RI 9009

Bureau of Mines Report of Investigations/1986

Geotechnology in Slate Quarry Operations

By Noel N. Moebs, Gary P. Sames, and Thomas E. Marshall

UNITED STATES DEPARTMENT OF THE INTERIOR

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Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Moebs, Noel N

Geotechnology in slate quarry operations.

(Bureau of Mines report of investigations ; 9009)

Bibliography: p. 35-37.

Supt. of Docs. no.: I 28.23: 9009.

1. Ground control (Mining). 2. Slate–Pennsylvania–Pen Argyl Region. 3. Quarries and quarrying–Pennsylvania–Pen Argyl Region. I. Sames, Gary P. II. Marshall, Thomas E. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 9009.

TN23.U43 [TN288] 622s [622'.354] 85-600255

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	m	meter
ft^2	square foot	MN/m^2	meganewton per square meter
h	hour	MPa	megapascal
in	inch	Ωm	ohm meter
in^2	square inch	psi	pound (force) per square inch
in/°F	inch per degree Fahrenheit	V	volt
lb	pound	V/in	volt per inch
lb/ft^3	pound per cubic foot	W	watt

GEOTECHNOLOGY IN SLATE QUARRY OPERATIONS

By Noel N. Moebs,[1] Gary P. Sames,[1]
and Thomas E. Marshall[2]

ABSTRACT

This report summarizes a Bureau of Mines study on the use of geotechnology to identify and reduce ground control hazards at slate quarry operations in eastern Pennsylvania. The major ground control hazard is falling rock, attributed to weathered bedding plane faults, which weaken quarry highwalls. It was demonstrated that these faults can be detected outside of the quarry perimeter using surface resistivity measurements. Falls of ice from quarry highwalls constitute a second major hazard, which requires water diversion as a basic control method. In situ stresses seemingly cause only minor problems in slate extraction although they could interact with developed stresses and lead to failure of barriers between quarries. Pull tests showed that rockbolts anchor firmly in slate and should prove effective in securing loose rock.

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INTRODUCTION

During the 1920's, when production of roofing slate in the United States had declined to low levels, the Bureau of Mines conducted studies to help the slate industry adopt more economical methods and use the most efficient labor-saving equipment. It was anticipated that this would promote economy and the reduction of waste in the industry. The principal investigator for the Bureau, Oliver Bowles, succeeded in encouraging industry to adopt the then innovative wire saw, which greatly facilitated the quarrying of slate and minimized waste. Bowles (1-7)[3] reported on several technical aspects of the industry, particularly in the Pen Argyl district of Pennsylvania, and Thoenen (8) authored a supplementary report on the wire saw in 1928.

Between 1928 and 1980, the slate industry received little attention because priorities and national interests had turned to a depressed economy, strategic minerals in times of war, and environmental protection. However, in recent years there has been a renewed interest in promoting health and safety technology through research. The Bureau, which is responsible for a broad spectrum of programs for improving technology to make production and processing of minerals more efficient, safer, and more healthful, once again recognized that the slate industry was in need of more up-to-date safety technology and production methods.

In response, the Bureau first conducted an overall study of the slate industry of the Vermont-New York district [Watson, Ohlsson, Shorey, Miller, and Whittier (9)], and second, initiated an investigation in the Pen Argyl district to identify quarrying hazards and to develop methods for reducing these hazards. This report describes the efforts in the Pen Argyl district to apply geotechnology to the reduction of safety hazards in slate quarrying and to test the practicality of using various methods and equipment for this purpose. While this study was conducted chiefly in the Pen Argyl district of Pennsylvania, some of the findings should be applicable to other slate districts or other types of quarries.

A brief reconnaissance was conducted of quarries in the Vermont-New York slate district, although no studies were attempted by the authors. These quarries are operated chiefly as unsymmetrical open pits using explosives for extraction, whereas in Pen Argyl the quarries utilize wire saws to achieve a relatively smooth-walled rectangular opening.

