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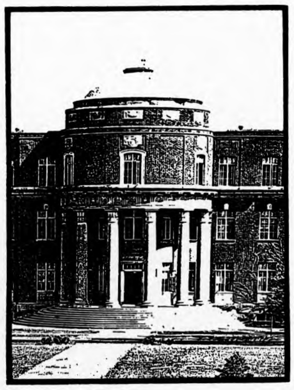

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Lateral Shortening of Layered Rock Sequences in the Foothills Regions of Major Mountain Systems

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Introduction

Thick sequences of layered rocks in low-lying unmetamorphosed foothills of mountain ranges the world over are commonly deformed into wave-like folds that diminish in size away from the mountain range (Figure 1). The second major feature of deformation is low-angle thrust faults, sub-parallel to layer boundaries along which the upper folded portions of the layered rock sequences have been transported away from the mountains.

The external folded provinces are integral parts of familiar mountain ranges such as the Canadian and Montana Rockies, the Quachitas of Oklahoma, the Juras of Switzerland at the foot of the Alps, the Caucasus, and, closer to home, the Appalachians of Central Pennsylvania (Figure 2).

Differential movements of rocks in the layered sequences attending the mountain-building deformation have laterally shortened the area of occurrence of the stratified rock sequence in a direction generally perpendicular to the long axes of the mountain range. As the sequence was shortened laterally, it was thickened by vertical displacements of the bedded rocks in folds and by vertical repetition and superposition of equivalent sheets of strata by overthrust faults. Both the buckling of the sequence during folding and the failure of the rock sequence along the bedding-plane thrusts appear to have resulted from compressive stress or an unbalanced force on the layered rocks.

A number of questions must be considered. Why do the layered rock sequences, composed of rock layers differing in composition and mechanical properties, yield to the deforming forces by wrinkling into folds that resemble sine-waves and by thrust faulting? Has the surface of the earth been forced to shrink and wrinkle like the skin of an orange left to dry in the sun? Or have surficial skin-like sheets forming the upper part of the stratified rocks been forced to detach themselves from deeper rock layers along semi-planar shear surfaces to crumple into long wrinkles like a rug shifted on a living-room floor? The answers to questions such as these are important in exploring for sites of accumulation of petroleum and natural gas and for further understanding of the deformation of rocks and the formation of mountain ranges.

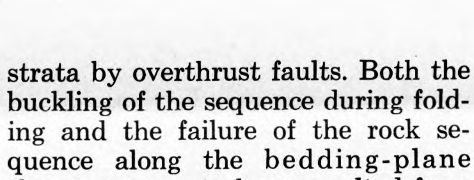

Fig. 1. A schematic transverse profile of a typical mountain range with a folded and low-angle thrust-faulted foothills belt on the left. The central mountain core is composed of intensely folded and metamorphosed rocks which have been intruded by granite batholiths.

This paper will discuss the nature of the layered sequence from a mechanical viewpoint. The principles will be illustrated by reference to the structure and form of the folded Appalachian terrain of Central Pennsylvania in the vicinity of University Park. Finally, the speculation will be examined that folding and sub-horizontal translation of strata in the foothills regions result from wrinkling of the thrust sheets moving away from the high mountainous terrain under the influence of gravity and, perhaps, of laterally-directed forces exerted by motion of rock masses in the mountains proper.

Inferred Physical Conditions During Deformation

The deformation of the stratified sedimentary and volcanic rocks in the flanking fold belts of most mountain ranges was apparently accomplished at low temperatures and pressures,

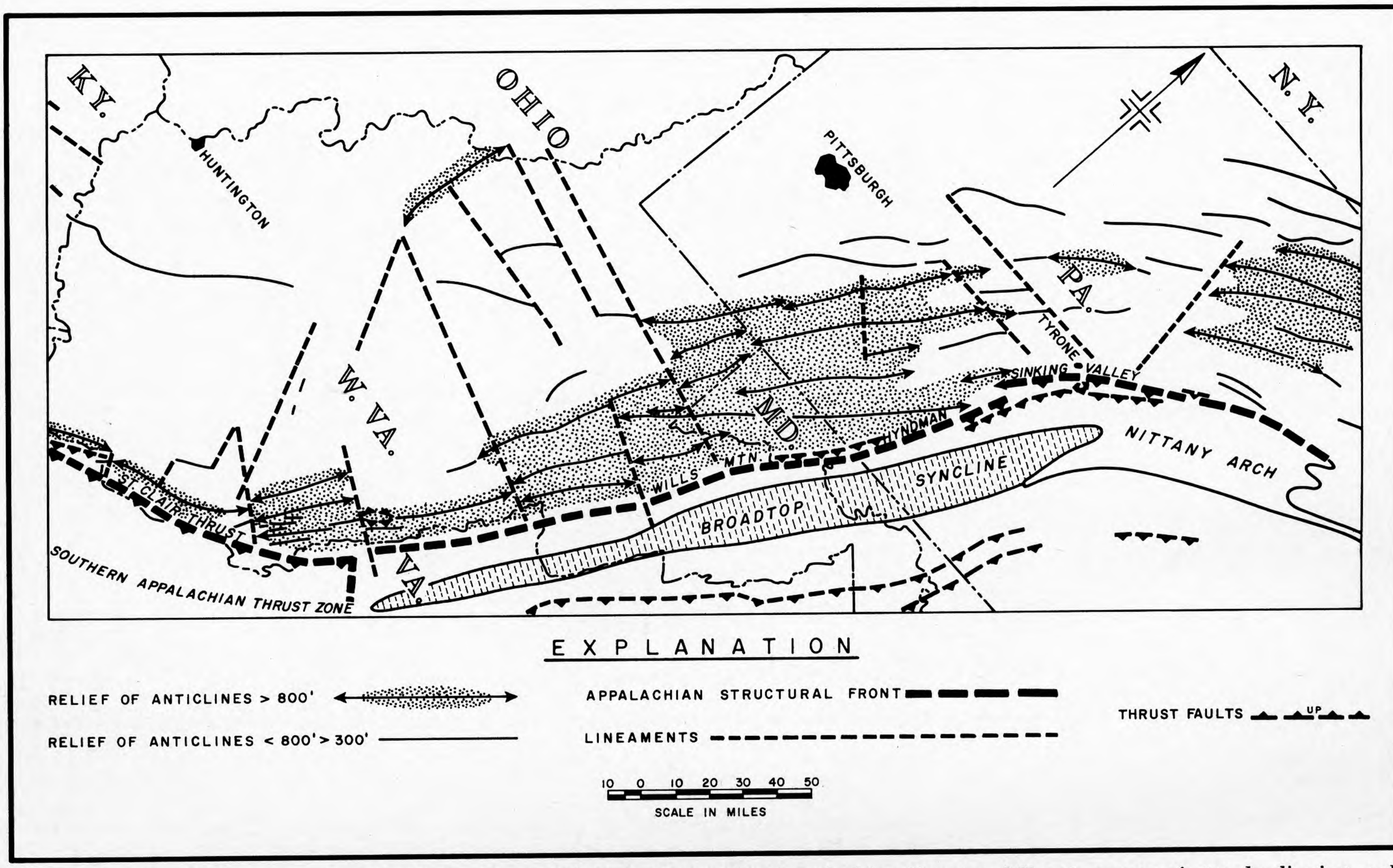

Fig. 2. Trends of folding and faulting in the Central Appalachians: The Appalachian Structural Front, a zone of steeply dipping rocks along the northwestern flanks of the Nittany Arch and Wills Mountain Anticlinorium, forms the boundary between older, more highly uplifted and deformed rocks of the Valley and Ridge Province on the southeast and younger, less intensely folded rocks of Appalachian Plateau on the northwest. This fold belt is similar to many other areas on the margins of major deformed mountain ranges.

