but rugged measuring devices available to the practicing engineer the time has come to take a fresh look at the subject. In the last few years an increasing interest has been observed in the field, and it may be predicted with confidence that this concern and inquisitiveness will continue to grow.

The importance and applicability of rock mechanics to mining problems is fairly obvious, and hence the efforts devoted by the mining engineer to the field are understandable. It must, however, be regretfully admitted that many mine operators do not grasp the full significance of rock mechanics. Some of them associate the usefulness of its techniques only to mines encountering expensive and hazardous rock failures, roof falls, or bursts. If a mine appears to be operating smoothly, they seem to question the benefits or profits to be accrued by spending money on rock mechanics.

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Mineral Industries

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COLLEGE OF MINERAL INDUSTRIES

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Madan M. Singh, assistant professor of mining engineering, received a diploma in mining engineering from the Indian School of Mines and Applied Geology, Dhanbad, India, in 1956, an M.S. from the University of Illinois in 1957, and a Ph.D. from Penn State in 1961. He then worked with Gulf Research and Development Company for 2½ years as research engineer, where he was active in fluids and rock pressure research related to drilling. He joined the Penn State faculty in July, 1963, and is currently responsible for the rock mechanics program.

Dr. Singh is a member of the American Institute of Mining, Metallurgical, and Petroleum Engineers and of the International Society of Rock Mechanics.

COLLEGE NEWS BRIEFS

The College of Mineral Industries is pleased to announce the establishment of a new scholarship fund, approved by the Board of Trustees as the Mineral Industries Alumni Scholarship Fund.

This new fund was given its start by a bequest of $15,000 from the late Gus Allen Beard, Mng. Eng. '21, who stipulated that it should be used, at the discretion of the College, for scholarship aid. The total amount of the bequest, together with subsequent contributions, will be invested and the income awarded in the form of undergraduate scholarships according to the best judgment of the Mineral Industries Committee on Scholarships and Awards. R. B. Hewes, committee chairman, stated that students in all classes and curriculums in the College will be eligible for the scholarships.

The College of Mineral Industries has been most fortunate in the support it has received from friends, alumni, and industry for the creation of undergraduate scholarships. This financial aid for students, directed either to the College or to individual departments, has contributed significantly to the maintaining of enrollments that are so necessary in the face of increasing demands for M. I. graduates, and to assuring a continued input of high-caliber students. This new fund, however, is the first to be established on a College-wide basis for the purpose of accumulating contributions of any amount into a joint effort. It is hoped that Mineral Industries alumni who are not already directing their Penn State Alumni Fund contributions to a specific department within the College will consider designating future contributions for allocation to the Mineral Industries Alumni Scholarship Fund.

Contributions from companies and from individuals who are not M. I. alumni also will be most welcome. They may be sent directly to Dean R. H. Jahns for incorporation into the Fund.

E. F. Danielsen, associate professor of meteorology, presented a paper on "The Influence of Extruded Stratospheric Layers on Severe Storms" at the Third Conference on Severe Local Storms at the University of Illinois on November 14, 1963.

Project Springfield II was directed by Dr. Danielsen during the last two weeks of November, 1963, from the U. S. Weather Bureau's Numerical Analysis Center at Suitland, Md. In the project, B47 and B57 aircraft equipped with radioactivity filter samplers are deployed to regions where stratospheric air is expected to be transported into the troposphere. If the transport process develops, a thin quasi-horizontal layer can be detected by the aircraft from the large temperature and wind changes across the layers. Numerous filter samples are made within and outside the layer to determine the source of the air from the relative concentrations of radioactive isotopes.

T. S. Spicer, professor of mineral preparation engineering, has been named Associate Editor of a new magazine, *COAL — Today and Tomorrow.* The February 1964 issue will feature an article by Professor Spicer entitled "Full Steam Ahead — With Coal."

Rustum Roy, professor of geochemistry and director of the Materials Research Laboratory, was called as one of six witnesses to testify before the House Administration Committee, Subcommittee on Accounts. His testimony was in support of HR 6866 and HR 8066 bills introduced by Representatives Sibal (R., Conn.) and Widnall (R. N. J.) to establish a Congressional Office of Science and Technology.

The bipartisan, bicameral measure (an identical bill S 2038 has been introduced by Senator Bartlett (D., Ala.)) seeks to establish a Congressional Office of Science and Technology which will provide information and briefing to Congressional members and Committees on the vast range of subjects involving scientific and engineering matters. Dr. Roy's testimony stressed the importance of the interpretation of science to the Congress and to the public in general, as well as the need for representation of the scientific community in the legislative branch of the government.

During the current academic year a number of leaders in the field of mineral economics are visiting the Department of Mineral Economics to present lectures on their areas of special interest and to discuss specific research problems with graduate students and members of the staff.

The fall term visitors included David Brooks, of Resources for the Future, Inc., Washington, D. C. Dr. Brooks gave a general lecture on the meaning of mineral economics, followed by two talks on his research interests with the economics of the minor metals. William A. Vogely, Chief of the Division of Economic Analysis of the U. S. Bureau of Mines, discussed the economics of conservation, and the regional impact of the mineral industries. In addition, he addressed the Economics Luncheon Seminar on the topic of "Regional Impact Analysis." Professor Elmer W. Pehrson of Columbia University and former Chief of the Foreign Mineral Division of the U. S. Bureau of Mines, gave a series of talks on the adequacy of mineral supply and on United States mineral policy.

During the winter term Steven F. Sherwin, Vice-President of Foster Associates, Inc., Washington, D. C., will present lectures dealing with the area of natural gas prices, costs, and regulation. Bruce C. Netschert, Director of the Washington office of National Economic Research Associates, Inc., will give a lecture on "Mineral Resources and the Economic Concept of Increasing Costs" and will discuss problems of natural gas regulation. W. Keith Buck, Chief of the Mineral Resources Division of the Department of Mines and Technical Surveys in Ottawa, Canada, will discuss some of the aspects of International mineral supply with particular emphasis on Canada; and Richard M. Foose, Chairman of the Department of Geology at Amherst College, will concentrate on industrial minerals.