Any discussion of the U.S. slate industry should include at least a passing reference to Wales, where most practices in slate quarrying and processing had their origin, and from whence many of the quarrymen emigrated to America in the 19th century. As an example of the importance of the Welsh slate industry, one quarry alone, the Dinorwic, employed nearly 3,000 men in 1900, and its workshop buildings now form the North Wales Quarrying Museum, demonstrating all the stages in the production of slate [Butt and Donnachie (10)]. Slate production from both the United States and Wales has diminished greatly, however, from previous high levels near the turn of the century.

The quarrying of slate in the United States began in the 18th century and by the mid-19th century was well established at several localities. By 1880, Pennsylvania had become the major center of production, although western Vermont followed closely (11). Pennsylvania continues to be the leading producer because of the active quarries located in the Pen Argyl district, along with some in nearby Slatedale, Lehigh County, also a part of the "soft (slate) belt."

In the United States, slate is produced by the open pit or quarry method of mining except at one locality at Monson, ME, where it is mined underground. In the Pennsylvania slate district, the quarries tend to be deep and narrow because, for the most part, beds of high-grade

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[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

slate are closely folded and steeply dipping, and the working of such beds down dip, rather than along strike, results in a quarry commonly several hundred feet deep.

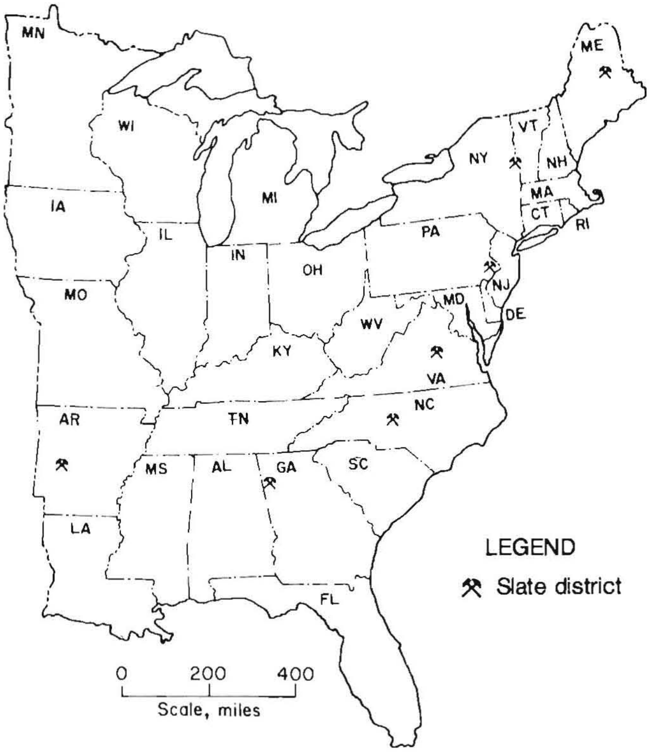
Underground mining of slate in Pennsylvania was attempted at one time by working laterally from the bottom level of an active quarry. This slate mine is no longer in operation despite certain advantages of working underground, such as a minimum disturbance of the surface environment and freedom from severe weather conditions.

Although more producers of crushed stone are considering underground mining, according to Robertson (12), dimension stone production is a special case because careful extraction and handling are essential. Some abandoned quarries have been used for solid waste disposal and petroleum product storage, and underground mining for dimension stone also could lead to end uses of the resulting space, which can constitute a source of income after closure. Many factors would have to be investigated thoroughly before planning underground dimension stone mining.

Slate is a fine-grained, low-grade metamorphic rock with a very pronounced cleavage, enabling it to be split readily into thin, smooth sheets. Its physical properties are shown in table 1. Most slate originally consisted of a clay or mud. It is composed chiefly of sericite, chlorite, and quartz, and occurs in a variety of colors. Red, green, and purple slates are common in the Vermont-New York slate district, while most slate in the Pen Argyl district of Pennsylvania is gray with thin beds colored nearly black by carbonaceous material.