inasmuch as the effects of metamorphism are essentially absent. New mineral assemblages indicative of high temperatures, large load pressures, or very high shearing stresses and thorough-going, penetrative metamorphic rock fabrics (mineral foliations, lineations, and cleavage) are typically absent.

Instead, the strata comprise unmetamorphosed rock types such as sandstone, shale, limestone, dolomite, gypsum, and rock salt. The mineral assemblages, except those of minor lavas and pyroclastics, are in chemical and physical equilibrium with the ranges of temperatures and pressures obtaining near the surface of the earth.

Anisotropy of the Layered Sequence

The stratified sequences, which have overall prismatic shapes as a result of the accumulation of greater thicknesses of rocks toward the present axes of the mountainous regions, can be considered ideally as composed of series of superposed individual sheets of rocks of the types listed above. Each vertically successive bed of differing lithology generally has internally homogeneous mechanical properties (e.g., crushing shear strength, tensile strength, elastic modulus, viscosity, ductility, specific gravity, and coefficient of sliding friction). But even at low temperatures and pressures, significant differences in mechanical properties exist between adjacent beds of contrasting lithology. The vertical differences in mechanical properties of the successive beds and the planar surfaces of discontinuity between them are the major elements of the anisotropy of the layered sequences.

Changing conditions of sediment deposition lead to layer-by-layer accumulation of contrasting materials in the subsequently deformed prism. Rather low cohesive forces act across the sub-planar surfaces separating the contrasting layers. These are surfaces of physical weakness along which stress could easily be relieved by shearing translational motion or *slip*. Slip along bedding occurs when the shear stress necessary to overcome cohesion and frictional resistance to sliding motion along the surfaces is less than the shearing stress necessary to cause failure across the bedding surfaces and the beds themselves.

As long as differences of mechanical properties affecting basic rock strength, cohesion, and frictional resistance exist between beds, it can be assumed that the bedding surfaces will be sites of important motion of one bed relative to another.

When the rock sequence becomes isotropic and physical contrasts between layers become minimal, failure and flow cannot be expected to occur with any greater frequency along the bedding surfaces than along surfaces of failure at angles to the bedding. In an isotropic sequence, where layer surfaces are no longer important zones of mechanical weakness, the layering has little or no control on the deformation; the layers are, so to speak, passive in their behavior.

Folds in which interlayer slip and interlayer mechanical contrasts have essentially no influence on patterns of deformation have been termed *passive folds,* in contrast to folds in which interlayer slip has played an important role.(1)

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The influence of the planar anisotropy of the layered sequence is largely to constrain slip and intra-bed flow to parallelism with the bedding surfaces. Donath(2) has demonstrated experimentally the marked tendency over a range of temperature and confining pressures for shear fractures to form parallel to surfaces of planar anisotropy for inclinations of the planes up to 60° to the direction of the maximum principal stress.

The ubiquitous occurrence of bed-parallel interstratal slip in sequences having major anisotropy leads to the general name *flexural-slip folding.* In forms of this type most beds maintain constant thickness across the limbs and axial hinge zone of the fold because the restriction of slip and flow to planes parallel to bedding surfaces precludes changes in thickness of the beds (see Figure 3).

Competent and Incompetent Layers

Rock layers that resist continuous flow, by virtue of lower ductility, higher viscosity, and greater strength, under given physical conditions of deformation, are termed competent beds or layers. Such rocks maintain approximately constant original thickness in folds, except where failure along discrete shear surfaces has caused extensional thinning or shear-fracture-induced thickening. Sandstones, chert, dolomites, and some limestones normally display competent behavior in non-metamorphic terrains.

Rock layers that undergo continuous flow, with attendant thickening and thinning of the layer in a fold, are called incompetent strata. Most shales, gypsum, rock salt, and some limestones, having high ductility and low strength, are incompetent in many areas of folding.

Competent and incompetent are relative terms. With changing physical conditions, the relative difference in competency between two types of rocks can change. Incompetent rocks, which undergo strain at lower magnitudes of stress than do competent rocks, tend to accommodate themselves to available space in a flexural-slip fold, whose shape is probably controlled in largest part by the form that the dominant competent layers assume.[3,4,5]

Characteristic Geometry of Structural Features

Folds in the foothills belts characteristically display a composite parallel-similar form in end profile view (see Figures 3 and 4). The strata are flexed to various degrees. As the fold limbs are rotated closer and closer to one another, incompetent layers tend to thin on the flanks of the folds and thicken in fold crests or troughs, as in similar folds; but the maintenance of constant orthogonal bed thickness in competent layers precludes infinite continuation of the folds upward and downward. It is seen that the fold, from its partially parallel geometry, necessarily has a termination downward against a flat surface of low cohesion or in a flat zone of weak, incompetent rocks.

The surface of detachment, or décollement, above which the fold limbs rotate inward by simple external shear, is observed usually to be in an incompetent weak zone of "slippery" shale, gypsum, salt, or argillaceous limestone. The incompetent rocks

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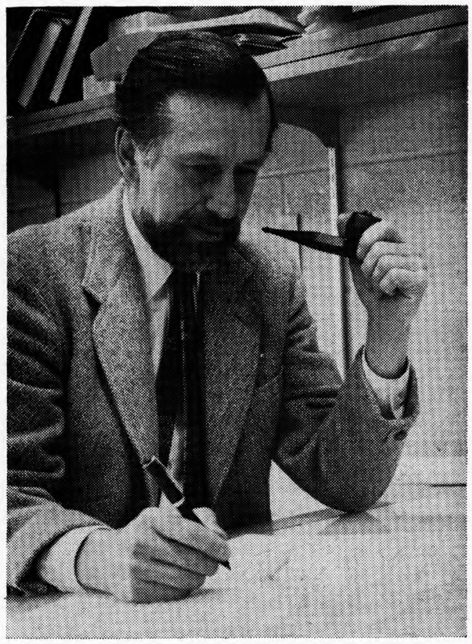