Roland D. Parks of Massachusetts Institute of Technology, Hubert E. Risser of the Illinois State Geological Survey, and Herbert J. Bickel of Texas Eastern Transmission Corporation in Houston will present discussions of mineral valuation, coal, and energy problems during the spring term.

ROCK MECHANICS —

(*Continued from page one*)

What is more unfortunate, however, is the general misconception as to the scope and range of application of rock mechanics. It appears to be the common belief that rock mechanics merely aids the mining engineer in strata control problems. That it certainly does, but it does much more. The scope of the subject is far wider, and it would be quite legitimate to compare its utility to that of basic mechanics in engineering problems. It needs to be emphasized that:

(a) the science of rock mechanics merits contributions from the several branches of engineering and science, and

(b) mining engineers should be called upon more often to share their knowledge of the behavior of rock in various engineering and scientific projects.

It is the intent of this article to touch briefly upon some of the recent developments related to rock mechanics in a few of the several fields that it encompasses. The list is by no means either complete or exhaustive but merely indicative of the potential and scope of rock mechanics.

The Rock Mechanics Laboratory at The Pennsylvania State University was established in 1957 within the Department of Mining. Opportunity is taken in this paper to mention some of the past accomplishments of the laboratory and the research that is being currently conducted. Owing to the location of the laboratory within the mining engineering facilities, the work done to date has, of necessity, been flavored accordingly. Yet considerable research work has also been oriented toward oil well drilling, and there is little doubt that problems of interest to other related areas will be undertaken in the future.

The Department of Mining currently sponsors the Annual Symposium on Rock Mechanics, jointly with the Colorado School of Mines, the University of Minnesota, and the University of Missouri. The symposium is one of a group of symposia that, in their present form, incorporate the Annual Symposium on Drilling and Blasting, and Exploration Drilling, founded in 1951 at the University of Minnesota by Professor Pfleider; the Symposium on Rock Mechanics founded in 1955 at the Colorado School of Mines by Professors Parkinson and Hartman; and the Annual Symposium on Mining Research also founded in 1955 at the University of Missouri by Professor Clark. Each of the four institutions acts in turn as host for the symposium to be held in a given year. Thus, better geographical representation, both in papers and attendance, results in wider dissemination of the knowledge presented. In 1959 the Exploration Drilling Symposium and in 1961 the Fourth Symposium on Rock Mechanics were held at The Pennsylvania State University. The proposed Symposium on Drilling and Blasting in 1965 is also scheduled for this campus.

Fundamental Studies on the Properties of Rocks

It seems appropriate to indicate briefly the present status of knowledge on rock properties, since this information forms the very foundation of rock mechanics. Unless the behavior characteristics of rocks are understood, little can be accomplished in attacking the problems of rock behavior scientifically and methodically. At the present time, although it cannot be claimed that our comprehension about rock behavior is by any means thorough or that accurate predictions can be made as to what rocks will do under any given conditions, it would be equally incorrect to state that little can be said about rock behavior merely because rocks lack homogeneity and are not ideally elastic. Considerable data now exist in the literature about the properties of aeolotropic and anisotropic materials as well as about those of granular substances. It might be instructive to point out that few materials on the market today exhibit ideal elastic or plastic characteristics, yet doubt is seldom cast on the engineer's ability to utilize them properly. At the same time, it deserves to be pointed out that the simplifying assumptions of homogeneity, isotropicity, and elasticity that are often made when confronted with problems concerning rock should not be ridiculed. The solutions obtained even with these restrictions can prove to be immensely valuable in obtaining an insight into the salient features involved and on occasion may predict rock behavior remarkably closely.

About 15 years ago the United States Bureau of Mines published a bulletin (Obert et al., 1946) describing "standardized" methods for testing rock properties. This instigated more intensive investigations leading to several elaborations of the procedures presented in order to obtain more meaningful results. Thus, for instance, the overriding influence of the quality of preparation of the ends of the specimens and the friction exerted by the platens on the "simple" compressive strength of rocks has been spotlighted. The implications of these findings are that the ends of the test specimens should preferably be ground optically flat and that the hardness of the platens employed during the determinations needs to be specified. In accordance with St. Venant's principle, it appears more logical to determine the strength for specimens with a length-to-diameter ratio of two, rather than one indicated at present. The stress distribution in such cylinders has been determined both mathematically and experimentally in the Rock Mechanics Laboratory (Conway, 1963). Further, the use of water during the coring of test specimens seems to be undesirable.

Methods for the determination of tensile strengths of brittle materials have also been suggested, though the Bureau of Mines does not recommend any specific procedure. One rather easy way consists in the compressive loading of a rock disk diametrically. The method has the advantage that it can be extended to denote the anisotropy of a rock by finding the tensile strength across several diameters. An alternative approach is to subject an annular cylinder to internal hydrostatic loading, and this method has also been employed quite successfully (Sedlacek and Halden, 1962).

Methods for establishing the elastic moduli of rock by means of dynamic tests have been used by geophysicists for several years, both for laboratory and *in situ* determinations. But it is only in recent years that cells have been designed in which *in situ* conditions can be closely approximated and pore and confining pressures applied. This has enabled laboratory evaluations of longitudinal wave velocity, for example, which can be correlated with the continuous velocity log (Wyllie et al., 1958). Biot (1955) has put forward a theory relating longitudinal wave velocity with rock porosity, and Geertsma (1961) has shown that this is at least applicable to sandstones in which the grains are nearly spherical in shape.