Because of its cleavage, ease of shaping, and stability, slate is useful for the manufacturing of a wide variety of products, including roof tiles, floor tiles, burial vaults, billiard table tops, and architectural stock. The high dielectric strength of slate (7,000-V minimum per 1-in thickness) makes it highly valuable for switchboards and similar applications. Slate is relatively inert, virtually nonradioactive, and nonpolluting, important properties in an environmentally sensitive society. Slate once was very popular for tombstones because it does not weather easily.

The major slate-producing districts in the United States (fig. 1) are the Vermont-New York district near Poultney, VT, and Whitehall, NY, and the Pen Argyl district in Northampton County, PA. Some slate also is produced in Maine, Virginia, North Carolina, Georgia, and Arkansas.



State	Number of quarries	Number of employees	Product
ME...	1	8	Dimension stone.
NY-VT	33	312	Do.
PA...	6	330	Do.
VA...	6	163	Dimension stone, crushed stone.
NC...	2	10	Do.
GA...	2	25	Crushed stone.
AR...	1	20	Do.

FIGURE 1. - Major slate-producing districts in the United States.

TABLE 1. - Physical properties of slate

Specific gravity..........................	2.79-2.83
Weight.......................lb/ft^3..	175
Rockwell "C" hardness..................	35
Shore hardness..........................	31-46
Brinnell hardness........................	320
Compressive strength..............psi..	15,500
Tensile strength...................psi..	2,500
Modulus of elasticity..............psi..	1.42×10^6
Poisson's ratio...........................	0.158
Coefficient of expansion........in/°F..	$0.5\text{-}1.0 \times 10^{-5}$
Point load......................MN/m^2..	2.26-6.29
Dielectric strength...............V/in..	7,000

The Pen Argyl district, subject of this report, is designated as being part of the "soft belt" of slate, a versatile, high-grade slate. Geologic structure in the Pen Argyl district is complicated by numerous folds, overturned bedding, and faults, which have been the major factors in determining the shape and size of quarries in the area. Much of the surface is covered by glacial deposits of ground and terminal moraine, in general less than 15 ft thick.

Slate in Pennsylvania has been the subject of several comprehensive reports that fully describe the geology, quarrying, processing, and marketing of this material, including reports by Behre (13-14), Stickler, Mullen, and Bitner (15), Mullen and Stickler (16), Hoyt (17), and Miller, Fraser, and Miller (18). Detailed geologic maps on selected areas of Pennsylvania slate belt have been prepared by Davis, Drake, and Epstein (19) and Epstein (20), while Epstein has also mapped the location of quarries and dumps in the Stroudsburg quadrangle, northeast of Pen Argyl, to show their environmental significance (21). Most of the literature, however, is largely devoid of any discussion of safety technology; it is hoped that some of the material in this report will contribute to an improved understanding of quarry hazards and the means to investigate and minimize them.

ACKNOWLEDGMENTS

The authours wish to express their appreciation to Anthony Dally and Sons, Inc., for providing material, for assistance in test procedures, and for providing unlimited access to quarry operations during the course of this investigation. The Pen Big Bed Slate Co. and Williams and Sons Slate and Tile, Inc., provided helpful information on the quarrying and processing of slate, for which the authors are grateful. Also, thanks are due to Charles Ratte, Vermont State Geologist, for conducting the authors on a reconnaissance tour of the Vermont-New York slate district.

QUARRYING METHODS

The details of dimension slate extraction cannot be described fully here because of the diversity of slate cleavage and bedding, and the variety of local mining techniques that are tradition bound, but a general description is essential to understanding the slate quarry operation.