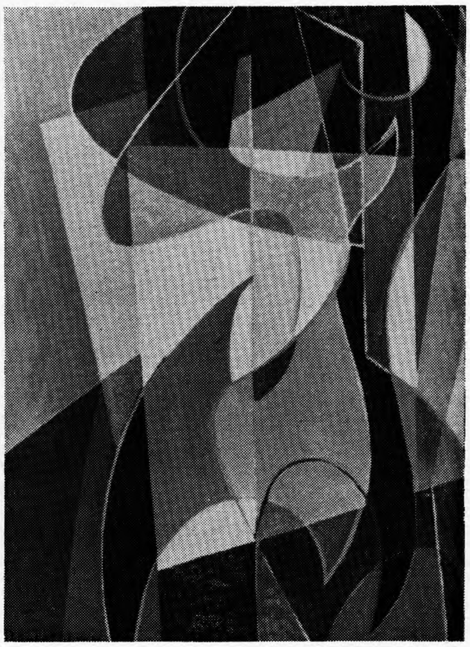

THE opportunity to spend six months on a sunny Greek island studying Minoan art and architecture would hold a strong appeal for most people, especially one who happened to be an accomplished artist. So thought Edwin F. Danielsen, associate professor of meteorology, as he embarked for the island of Crete accompanied by his wife and two small sons. Unfortunately, Dr. Danielsen's visions of an idyllic existence were soon shattered by, of all things, the weather, for the time was the year 1958-59, and Crete was beset by the worst winter weather in more than a century.

Living in an unheated house in the fishing village of Kalibes, the Danielsens endured incessant rain, snow, and bone-chilling cold, and our erstwhile artist-meteorologist was soon reduced to spending the majority of his waking hours as a literal hewer of wood and drawer of water. Despite the weather and the problems of day-to-day living in a primitive fishing village, Dr. Danielsen did manage to do some sketches, and it was with some regret that they finally left Crete for Germany, where Dr. Danielsen became a guest research scientist with the German Weather Service.

This sudden change of careers is not as strange as it may sound, for Dr. Danielsen has an impressive background in both art and meteorology. He attended the Art School in Layton, Wisconsin, the Corcoran Art School in Washington, D. C., and the Art Students League in New York City. During World War II, he attended the Air Force Meteorology Observing and Weather Forecasting School at Chanute Field, and after the war he joined the meteorological division of Continental Airlines. Eventually he returned to the University of Washington where he received the B.S., M.S., and Ph.D. degrees.

Following his stint with the German Weather Service, Dr. Danielsen joined the department of meteorology at the University of Washington. Then, in 1962, he became a member of the Penn State faculty. While working on his doctoral thesis on the structure of the tropopause, the boundary between the troposphere and stratosphere, he constructed three-dimensional diagrams and discovered inconsistencies in the conventional analyses which led him to recheck the original radiosonde records of temperature, pressure, and relative humidity obtained by balloon-borne instruments. Using complete, original soundings, he made vertical models of the temperature field which proved that the stable layers were not only organized in space, but also could be traced in time. When Dr. Danielsen subsequently published his findings many people began to refer to these layers as "Danielsen layers."

At the University Dr. Danielsen has carried out contract research dealing with the three-dimensional structure of the atmosphere, and he has made many studies of the way in which atmospheric layers are formed and are propagated. In 1964 he directed a project for the Defense Atomic Support Agency attempting to prove that certain layers contained radioactivity deposited in the stratosphere which contributed significantly to the fallout of radioactive debris. He also carried out extensive studies and authored a report on "Research in Four-Dimensional Diagnosis of Cyclonic Storm Cloud Systems" for the Air Force Cambridge Research Laboratories. Recently he has been attempting to determine the manner in which stratospheric air descends into the atmosphere and the relationship of this phenomenon to developing storm systems.

Soon Dr. Danielsen will give island living another chance. In September he and his family will leave for Hawaii where he will join the department of geosciences at the University there. In such surroundings he hopes to take a few months off to return to his first love, painting, and indulge another pastime — photography, which he very much enjoys.

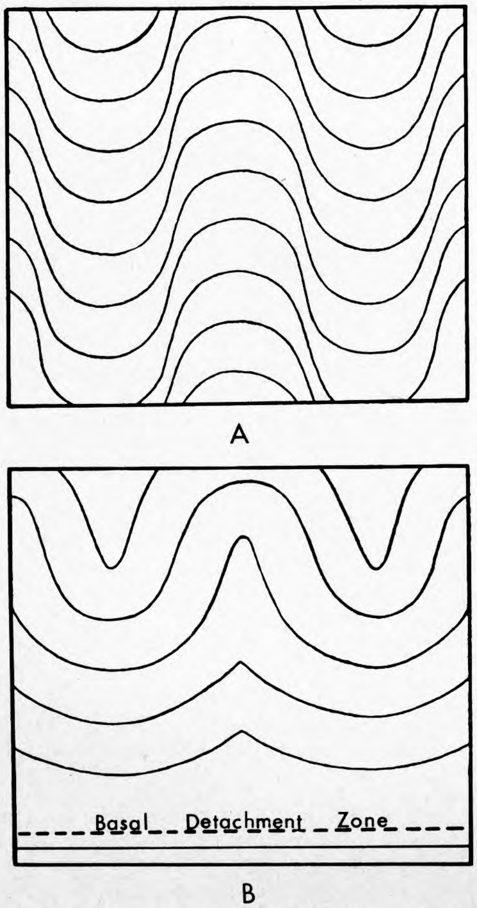

Fig. 3. Basic types of folding caused by lateral shortening: (A) SIMILAR FOLDING. *The form of the fold persists downward; beds thin markedly on limbs and thicken markedly in crests and troughs. Similar folding is typical of metamorphic terrains or thick sections of unmetamorphosed, but very weak rocks. (B)* PARALLEL FOLDING. *Beds are parallel and maintain constant thickness. The geometry of the fold precludes its persistence at depth, and it terminates against a "detachment surface" or "décollement." Parallel folding is typical of strong, non-ductile rocks.*

of the detachment zone are intensely folded and faulted in the cores of anticlines, where they have been forced to accommodate themselves to the geometry of the core of the fold as its limbs close on one another.

The deviation from pure parallel folding increases as the fold limbs close, because the incompetent material migrates upward in the core region and also because the horizontal-directed stress induces increasing flow of material from stratigraphically higher incompetent beds in the flanks as the stress becomes more normal to the progressively steepening bedding surfaces.