Hardness of rocks requires a considerable amount of attention. The term is vague, as it may denote the resistance of a material to abrasion, scratching, impact, crushing, or indentation. Attempts at quantification have not been lacking, and correlations between the various types or with other properties do exist. Gilbert (1954) has related scleroscope hardness with Moh's scale, Brace (1960) has found agreement between Vicker's indentation hardness and compressive strength under triaxial loads, and Harvey (1963) has suggested an impact testing device and indicated relationships with effective porosity and median crystal size, to mention only a few. The entire concept of hardness, however, needs to be re-examined and re-evaluated and put on a more scientific footing.

Several investigators have studied the effects of both pressure and temperature on the strength of rock and its elastic-plastic properties. The transition of some rock types from the brittle to the plastic state has been clearly demonstrated. The work is signficant from the geological viewpoint as well as in oil well drilling operations. The interrelationship between these parameters and rock porosity is also of importance to the petroleum engineer in evaluation and design of production procedures for oil and gas reservoirs. Models, mathematical and experimental, have been suggested to represent fluid flow through porous media with a certain measure of success.

Practical engineering problems have generated interest in the response of rocks to continuous loads. Investigations of the creep of rock received fairly early attention (Griggs, 1939), and are continuing (Hardy, 1959; Vigier, 1962). A phenomenological approach has enabled the time-strain behavior of rocks to be depicted approximately by a Burgers rheological model, or perhaps more exactly by a combination of a Maxwell and several Kelvin units. Viscoelastic characteristics in rock are evident at all rates of loading, but at the higher rates these may be accompanied by a microfracture mechanism.

Reference has already been made to the consideration of rocks as granular substances. Analysis of a representative model explains why no single value can be found for Poisson's ratio and Young's modulus in granular rocks, a fact already established by experiment. Only rheological interpretation of compression and creep tests can lead to meaningful information on safe loading rates and ranges. Prediction and analytical treatments of failure patterns can be intelligently made only if the residual strains in the rock are taken into account. Stress concentrations vary in the rock body, both between individual grains and between the grains and the matrix, resulting in considerable variations in strain differentials. Knowledge of the original orientation of the specimen is essential to proper insight into the failure mechanism (Emery, 1960). But relatively simple globular models, consisting of spherical grains, for instance, can be postulated to give reasonably good predictions of behavior of common rock types such as sandstones and limestones.

(*Continued next page*)

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Strata Control

The usefulness of rock mechanics in the control of problems related to underground openings has been well recognized. Knowledge of the stress distribution around openings of various shapes has prompted proper design of mine roadways. Elliptical shafts and galleries have become accepted almost universally in deep mines (Isaacson, 1958). Attempts have been made to assess the configuration of the stress pattern with multiple openings and to use this information in the location of new roads. Theoretical patterns cannot be indiscriminately applied to practical conditions, but a prior knowledge of the stress redistributions with the addition of new openings is certainly a great asset in design. Care should be taken, however, to allow for the effects of preferred shear surfaces, bedding planes, and foliation. Besides, not only the mechanical properties of the ore body but also those of the surrounding rock should be taken into account for fruitful application of the principles discussed.

In the design of new mines, an idea of the stress trajectory pattern in the ore body can be very valuable in optimizing the orientation of workings and in establishing the direction of mining. This could lead to considerable savings in layout, result in greater safety, and prevent the inconvenience and expense of changing the orientation of the mine at a later date.

The study of pressure distributions in underground openings has necessitated observations of stress *in situ* to confirm theoretical calculations. This need has resulted in the development of stress meters and load cells of several varieties (Potts, 1957; Hast, 1958; Griswold, 1963). The available instruments are capable of measuring stress changes in competent strata but do not respond satisfactorily in fractured and incohesive rock. Besides, it would be of great benefit to determine stresses in virgin rock, without redistributing the existing tectonic stresses. Efforts are being made to accomplish this, and a significant achievement along these lines would be a definite breakthrough in predicting rock behavior under routine practical conditions. The importance of underground stress instrumentation was recognized early by the Rock Mechanics Laboratory, and definite advances have been made in this direction (Stefanko, 1960).

Microseismic detection devices have been developed which enable the prediction of rock failure prior to the event. Not only do these instruments forewarn of imminent failure, but a study of the intensity of "acoustic clicks," as well as the frequency spectrum, can aid in forecasting the nature of the failure; viz., shear or tensile. The adaptability of such sonar-type techniques to the detection of major cracks or weakness planes in mine roofs is being currently explored, and there seems to be little reason to doubt that a commercial instrument based on these principles will be available for general use in the foreseeable future.

The development of stress-measuring instrumentation has, as a matter of course, led to the determination of stresses in mine pillars, sides of tunnels, and regions of stress concentration in underground installations. This has made it feasible to determine the extent of Trompter's zone of relaxation in mine pillars and detect asymmetric loading of such rock masses. The changing stress patterns as the workings advance can also be studied, giving a continuing picture of the redistribution of loads in pillars. In longwall workings, abutment pressure variations have been carefully recorded in numerous instances, and an analysis of these data has led to a fairly good understanding of coal seam behavior under a given set of conditions.

The concept of the rock bolt is a direct consequence of the principles of rock mechanics. At present a vast majority of the mines in the U. S. and numerous mines abroad use rock bolts as a means of support. Adoption of rock bolts has led to greater efficiency in mining, better roof control, and increased applicability of machines, and has resulted in overall reduced costs. Loss of bolt anchorage due to creep in rocks has been recognized. Improved shell designs as well as alternative methods of anchorage have come forth. Grouted bolts are no longer rare, and bolt lodgment with epoxy resin is also in evidence. Even mooring in fractured strata by explosive forming has made its debut (Parsons, 1963). Penn State has been actively engaged in rock bolt studies and has made valuable contributions (Terichow, 1958; Stefanko, 1961). Studies of this nature are of significant help to the mineral and related industries and are continuing. Figure 1 shows some of the apparatus used.