Price[6] and the writer[7] have noted the common occurrence of small-displacement longitudinal-bedding thrust faults on both flanks of folds in the Appalachians (Figures 4 and 5) and eastern Canadian Rockies. The faults dip parallel to bedding along much of their length, shearing up across bedding to transport rocks toward the anticlinal crest. The faults occur on either one or both flanks of a fold, symetrically displaced with respect to the fold axis and upthrown on the synclineward

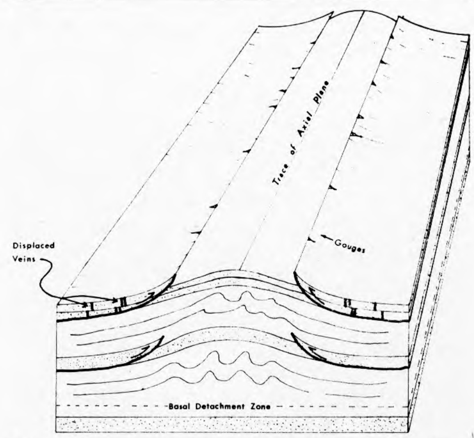

Fig. 4. A schematic block diagram of an anticline typical of the marginal fold belts, illustrating deformation by flexure and bedding slip, with modest flowage and intricate folding of incompetent beds in the vicinity of the fold's basal detachment zone.

side. They occur on oversteepened as well as upright folds.

These folds are associated with major low-angle thrust faults with displacements measured in miles. The slip of the faults is parallel to bedding over most of their area of occurrence, only shearing upward across the strata locally. Folding is often restricted to the rocks above the major thrust faults and does not persist below them.[7] The faults usually serve as the downward termini of the folding, from which is derived the name detachment or décollement thrusts.

Folding Processes

Abundant evidence in the foothills folds illustrates omnipresent interstratal slip and the maintenance of a high degree of vertical anisotropy during deformation. From these data, it is concluded that the predominant mode of folding was by flexure and intrastratal slip. The principal types of structural evidence supporting this conclusion (Figure 5) are: gouges (slickensides) on bedding surfaces; displacements of veins normal to bedding by bedding surface-slip; maintenance of constant thickness of many beds across folds; presence of small displacement thrust faults generally paralleling bedding in one or both flanks of many folds; and the downward termination of folds against detachment zones of ductile incompetent strata.

In the flexural slip fold, individual beds are bent around the hinge zone. Price[6] noted that interstratal slip and modest interstratal flow occur parallel to the planar surfaces of anisotropy. The flexing results in compression on the lower part and extension in the upper part on either side of a surface of no strain (CL in Figure 6 from Price). Because the complementary extension and compression occur parallel to bedding, there is no change in thickness.

The upper parts of beds tend to slip toward the anticlinal crests perpendicular to the fold axis (Figure 6). The lower parts of beds tend to slip toward the synclinal axis.

Where bed thickness remains constant in a majority of the beds in the folded sequence, the fold cannot possibly be propagated downward infinitely. The constriction of beds low in the fold creates a "room" problem (Figure 7A). Intense crumpling or faulting must take place to allow the core beds to adjust to shapes imposed by flexing competent beds.

The formation of bedding-plane flexural-slip faults in the limbs of flexural-slip folds alleviates some of this constriction in the central part of the fault caused by the interlayer flow and interstratal slip (Figure 7B).

The over-all pattern in the fold is to shorten the involved beds. Bedding slip in the flanks is a shortening mechanism. The faults, which rise out of bedding planes in the limbs, increase in displacement toward the fold axis as bedding slip is cumulatively added from bed after bed.[6] The necessity for shortening of the continuations of the faulted beds updip toward the central part of the anticline is reduced.[7]

Major Translation Displacements Along Low-Angle Thrust Faults

That major low-angle thrust faults should occur in association with flexural-slip folds in the foothills regions (Figures 1 and 8) is apparent from the identity of the orientation of the principal stress axes during formation of the two structures.[8] Major motion on the thrust faults occurs subparallel to the maximum principal stress. Folds in the thrust sheets and in the zones where the faults locally shear across bedding normally are elongate parallel to the intermediate principal stress and perpendicular to the maximum stress.

In an isotropic rock, failure under compressive stress normally occurs along paired conjugate shear planes that parallel the intermediate stress axis and are inclined to the axis of maximum stress at angles of 20 to 30 degrees.[9] In an anisotropic, layered medium, however, it has been shown that shear failure under compression tends to occur along the planes of anisotropy.[2]

Giffin Dome, Chestnut Ridge

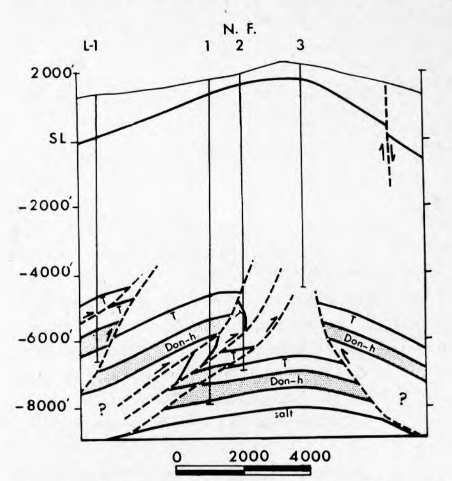

Fig. 5. Flexural-slip thrust faults in the sub-surface flanks of Chestnut Ridge Anticline, Giffin Dome, northern Westmoreland County, Pennsylvania. Note that the thrust fault disappears in the zone of relative extension high in the fold (Don-h= Lower Devonian strata, stippled; T=Tully limestone, and solid line is base of Mississippian strata).

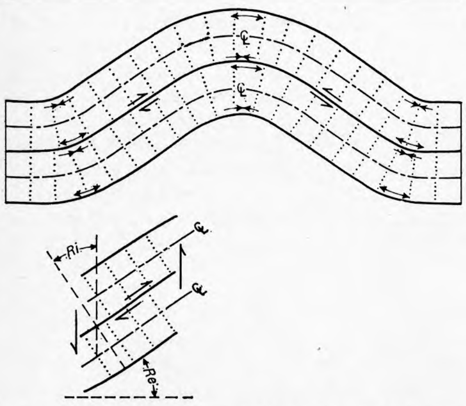

Fig. 6. Idealized representation of interstratal slip and intrastratal strain in flexural-slip folds: Dotted lines divide the beds into units which were originally rectangles symmetrically displaced about the centerlines (CL) of the beds; small whole arrows show bed-parallel compression in the bases of beds and extension in tops of beds; half arrows indicate simple shear between beds (interstratal slip). Large vertical arrows in the downset segment of the left limb illustrate external rotation of the limb which induces the interstratal slip (r_e=angle of external shear; R_i=angle of internal shear. Reproduced from Price,[6] with the permission of the Geological Survey of Canada).

Shear segments of thrusts form when bedding-surface slip is inhibited, probably most typically by rotation of beds to angles unappropriate for slip.[2] However, thrust segments at low angles to bedding do form in rocks early in the folding, prior to rotation of the limbs far from the horizontal.[10, Fig. 141]

Causes of the low angles between surfaces of failure and bedding in barely flexed sequences are not easily assignable, but it can be speculated that they may be related to irregularities atop rock units deep in the sequence[11] or to horizontal variations in the mechanical properties of rocks in the zone of bedding thrust that would tend to inhibit bedding slip.[7,12]

Rise of Major Anticlines above Shearing Segments of Low-Angle Thrust Faults

Rather large folds are developed above the narrow strike-parallel zones where the thrusts locally shear upward across the stratigraphic sequence from a bedding slip position low in the sequence to a higher bedding slip position (Figure 9B).

The shortening introduced by the thrust-induced superposition of parts of the sequence on laterally extensive segments of the same beds below the thrust necessarily produces a flexural-slip fold in the rocks above the upward-shearing segment of the thrust.

One example of high folds above the site of a major change in stratiographic position of low-angle thrust faults occurs on the west side of the Nittany Anticlinorium in Central Pennsylvania, along Bald Eagle Valley beneath the high ridges and carbonate lowlands immediately southeast of Tyrone, Port Matilda, Lock Haven, and Williamsport and a few miles northwest of State College. Figure 9 presents a somewhat generalized configuration near Tyrone, Pennsylvania, of the surface rocks at the western edge of the anticlinorium and interpreted relationships in the subsurface.[7] (The relationships were confirmed in late 1964 by the drilling of a 17,000 foot deep well along the anticlinorium to the north, near Bellefonte.)

Cambrian rocks along the crest of the fold come to the surface on the anticlinorium only above the sites of change in level of two major thrusts. The uppermost low-angle thrust actually crops out in the Birmingham area along the Little Juniata River (see Figure 2 for location), where it has been arched upward and a hole has been eroded through it. A small area of young Ordovician and Silurian rocks seen in the erosional "window" in the bottom of the valley near Birmingham is surrounded on all sides by the older Cambrian rocks of the thrust sheet. Minimum lateral displacement on the upper fault is 2½ miles.

The arching of the highest thrust probably is related to reinitiation of bedding slip along a zone at depth northwestward from the site at which the early (upper) thrust sheared upward across section. The upper thrust surface is thought to have been flexed by the upward shearing of the deeper bedding thrust.

Flat-lying, essentially undisturbed rocks underlie the deepest thrust. The undisturbed deep strata, actually younger than the rocks at the surface, were penetrated beneath the deepest or "sole" thrust in the deep well near Bellefonte (Gwinn, 1967, ms.) and in other wells in West Virginia.[7]

Folding of the Detached Thrust Masses

Continued application of stress after initial thrusting results in further wrinkling of the rocks above the detachment thrust (Figure 9C). Flexural-slip and folding proceeds above the thrust. Flexural-slip faults develop in the flanks of the anticlines in the thrust sheet as shortening continues.

Geophysical Data on Configuration of Crystalline Basement Rocks

Geophysical evidence[7] seems to corroborate the implications from observed structure at the surface of the earth and in boreholes that the major folding is only skin-deep.

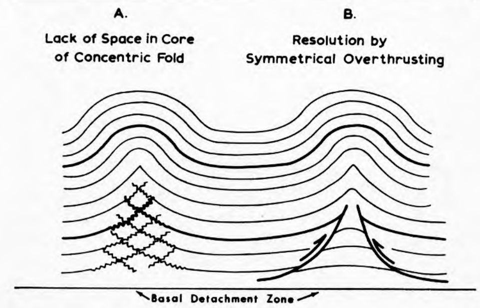

Fig. 7. Parallel folds: (A) Crowding in the core-axial region of a parallel fold because of "lack of room" for shortening of beds low in the fold near the detachment surface; (B) Resolution of the room problem by the formation of flexural-slip thrusts, which rise out of bedding, shear upward across section toward the crest, and achieve shortening required in the axial region.[8]

The geophysical and geological evidence for the nonconcordance of shallow and deep rock configuration in the outer Appalachians is reviewed elsewhere.[8] Similar patterns of shortening are indicated in the Rockies([6,13] and the Juras at the foot of the Alps,[14] to cite two examples. Contrary opinions have been expressed, e.g., by Lees,[15] who presented the general thesis that the foreland fold-belt structures of most mountain ranges were deep-seated in basement rock movements that perpetuated themselves up through the passive cover of stratified rocks. Considerable difficulty is encountered in applying his thesis in most marginal fold belts.

Nature of the Deforming Forces

The great width of the folded belts underlain by the low-angle thrust faults, the relative thinness of the sheets of wrinkled strata that have been translated, and the low crushing strengths of the constituent rock layers cause a major geological para

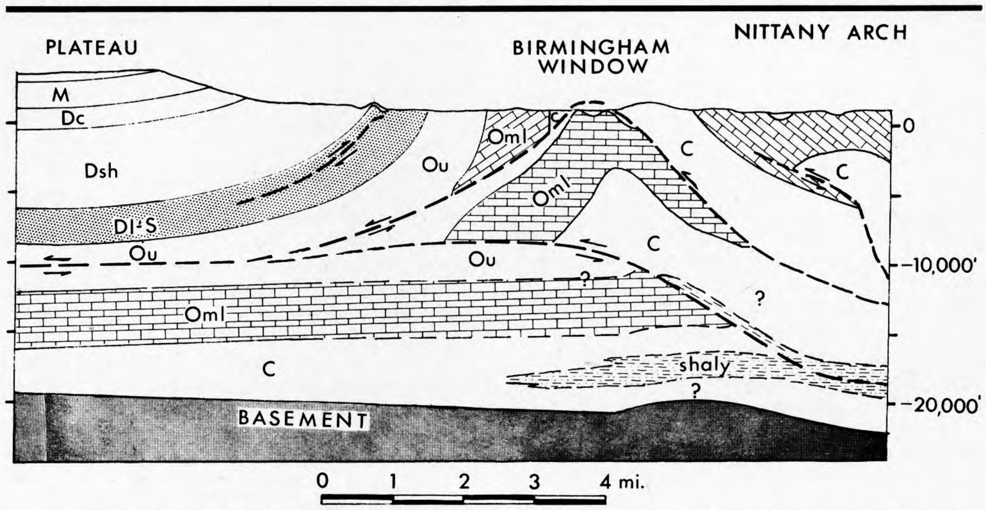

Fig. 8. Interpretation of structure on the northwest flank of the Nittany Anticlinorium, Central Pennsylvania, based on shallow drill holes around the Birmingham "window," geophysical data, and a deep well drilled along the trend of the fold near Bellefonte by Mobil Oil Co. in 1964 (Gwinn, 1967, ms.). From bottom to top at left hand side of figure, letters are abbreviations for progressively younger stratigraphic units of Central Pennsylvania.[8]

dox: How can the sheets transmit and sustain the stresses that would be necessary to put them in motion if the motive forces were applied externally on the back edge of the thrust sheets? Translation and folding has occurred, for instance, in stratigraphic sequences, 7 or 8 miles thick at most, which extend across zones up to 180 miles wide in the Appalachians and up to 300 miles wide or more in the Nevada-Utah portion of the Western Cordilleran region of the United States.