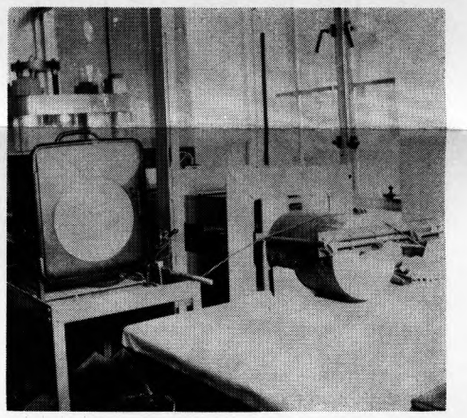

Figure 1. Apparatus for roof bolt anchorage studies.

Just the application of rock bolts, of course, does not suffice to optimize mining operations. It is necessary to gain a thorough comprehension of the principles involved and to bear them in mind continually. Only such understanding can result, for example, in the use of tensioned bolts in mine shafts located in regions prone to rockbursts (Isaacson, 1961). It is unfortunate that in many mines the use of a "standard" bolt length and bolting pattern has become common practice. This could be disastrous. There are always changes in rocks and conditions, locally, and hence no single length or pattern could be expected to perform optimally throughout the mine. Taking account of localized variations not only implies the intelligent use of rock bolts but could also effect reductions in support costs. The existing forces in an ore body may affect the opposite walls of a stope quite differently, and the consequent reactions to drilling and blasting could be dissimilar. In addition, the preferred surfaces of shear should be considered; e.g., it is common knowledge that a hole drilled at right angles to the shear planes tends to open up more shears than a hole drilled parallel (Emery, 1963).

The effects of gravity in certain methods of mining, such as block caving, can be assessed by means of a centrifuge. This device has been very useful in the study of body forces in various situations including dams and pit slopes. Investigations of the strength of specimens in the apparatus, utilizing the principles of dimensional analysis, can be very helpful in providing design data and rock characteristics. An oil shale mine at Rifle, Colorado, was projected by the U. S. Bureau of Mines from such information, and the predictions were found to be quite reliable.

Not all rock is massive, and the alternative situation of locating underground openings in sedimentary strata has also been evaluated by a number of investigators (Merrill, 1957; Adler, 1959). Experiments on layered media have been reported and mathematical analyses considering rocks as beams are available in the literature, although more correctly they should be considered as plates. This enables proper design of roof span and indicates the role of roof deflection at the support; when such deflections are indeterminate, methods to minimize them should be invoked in order to prevent dangerous breaks. However, if the plans permit controlled deflection, the loads on props or bolts may be reduced. Loads on the rib could be used to advantage in longwall workings, if the cantilever action of the roof is exploited.

The discussion in this section has been largely slanted toward mining, not because the use of this information is restricted to such applications, but merely because mining engineers have acquired this knowledge during the course of routine confrontation with strata control problems. It is the sincere belief of the author that this experience would only be partially utilized if it were not applied or adapted, whenever possible, in driving tunnels, subway construction, sewage and waste disposal channels, excavations for underground installations, and a host of other situations unrelated to mining.

Subsidence

The advantages of minimizing surface damage to property due to mining operations are obvious, and efforts to this end have been in progress since the thirties. Lehmann (1938) was the first to publish a planned method of coal extraction designed to cancel out surface strains and thereby reduce harm to buildings and structures. Grond (1950) also demonstrated similar results from experimental studies. Both Lehmann and Grond envisaged "harmonious mining" in terms of the simultaneous extraction of several seams. Grond indicated how the tension anticipated from workings in one seam could in practice be offset by compressions caused by workings in another seam, if the layout and rate of advance of the faces was properly planned and carefully executed. Lehmann's principle was to achieve a supercritical region by the simultaneous exploitation of three or four horizons so as to effect uniform vertical settlement in the center of the subsidence basin and thus eliminate the occurrence of strains in the area to a large extent.

Wardell (1953) recognized the role played by traveling movements in the process causing damage to structures and also took into account transverse movements. With this in-

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formation optimum design led to a reduction of surface strains while working a single seam. Although it becomes virtually impossible to cancel out the strains observed on the surface completely, when working only one seam, the "stepped face layout" that he adopted has extended the scope of application of such methods considerably. Even such partial harmonious mining has been successfully employed. Wardell has also emphasized the importance of size and shape of buildings in planning subsidence without damage.

Theoretical work connected with subsidence has progressed hand-in-hand with experiment. Perz (1957) has reviewed the literature in the past and presented some mathematical relationships related to subsidence troughs.

These studies have been rather dramatically reinforced by actual applications of these methods. Thus, in England, mining operations have been conducted below a school without appreciable injury to the structures, while in Germany a whole town has been successfully lowered five and a half feet! An understanding of the theory of surface damage due to subsidence has been further used in the construction of new buildings in regions subject to subsidence. If the structure is rigidly anchored to the subsoil, the deformations sustained by the ground are transmitted to the building, causing undesirable destruction. This can be avoided by reducing the frictional coefficient between the foundation and the soil. Thus, in Britain, houses have been placed on lightly reinforced concrete rafts which, in turn, rest on a layer of friable material such as sand, having a coefficient of friction of less than one-half. In Belgium, an experimental station has been constructed that stands on boxes containing steel roller bearings with a coefficient of friction of only one-fiftieth.

Slope Stability

Prevention of failures in sloping embankments is of the utmost importance, from the viewpoints of both safety and cost. Yet, from an economic standpoint, it is also advisable to maintain the steepest possible slope. These statements hold true whether the slope is the wall of an open pit mine, embankment for a road, or cutting for a railroad track. Optimum conditions can be estimated, once again, by judicious use of the principles of rock mechanics.

In general, four types of slope failures have been recognized: (a) falls of loose rock; (b) rotational shear failures in incompetent strata; (c) failures along existing planes of weakness when ground water level, blasting vibrations, or other causes upset the equilibrium; and (d) general block flow — i.e., failure of the rock mass along joints, structural features, or crushing, due to high stresses. It may be readily and correctly concluded, even from a superficial examination of the manner in which slopes may fail, that no single simple method exists for the determination of optimum slope angles. Attempts are, however, under way to collect pertinent data from slope failures that occur and to analyze them so as to give useful relationships (Soderberg and Rausch, 1963; Coates et al., 1963). For particular cases, such as incompetent strata where rotational shear failures may be expected, correlations between the significant parameters — viz., slope angle, cohesion of wall rock, bulk density of the rock, slope height, depth of ground water level from crest of slope, and angle of internal friction of the wall rock — have already been established (Coates et al., 1963). Theoretical treatments of the problem have also been attempted (Jenike and Yen, 1962) and the slope configuration determined as a function of the rock properties.

Figure 2 shows two families of curves, one illustrating the relationship between the depth of pit and slope angles projected for different factors of safety against slope failure and the other relating pit depth and slope angles resulting from the maintenance of different instantaneous stripping ratios. If the excavation is deepened below the water table, it becomes necessary to flatten the slopes of the pit walls. This is also indicated on the diagram. Thus the graph defines the scope within which the pit can be operated (Jennings and Black, 1963). The operator may choose to mine anywhere between the barriers imposed by a predetermined maximum value of instantaneous stripping ratio and minimum value of the factor of safety. If, for example, the instantaneous stripping ratio does not surpass 10, nor the factor of safety fall below 1.3, the depth and angles of slope may be varied within the shaded zone in the figure.

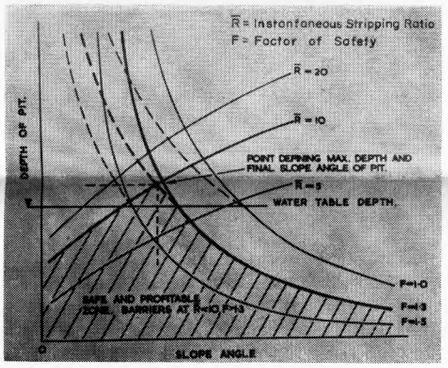

Figure 2. Graph depicting design criteria for open pit operation (After Jennings and Black).

It seems likely that with continued study it may soon become feasible to establish a curve which relates the probability of failure with the parameters employed as design criteria. If such a curve were defined, it would be possible to determine the volume of slides that could be tolerated for maximum economy in mining or other excavation operations.

Various types of investigations are currently under way to provide better control over slopes. The Bureau of Mines at Reno, Nevada (Long, 1963), has undertaken projects: (1) to analyze the geometry of stresses in pit slopes using a centrifuge to body-load photoelastic models and by *in situ* measurements in rock zones influenced by excavated pits; (2) to develop, in the laboratory, techniques to estimate coefficient of friction and shear strength of block fragmented, compact rock; (3) to compare photogeologic pattern plotting of rock structures with surface mapping, as well as micropetrofabric patterns and orientation with macrostructure; (4) to analyse statistically, by graphic and computer techniques, rock structure and strength data obtained by detailed logging of diamond-drill cores and supplemental information from borehole pictures; (5) and to apply geophysical methods to *in situ* estimation of strength and stability moduli of rock slopes and to apply microseismic or other methods to develop slope-failure warning devices.

The study of geologic factors that affect slopes should be emphasized to underline the need for contributions from geologists and geological engineers. In the planning of a new slope it is invaluable to examine the surrounding topography and to observe the shape of the natural slopes in the vicinity. This may assist the understanding of slope behavior considerably. The geology of the region should be studied thoroughly, including dip directions of the strata, folding, faulting, joint patterns, gouge materials on joints and other structural features. These factors may well provide a key to the behavior of the controlling geological structures behind the working slopes of the pit. The degree of homogeneity of the materials is of importance, as are ground-water levels and pressures. After excavation work has been initiated, a continuous check should be made to determine changes in these conditions. Relief of stress will tend to cause vertical expansion and, perhaps, decrease in cohesion. As time elapses, the water content in rock may increase; and, with the drawdown toward the sump establishing lateral flow, the seepage forces may push the slope inward. The slopes will also yield inward slightly because of the redistribution of stresses.

The principles of slope stability can also be extended to landslides. In some areas these can assume tremendous proportions and cause havoc in the vicinity. Geologic characteristics that affect slides include rock and soil material, ground-water conditions, terrace height, drainage, original slope, submergence, culture, and material removal. The extent of the slide and the damage done depends on its cause and nature. One classification recognizes four types of landslides: slump-earthflow, slip-off slope, multiple-alcove, and mudflow. These are distinguished by the form of the scars and the kinds of movement in sliding. Needless to add, other classifications exist. The ability correctly to predict and control landslides in certain regions could result in great economic benefits.

Drilling

Attack on rock for purposes of penetration can be effected in a variety of ways, and the instrument of assault may be mechanical, hydraulic, thermal, chemical, electrical, or sonic. The most common and economic of the prevalent methods, however, depend on some type of mechanical device. Percussive, rotary, and roller bits dominate the field, whatever the drilling operation — rock breakage for construction, drilling deep wells for petroleum, or sinking large-diameter silos for missiles.

It is evident, therefore, that an insight into the rock failure mechanism might lead to more efficient utilization of the applied energy and much greater control over the penetration process. Of course, the influence of other pertinent parameters has not been neglected. In rotary drag-bit drilling the effects of thrust, torque, penetration rate, rotation speed, rock type, bit design, drill-rod design, and flushing conditions are now well established. With percussive impact, the mechanics of the stress waves in the drill-rod have received attention in several studies. Both laboratory and field investigations with

(*Continued next page*)

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roller-cone bits have been conducted to correlate the important parameters. It is generally agreed, for instance, that drilling rate increases directly with bit load and rotary speed until some optimum, which is a function of the rock type, is reached. But an understanding of rock breakage still remains the key to the launching of a methodical offensive on the problem.