If the folds were generated only by the application of tangential external forces, the rocks would be expected to be tremendously deformed for a few tens of miles away from the line of application of force and only modestly deformed at greater distance. The limited width of the deformed terrain would result from the almost complete uptake of stress by intense strain of the weak rock materials in the zone near the application of stress. No means of propagating the folds outward for tens and hundreds of miles purely by application of external force is at present imaginable. If the thrust sheets were scaled down to a pancake the size of an average rectangular dining table and maintained dynamic similitude, the thrust sheet would have about the same strength as a pancake!

The paradox is eased by postulating that the sheets are buoyed up by high pressure intergranular fluids in zones at depth.(16) The sheets might essentially float, removing much normal stress on the bedding surfaces in the high pressure zone, greatly reducing the resistance to motion along the base of the thrust sheet, and making possible the movement of wider sheets.

Further assistance in explaining the breadth of the deformed terrain is given by postulating that much of the motive force has been provided by the weight of the rocks themselves. Tilting of the sequence away from the high interior part of the mountains would result in a component of the force of gravity acting parallel to, and down the dip of, the bedding surfaces into the flanking foothills region. Movement along stratigraphic zones of weakness, perhaps sites of high fluid pressure, would proceed under the influence of gravity. The movement by gravity of the "gravity thrust" sheet down the inclined detachment surfaces would bring about a more stable mass distribution by lowering the center of gravity of the rock sequence superincumbent on the gliding thrust zones.

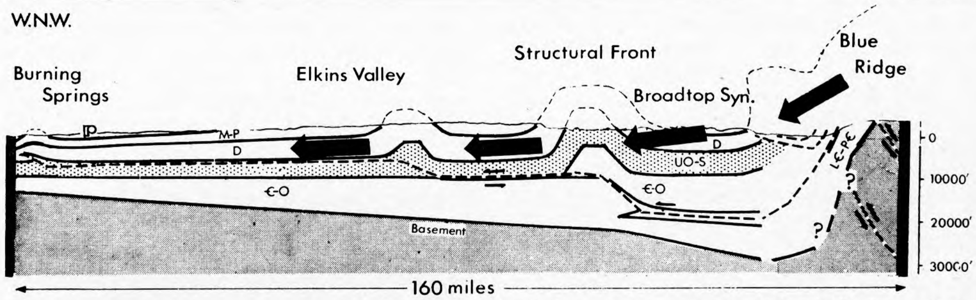

Fig. 10. Schematic transverse section of the folded and thrust faulted foothills belt of the Central Appalachians in the Virginias, demonstrating detachment thrusting and flexural folding. Bold arrows indicate possible descent of sheets of the anisotropic layer cover to the west by gravity sliding atop the detachment zones.

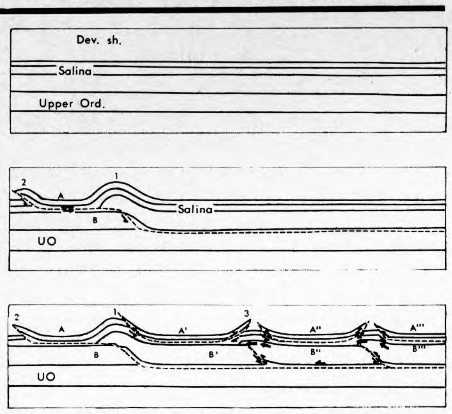

Fig. 9. Deformation model: (A) Undeformed sequence, with incompetent stratigraphic units of the Central Appalachians named. (B) Detachment of upper part of the sequence from the lower, along bedding zones of weakness, and formation of a major anticline above segments of faults where thrusts shear upward across section from one bedding slip to a higher slip zone. (C) Flexural-slip folding and flexural-slip thrusting of strata superincumbent on the detachment surfaces as continued shortening occurs above the detachment behind the major anticline.(8)

Figure 10 is a schematic diagram of the Folded Appalachians in the Virginias(7) demonstrating postulated westward gliding of the sedimentary cover under the influence of gravity, perhaps aided by a tectonic shove from the southeast in the Blue Ridge region.

Conclusion

The strata in the foothills marginal to many principal mountain ranges have been folded by wrinkling of sheets of the stratified rock sequence that moved away from the mountain on low-angle thrusts. Translation has occurred in zones of rock of low strength, high ductility, and low sliding friction.

The basement surfaces on which the sedimentary rocks were deposited are broadly warped, locally faulted, and display only minor structural relief. Structures in the surficial cover generally diminish in size downward to terminate against basal detachment surfaces or sole thrusts that have accommodated the translation of the thin anistropic sheets of layered rocks outward from the centers of the mountain ranges.

Because of the great width of the thin sheets and because of the low strength of the constituent rocks, it is difficult to accept that a piston-like shove on the margin placed the sheets in motion and propagated folds across broad regions hundreds of miles wide. In contrast, this difficulty can be avoided if it is postulated that the motion of the sheets was stimulated by gravity acting parallel to the bases of the inclined thrust sheets, causing their own weight to provide much of the motive force to move the broad, thin, weak sheets away from the topographically high central mountain regions.

Acknowledgments

The writer wishes to acknowledge the continuing support for tectonic investigations in Pennsylvania extended from 1964 to the present time by the Pennsylvania Geological Survey, Dr. Arthur A. Socolow, State Geologist, and to express his thanks and to acknowledge the personal benefits gained from having had the privilege of spending the year 1965-66 as a visitor at the Pennsylvania State University under the auspices of Dr. M. L. Keith, Director of the Mineral Conservation Section, and Dr. Lauren Wright, Head of the Department of Geology and Geophysics.

References

1. Donath, F. A., and Parker, R. B. Folds and folding: *Geol. Soc. of America Bull.* 75:45-62 (1964).

2. Donath, F. A. Experimental study of shear failure in anisotropic rocks: *Geol. Soc. of America Bull.* 72:985-990 (1961).

3. Biot, M. A. Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis: *Geol. Soc. of America Bull.* 72:1595-1620 (1961).

4. Biot, M. A., Ode, H., and Roever, W. L. Experimental verification of the theory of folding of stratified viscoelastic media: *Geol. Soc. of America Bull.* 72:1621-1631 (1961).

5. Currie, J. W., Patnode, H. W., and Trump, R. P. Development of folds in sedimentary strata: *Geol. Soc. of America Bull.* 73:655-674 (1962).

6. Price, R. A. Flathead map area, British Columbia and Alberta: Geol. Survey of Canada, *Memoir* 336, 221 pp. (1965).

7. Gwinn, V. E. Thin-skinned tectonics in the Plateau and Northwestern Valley and Ridge Provinces of the Central Appalachians: *Geol. Soc. of America Bull.* 75:863-900 (1964).