In rotary-drag drilling it appears that the chip-generating cracks usually have an initial orientation related to the resultant of the external forces. The later part of the crack tends to deflect toward the free surface owing to a cantilever action. The failure is brittle and apparently tensile. The size of cuttings tends to increase with increased cut depth and rake angle, but drops somewhat at higher cutting rates (Gray et al., 1962). Investigations at the Rock Mechanics Laboratory have also shed light on the rotary drilling process. The rounding of the cutting edge causes a substantial portion of the applied force to be directed downward as a ploughing force, which increases the torque and thrust requirements for cutting. As thrust is increased, the rise in torque may be slight initially but becomes directly proportional later. Low rake angles produce minimal torques. Tool wear rates are independent of rake but are enhanced by inadequate thrusts, or if grinding rather than cutting occurs (Jackson, 1962).

Penn State has also contributed toward explanation of the rock failure mechanism under percussive blows. The stress distribution beneath a statically loaded drill-bit has been determined. As the load on the bit increases, tensile stresses build up transversely below the central portion of the bit and combine with the existing axial stress to produce shearing stresses of great magnitude. If the shearing strength of the material is exceeded under these conditions. a major fracture develops axially, followed by fractures which occur along shear stress trajectories curving upward to the surface. The dimensions of the major crack and the formation of shear fractures depend on the extent of load, shape of wedge, material properties, and boundary conditions (Tandanand. 1962). The sequence of events under dynamic loads has also been studied, and the complications that are introduced by flaws. vugs, heterogeneities, and granularity have been considered. The compressive stress pulse through the rock due to impact is preceded by a tension peak which initiates some cracks on the surface. A major tension fracture originates somewhat below the bit edge and runs almost vertically below the wedge. A system of shear stresses is induced in the rock causing the formation of chips. The differential stresses due to the grain-and-matrix structure, as well as the planes of weakness in the various minerals. create a very complex shear network and cause an intense shearing of the rock which account for the fines that may be produced by the blow (Singh, 1961). Correlations have also been found for single blows between crater volume and bit energy, bit geometry, and rock resistance. A simple exponential relation exists between crater volume and blow energy. With wedges, the crater volume is an inverse, exponential function of the tangent of one-half the included angle, the exponent decreasing as the resistance of the rock to penetration increases, thereby indicating that little benefit is to be derived from employing sharp bits in hard rock (Hartman, 1962). The tests have been extended to indexed blows on fresh and damaged rock surfaces which show that, for any shape of chisel and surface condition, an optimum index distance exists which produces a maximum crater volume for a given blow energy. This optimum index distance is greater on a damaged surface than on a fresh one, and it varies directly with blow energy (Chao, 1962). Studies have also been initiated on fracture propagation (Figure 3), and the results of these investigations appear very promising.

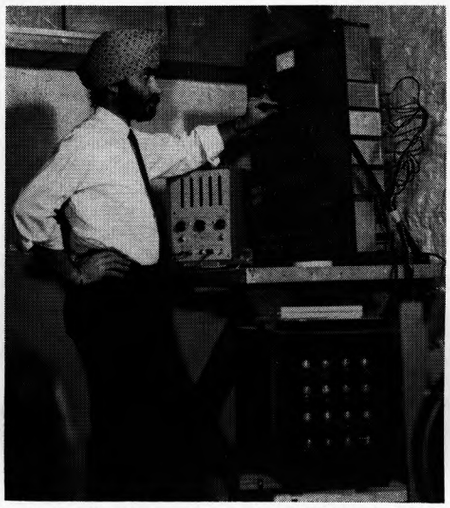

Figure 3. The author adjusting the ultra-high speed (half a million frames per second) camera for fracture propagation studies.

A mechanism of drilling with roller-cone bits has also been advanced (Cunningham and Eenink, 1959). The drilling rate is found to be dependent on the differential between the formation and borehole pressures, and this is effective owing to the formation of a layer of filter cake at the hole bottom. A chip formed by a bit-tooth can only be removed from place when the pressure on both sides has nearly equalized by filtrate flow, and the filter cake impedes this by reducing permeability. Cuttings on the hole bottom also hinder drilling. The need for better hole cleaning is, therefore, evident. The hypothesis has been elaborated upon (Garnier and van Lingen, 1959), and it has been suggested that the pressure differential across the chips could be both static and dynamic in origin and can also account for the phenomenon of balling-up.

Although the emphasis has been on the mechanical methods of attack on rock, it should not be inferred that the other modes are only of theoretical importance. Jet piercing is well established in the taconites of the Mesabi Range and depends on the spalling characteristics of rock. Favorable properties include large linear thermal expansion, high thermal diffusivity, equigranular interlocking structure with little fine grained material, few low-melting minerals, and low strength. Hydraulic monitors have been employed in the mining industry for a long time; and jets have been adapted for the exploitation of coal, gilsonite, phosphates, and the St. Peter sandstone. The technique has been modified for abrasive jet perforating by the petroleum industry. Research has been actively pursued and is continuing to produce effective chemical rock softeners. Experimental drills have been constructed and are under test for electrical disintegration of rock for drilling boreholes. In spite of these efforts, of course, there is always scope for improvement, necessitating further examination of the various rock properties.

Blasting

Several phases of industry use blasting: mineral recovery, military or civilian demolition projects, and canal or harbor construction. To harness such sudden releases of energy and to utilize more fully the potential of the process, it behooves the student of rock mechanics to explore the action of explosives more thoroughly.

It is generally accepted that detonation of an explosive generates a pressure front which travels away from the explosion at very high speeds. The rock immediately surrounding the explosive is shattered and the front propogates through the medium, largely as elastic waves. If the stress pulse encounters a free face, reflection occurs producing scabs by failure in tension, provided sufficient energy is available. The shock wave is accompanied by the formation of gaseous products during explosive detonation. This gas bubble expands, causing some compaction of the enclosing medium. It also tends to heave the material out in the direction of least resistance. In the course of expansion the gases work their way through the fractures, churn the pieces, and augment fragmentation.

Even an elementary understanding of blasting phenomena, such as indicated above, has led to innovations such as delay blasting caps in which successive holes in a blasting operation are detonated at short intervals, calculated to improve fragmentation and reduce vibrations. Control over the vibratory motion of the ground is especially desirable in the thickly populated and densely built areas, to minimize injury to humans and structural damage.

Extensive investigations are required to study the types of pulses propagated through rocks, the manner and rate at which they attenuate, the effects of impedance, and numerous other factors that play a role in the blasting mechanism. There is need to comprehend stress pulse behavior in different types of rock, varying from unconsolidated soil to hard, massive granites, as well as the effects of stratigraphic features, such as joint planes, on the pattern of the fragmented material. Diverse accelerations, energies, amplitudes, and frequencies are demanded of the vibrations resulting from explosions, dependent upon the operation for which the blast is conducted. Quarries, for example, present a high vertical face and strive for rock fragments that may be readily handled by shovels, trucks, and crushers, or to obtain large blocks for building stone. Tunnels, on the other hand, require small amounts of explosive with delay blasting to cut effectively into a working face, which is itself below the ground surface. Recently, blasting with large amounts of explosive placed on the top of an underwater limestone layer proved successful in dredging operations along Chesapeake Bay.

The Department of Mining has not ignored the subject of blasting. Research has been conducted to establish the greater efficiency of angle drilling and to get an insight

(*Continued next page*)

GRADUATES RECEIVE ADVANCED DEGREES

December 14, 1963

Major Field	Name	Degree	Thesis
Fuel Technology	Richard Allen Anderson	Ph.D.	Iron Catalysis of the Carbon-Carbon Dioxide Reaction
	James Joseph Tietjen	Ph.D.	The Thermoelectric Power of Graphite as Affected by Oxygen Chemisorption
	Sarah Marie Kemberling	M.S.	Factors Influencing the Strength of Natural Graphites
Geochemistry	Dean Carl Presnall	Ph.D.	The Join Mg_2SiO_4-$CaMgSi_2O_6$-Iron Oxide at Oxygen Pressures from 0.21 to 10^{-8} Atmospheres
	Burke Osgood Trafton	M.S.	Experimental Hydrothermal Alteration of a Quartz Monzonite Porphyry
	David Evan William Vaughan	M.S.	The Crystallization Ranges of the Spruce Pine and Harding Pegmatites
Geology	Samuel William Crawford	M.S.	Distribution of Certain Elements in Four Areas of Hydrothremal Alteration
	Charles Alexander Landis, Jr.	M.S.	Geology of the Graphite Mountain-Tepee Mountain Area Montana-Idaho
Geophysics	John Henry Pfluke	Ph.D.	Seismic Model Studies of First Motions Produced by an Actual Fault
Metallurgy	James Kitchener Magor	Ph.D.	Kinetics of the Decarburization of Iron-Chromium Alloys
Meteorology	Harry Robert Glahn	Ph.D.	Decision Theory Concepts Applied to Ceiling Height Prediction
	Stephen Berman	M.S.	Estimating the Longitudinal Wind Spectrum Near the Ground
	Richard Doddridge Lyons	M.S.	Turbulence Near the Ground at Night and Fog Formation
	Wilbert George Maunz	M.S.	Variability of Wind with Cold Frontal Passage (A Study of the Wind Field in the Lower 15,000 Feet by Serial Balloon Ascents)
Mineralogy and Petrology	Edwin Sylvester Erickson, Jr.	Ph.D.	Mineralogical, Petrographic, and Geochemical Relationships in Some High-Alumina and Associated Claystones from the Clearfield Basin, Pennsylvania
Mineral Preparation	John Asa Lewis Campbell	M.S.	The Electrokinetic Behavior of Anthracite Coals and Lithotypes

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as to the reasons for this (Kim, 1960). The method has been widely accepted by the open-pit mining industry and acclaimed for its economy (Kochanowsky, 1963).

Comminution

Rock crushing and grinding constitutes an integral and important part of modern industry and makes itself evident in numerous phases of production ranging from road ballast to cosmetic talcum powder. Until recently, comminution processes were solely dependent on empirical design relationships established through experience, but now the need has been felt for a unified theory of crushing.

It is essential to understand single particle crushing in order to lay the foundations for the theoretical concepts involved. This has aroused the curiosity of several researchers. Gilvarry (1961) has proposed that the flaws associated within an infinite specimen undergoing fracture must necessarily be flaws occurring within the volume of the body, on new surfaces created within the body, or on new edges created within the body. Based on the assumption that these flaws exist independently of one another, a relationship between the fraction of the total particle passing a given size and the distribution density of the flaws has been established. Gaudin and Meloy (1962) have also done the same with a somewhat different model and applied it to repeated fracture. Bergstrom (1963) has extended the work to energy-size relationships and comparisons with crusher and grinding mill data.

Zeleny and Piret (1959) have determined the relations between work input, new surface area created, the surface energy required, and heat produced in the case of both single and multiple particle crushing. It was also demonstrated that appreciable amounts of energy are lost due to the plastic deformation of the crushing device.

Research of this type could lead to fundamental changes in the design of crushers and grinding mills. Autogenous milling is gaining popularity, but further study is necessary before any revolutionary machines can be conceived with theoretical backing.

Structural Geology

It is evident that the geologic structure of a region, especially the folding and faulting processes, is dependent upon the tectonic stresses in the earth's crust. Consequently, attempts have been made to explain the behavior of rock from a mechanical viewpoint. Some investigators (Currie et al., 1962) have combined field information with a study of theoretical and experimental systems which appeared mechanically analogous, to explain the factors controlling the development of folds in sedimentary rocks. It is concluded that folding and faulting of strata are related to deformation in the buckling process, and that the physical properties as well as the thickness of a dominant member control the fold wave length that develops in the early stages of deformation.