8. Anderson, E. M. *The Dynamics of Faulting,* Oliver and Boyd, London, 2nd ed., 141 pp. (1951).

9. Turner, F. J., and Weiss, L. E. *Structural Analysis of Metamorphic Tectonites,* McGraw-Hill, New York, 545 pp. (1963); (comprehensive bibliography on conjugate shear fracture failure on p. 292).

10. de Sitter, L. U. *Structural Geology,* McGraw-Hill, New York, 551 pp. (1964).

11. Harris, L. D., and Zeitz, I. Development of Cumberland Mountain overthrust block in the vicinity of Chestnut Ridge fenster in Southwest Virginia: Am. Assoc. Petr. Geol., *Bulletin* 46:2148-2160 (1962).

12. Woodward, H. P. Structural interpretation of the Burning Springs Anticline: *in* Woodward, H. P., ed., A symposium on the Sandhill deep well, Wood County, West Virginia: *W. Va.*

13. Rubey, W. W., and Hubbert, M. K. Role of fluid pressure in mechanics of overthrust faulting, Part I., Mechanics of fluid-filled porous solids and its application to overthrust faulting: *Geol. Soc. of America Bull.* 70:115-166 (1959).

14. Pierce, W. G. Jura tectonics as a décollement: *Geol. Soc. of America Bull.* 77: 1265-1276 (1966).

15. Lees, G. M. Foreland foldings: *Quart. Jour.*, Geol. Soc. London, 108:1-34 (1952).

16. Hubbert, M. K., and Rubey, W. W. Role of fluid pressure in overthrust faulting, Part II., Overthrust belt in the geosynclinal area of Western Wyoming in light of fluid pressure hypothesis: *Geol. Soc. of America Bull.* 70:167-206 (1959).

17. Badgley, P. C. *Structural and Tectonic Principles*, Harper and Row, New York, 521 pp. (1965).

About the Author

Vinton E. Gwinn, associate professor of geology, Louisiana State University, Baton Rouge, Louisiana, received the B.A. degree from Rutgers University in 1956 and the Ph.D. degree in 1960 from Princeton University. During his studies, the author, a native of the Appalachians (having been born in Virginia and raised in West Virginia), worked for the Montana Bureau of Mines and Geology, Mobil Oil, and Shell Oil in structural and stratigraphic investigations. In 1957, he worked with recent coastal and alluvial sediments in southwestern France. After two years with Mobil Oil Company, pursuing the problems of deformation of folded mountain terrains developed in this paper, he joined the faculty of the McMaster University Geology Department in 1962. He was a visiting professor at The Pennsylvania State University in 1965-66, under the auspices of the Mineral Conservation Section and the Department of Geology, prior to assuming his present position at L.S.U.

College News Notes

At the Northeastern Regional Geological Society of America meeting held in Boston March 16-18, the following papers were presented by members of the Department of Geology and Geophysics:

D. P. Gold and Barry Voight: "The Mecatina Basin, Eastern Quebec: Astrobleme or Interference-Fold Depression?"

E. G. Williams and Russell R. Dutcher, with co-author David R. Reidenouer, Pennsylvania Department of Highways: "The Relationship between Paleotopography and the Distribution of Pyritic Sulfur in Some Coals of Western Pennsylvania."

Barry Voight: "Hypothesis of Denudation as a Determinant of Tectonics."

B. F. Howell, Jr., professor of geophysics, presented two lectures at Wagner College, Staten Island, New York, on February 21, entitled "The Interior of the Earth" and "Frequency Spectra of Seismic Waves."

The Department of Mining has announced the receipt of a $2,000 grant-in-aid from the Rochester and Pittsburgh Coal Co., Indiana, Pa., to support research in the field of operations research.

Minerals and Men, a highly-regarded survey of the metals field published in 1965 by The Johns Hopkins University Press for Resources for the Future, Inc., is being reprinted in a weekly serialized form in *American Metal Market,* the daily newspaper of the metal industries. The first installment appeared in the January 23, 1967, issue.

James F. McDivitt, the author of *Minerals and Men* (which has been widely adopted as a standard text on metals), wrote it while he was an associate professor of mineral economics in the College of Earth & Mineral Sciences. In 1966 Dr. McDivitt left the University to join the staff of UNESCO.

John D. Ridge, head of the Department of Mineral Economics, has been appointed the representative of the Society of Economic Geologists to the National Research Council for the year beginning April 1, 1967.

Harold J. Read, professor of metallurgy, addressed the Philadelphia section of the Electrochemical Society on March 8. Speaking on "Metallurgical Aspects of Electrodeposits," Dr. Read discussed the means by which the strength, ductility, and hardness of electrodeposited metals can be controlled by manipulating electrochemical variables during the deposition process. He also spoke about the effects of subsequent heat treatments on the properties of the deposited metals.

In his capacity as president of the Electrochemical Society, Dr. Read reported on recent activities relative to publication policies and procedures.

H. R. Hardy, Jr., associate professor of mining, is the author of a paper entitled "A Loading System for the Investigation of the Inelastic Properties of Geologic Material," which appeared in *ASTM Special Technical Publication* No. 402 in December, 1966.

In January, Dr. Hardy addressed the Third Conference on Drilling and Rock Mechanics held at the University of Texas, Austin, on "Determination of the Inelastic Parameters of Geologic Materials from Incremental Creep Experiments."

Robert F. Schmalz associate professor of geology and geophysics, has been elected to the Board of Trustees of the Bermuda Biological Station for Research in St. George's West, Bermuda. He will serve until March, 1971.

Krynine "Portrait" Published

The attention of all interested readers is directed to an article entitled "A Portrait of Paul D. Krynine" which appeared in the December 1966 issue of *The Journal of Sedimentary Petrology.* It was written by two former students of Dr. Krynine, namely, R. L. Folk of the Department of Geology, University of Texas, and J. C. Ferm of the Department of Geology, Louisiana State University.

Contributions to the Paul D. Krynine Fund continue to be received, and the Departments of Geochemistry & Mineralogy and Geology & Geophysics extend their thanks and appreciation to all those who have responded. Income from this fund will be used to assist graduate students in support of their thesis research.

Donations will, of course, continue to be welcome. Those wishing to contribute should make checks payable to The Pennsylvania State University Alumni Fund and send them to Dr. J. C. Griffiths, Department of Geochemistry & Mineralogy, or to Dr. Lauren A. Wright, Department of Geology & Geophysics.

New Appointment For Bates

Dr. Thomas F. Bates, who has been on leave of absence for the past two years to serve as Science Adviser of the U.S. Department of the Interior, has been named vice president for planning at the University, effective June 1, 1967.

In this new position, Dr. Bates will have responsibility for devising plans and procedures by which the University can reach its long-term goals. He will take possible new programs and plans suggested by faculty members and others and try to determine what resources must be committed and what schedules must be followed to insure success. On the basis of such studies a decision will be made as to whether or not it is in the best interests of the University and the Commonwealth of Pennsylvania to proceed, or whether other goals should take precedence.