(*Continued next page*)

COLLEGE NEWS BRIEFS

(*Continued from page two*)

George W. Healy, associate professor of metallurgy, presented the opening paper at the Twenty-first Electric Furnace Conference of the Metallurgical Society of the American Institute of Mining and Metallurgical Engineeers at the Drake Hotel in Chicago, Illinois. Speaking to an audience of almost a thousand steelmakers, Dr. Healy discussed the "Pyrochemistry of Reactions Between Molten Steel and Slag." This was part of a program arranged by the AIME committee on the Physical Chemistry of Steelmaking.

Robert T. Duquet, assistant professor of meteorology, conducted a workshop on computer programming in conjunction with the staff of the University Computation Center, December 16 - 20, 1963.

A paper, entitled "Operational Analysis and Agricultural Climatology," was presented by Dr. Duquet at the annual meeting of the NE-35 Technical Committee on Agricultural Climatology in New York City, January 8 and 9, 1964.

The Board of Trustees has approved a change in the name of the Pottsville Center to the Schuylkill Campus, effective immediately, in anticipation of the move to the new site of the facility just east of Schuylkill Haven, on Rt. 61, sometime next year or the early part of 1965. The Schuylkill Educational Foundation, Inc., which has served as the advisory board for the Center since 1944, recommended the name change.

When the new campus opens, it will add to its offerings an associate degree program in electrical and electronics technology.

The new site, which was donated in April, 1962, was formerly Rest Haven, operated by Schuylkill County as a sanitarium and hospital. It has an estimated value of $1,250,000. The General State Authority has allocated $467,670 for renovations, and the Schuylkill Educational Foundation will pay for some site preparation and for demolition of unsound buildings through a grant from the Will S. Fox Foundation.

Revised sketch plans for the addition to the Hetzel Union Building were approved at a recent meeting of the Board of Trustees.

The addition, to be built at the southeast corner of the present structure, will be a ballroom, adjoining the existing ballroom; a new terrace room with new kitchen facilities which will help to meet the need for expanded cafeteria service; and offices and meeting rooms for student organizations on the ground floor.

The addition, expected to cost approximately $2,000,000, will be financed through borrowing, as was the initial structure completed in 1955 at a cost of $3,000,000.

The present facilities, Stanley H. Campbell, vice-president for business, explained, are considered inadequate for the present enrollment of 18,600 students on the campus; and long-range plans of the University visualize a steady increase in enrollment to 25,000 at University Park by 1970. The campus enrollment was 12,000 when the existing building was completed nearly 10 years ago.

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Studies of this nature also bring out the fact that explanations for the formation of geologic structures must also take into account the progressive sequence of structural events in the development of fold systems. The nature of these structural lithologic units, the effectiveness of the dominant members, and the significance of incompetent beds may all be influenced by these events. Two competent members may act together within a single structural lithologic unit in the early stages of deformation but may begin to act independently at a later stage, thereby modifying the original unit toward a major element that contains a minor lithologic unit within it. Or a dominant member that controls deformation may fold initially but may serve as the locus of displacement on a fault later. Again, a sequence of structural events that places an increasing restriction on incompetent beds at the core of a fold in the dominant member may finally curtail the folding process and require that further relief be obtained by fault displacement.

Other explanations for the faulting process have also been offered. Study of the mechanics of fluid-filled porous rocks has led to the formation of one theory for overthrust faulting (Hubbert and Rubey, 1959). It has been found that the frictional resistance to sliding of large overthrust blocks is reduced by interstitial fluid pressure. This reasoning has been employed to explain the existence of several well-known overthrust regions in the United States. Another hypothesis depicts faulting as a velocity discontinuity in plastic deformation (Ode, 1960). Triaxial loading of certain rocks in the laboratory sometimes shows faulting without sudden displacements. Such ductile faulting has been explained by the theory of plasticity for plane strain. It has been proved that, across certain planes in the plastic mass, velocity discontinuities are possible even though the stresses remain continuous. These planes have been identified with the planes of ductile faulting. Another postulate scrutinizes the causes of deep-seated earthquakes and observes that the only plausible reason for their occurrence could be creep (Orowan, 1960). If such unstable plastic deformation produces structural changes that accelerate further creep, the yielding concentrates gradually into thin layers in which high flow rates develop, and finally even produce enough heat to induce shear melting.

The formation of salt domes can be exemplified as being due to unstable equilibrium in a layer of light salt buried deep under heavier rocks. If the average weight of the strata above the salt is slightly lower than that of the surrounding material, or the area has been weakened locally by faulting, the salt which is highly deformable, plastically flows toward the center of this tract and rises. The elevated temperatures prevalent at depth facilitate the flow. Balk (1949, 1953) has described the internal structure of such piercement domes and found large-scale lineation mainly in steep, almost vertical direction along with limbs of small folds, confirming the theory of origin. Further substantiation of this mechanism is offered by the existence of almond-shaped halite crystals oriented with their maximum elongations in a vertical direction, alignment of inclusions in the same direction, and numerous other signs of similar deformation of the salt fabric.

The study of stress trajectory patterns, together with the kind, frequency, and orientation of preferred shear surfaces in an ore body, recently has been applied successfully to the location of additional deposits. Petrofabrics (the science dealing with spatial data obtained by the study of rock fabric) opens up another new avenue that could be exploited to advantage by the structural geologist. It has been shown by such analysis that rocks move both by permanent deformation of constituents in which the yield stresses have been exceeded and by elastic strain indicated by cracks or joints. The latest movement pattern recorded in a rock fabric can show the position of latent planes of weakness that may be the locus of future displacements (Knopf, 1957). These sources of potential weakness are of great significance to engineers. Knopf (1957) quotes several locations in Austria, Argentina, Sweden, and Australia where fabric analyses have been applied to geologic studies of dam sites, tunnels, spillways or water power construction, and installation of underground powerhouses. There is little doubt that the techniques of rock mechanics can be adapted to a number of other problems in structural geology.

(*To be concluded next month*)

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