During his career at the University, Dr. Bates, who will, in addition to his new duties, continue as professor of mineralogy, has been director of the Institute for Science and Engineering, assistant to the vice president for research, and also assistant dean of the Graduate School.

While on leave, Dr. Bates has been the representative of the Department of the Interior on the Federal Council of Science and Technology and a member of the Secretariat of the Department of the Interior.

A native of Evanston, Ill., Dr. Bates received his undergraduate education at Denison University, Granville, Ohio, and holds the M.S. and Ph.D. degrees in geology from Columbia University. He joined the Penn State faculty in 1942 as instructor in mineralogy and has been a full professor since 1953. From 1950 to 1957 he was also director of the University's Mineral Constitution Laboratory in the College of Earth & Mineral Sciences. In 1963, Dr. Bates was named director of the Institute of Science and Engineering and he supervised the work of ten research institutes on the campus. He has coordinated graduate academic programs of an interdisciplinary nature, as well as the University's grants and facilities program since he was named in 1964 as assistant dean for programs of the Graduate School.

F. B. Stephens Dies

Dr. Frank Briscoe Stephens, associate professor of meteorology and coordinator of mineral industries correspondence instruction, died in Bellefonte, Pa., on December 21, 1966.

Dr. Stephens, who graduated from the Naval Academy at Annapolis in 1929, served in the Navy for 15 years, retiring as a commander in 1945. He received a master's degree from the California Institute of Technology in 1939 and the Ph.D. degree in meteorology from Penn State in 1949. In 1945 he joined the Department of Meteorology at the University, teaching various courses until 1956, when he undertook the writing and servicing of correspondence courses in the field of meteorology.

On July 1, 1965, in addition to his duties as associate professor of meteorology, Dr. Stephens was appointed coordinator of mineral industries correspondence instruction, in which position he was responsible for all administrative matters related to the planning, development, and operation of mineral industries correspondence courses, including college credit courses in geological sciences and meteorology and unit courses for industrial employees in ceramic science, fuel science, metallurgy, and petroleum and natural gas engineering.

Rose Joins College of E&MS

Arthur W. Rose recently joined the College as staff geologist of the Mineral Conservation Section and assistant professor of geochemistry. The main emphasis of his work with the Mineral Conservation Section will be on regional geological and geochemical approaches to prospecting techniques.

Dr. Rose received the B.S. degree in 1953 from Antioch College, Ohio, and the M.S. and Ph.D. degrees in 1955 and 1958, respectively, from the California Institute of Technology. His Ph.D. research concerned the distribution of trace elements in sulfide minerals. From 1957 to 1964 he worked in Arizona and Utah with Bear Creek Mining Co. (a Kennecott Copper exploration subsidiary), carrying out research on the geochemistry and mineralogy of porphyry copper deposits. During the last three years he served as a geologist with the Alaska Division of Mines and Minerals, where he was engaged in geologic mapping and geochemical exploration projects, including studies of ultramafic rocks and the structure along the Denali fault, a major strike-slip fault.

Dr. Rose, who is married and has three children, is a native of State College. He is the son of Arthur Rose, professor emeritus of chemical engineering and president of Applied Science Laboratories.

Geological Field Institute 1967

Dr. Daniel F. Merriam of the Kansas Geological Survey, who will be the Director of the American Geological Institute to Japan during the summer of 1967, has announced that Dr. Charles Thornton, associate professor of petrology in the College of Earth & Mineral Sciences, has been selected to participate in the Institute. Dr. Thornton will fly to Japan from San Francisco on June 17. The Institute, which will last approximately six-and-a-half weeks, will be the seventh foreign field institute sponsored by the National Science Foundation for American college and university geology teachers, and only the second to be held outside Europe.

The International Field Institute to Japan is intended primarily to enrich the teaching and research capability of American geology teachers by providing them with firsthand field experience in some of the classical geological regions of Japan. In addition, it should provide increased contact between representatives of Japanese and American universities in the hope that greater interchange of personnel and research material, as well as joint research projects, may result.

Several areas that specifically exhibit orogenic sedimentation have been selected for detailed study, and other geologically interesting and significant areas will be visited where possible.

Reprints Available

Recent publications of the College of Earth & Mineral Sciences are listed below. Those desiring reprints should address their requests to the author whose name appears in italics (if there is more than one), 5 Mineral Industries Building, University Park, Pa. 16802.

Title, Author, and Source

A Numerical Method for the Determination of Stresses Around Underground Openings. *Yih-Jian Wang* and Madan M. Singh. Proc. First Int. Conf. on Rock Mech., Lisbon, Portugal, 1966.

The Crystal Structure of $HoZn_2$. *D. J. Michel* and Earle Ryba. Acta Crystallographica, 21, 5, 1966.

Grain-Boundary Reactions in Magnesia-Chrome Refractories: Application of the Electron Probe, I. *V. S. Stubican* and I. de Menezes. Amer. Cer. Soc., 49, 10, 1966.

Grain-Boundary Reactions in Magnesia-Chrome Refractories: Application of the Electron Probe, II. I. de Menezes and *V. S. Stubican*. Amer. Cer. Soc., 49, 11, 1966.

Chemiluminescent Emission Spectra of Tin Mono- and Di-Halides. *David Naegeli* and H. B. Palmer. Jour. Molecular Spectroscopy, 21, 3, 1966.

Stress Distribution at the Bottom of a Borehole by a Numerical Method. *Y. J. Wang* and M. M. Singh. VII Symp. on Rock Mech., 1965.

The Preparation of Coal Refuse for the Manufacture of Light Weight Aggregate. R. W. Utley, H. L. Lovell, and *T. S. Spicer*. Trans. SME, 346-351, Dec. 1965.

Train-in-a-Tube for Bulk Handling. George H. K. Schenck. Material Handling Eng., 22, 2, 70-73, Feb. 1967.

Minerals and Men. George H. K. Schenck. Jour. Reg. Sci., 6, 2, 79-80, 1966.

New Dimensions in Overland Transportation. George H. K. Schenck. Mining Eng., 37-41, Jan. 1967.

Factors Affecting the Results of the Hardgrove Grindability Test and a Proposed Method of Correction. M. I. Guner, H. L. Lovell, and *T. S. Spicer*. ASME Publication.

An Evaluation of the Self-Heating Characteristics of Coal Refuse and Their Relationship to Combustible Content. S. D. Irons and *T. S. Spicer*. Am. Meeting AIME, Los Angeles, Calif., Feb. 1967.

The Industrial Uses of Anthracite. C. G. Zink and *T. S. Spicer*. SME Fall Meeting, Tampa, Florida, Oct. 1966.

Luminescence in the Glassy State. Guy E. Rindone. Luminescence Inorg. Solids, 419-464, 1966. Academic Press, Inc., New York.

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