Slate in Pennsylvania is obtained from open quarries, where narrow, deep pits are the rule because beds of quality slate tend to be steeply dipping (fig. 2). Working down dip, sometimes to 900 ft, is more advantageous than quarrying along strike, because at shallow depths the stone is weathered and stained, and

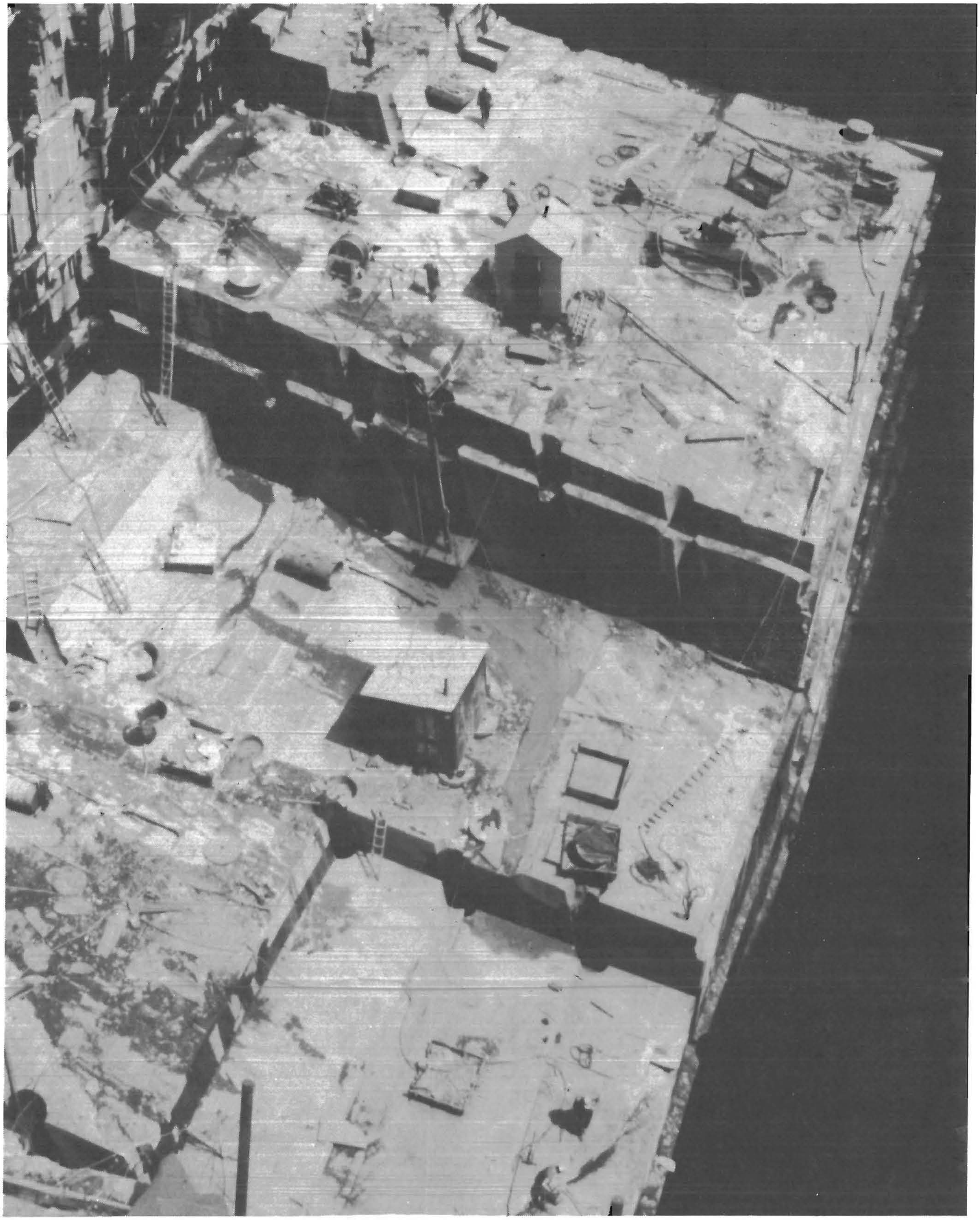


FIGURE 2. - Method of benching used to quarry slate when cleavage is nearly horizontal and bedding is steeply dipping.

a large amount of both loose overburden and weathered rock must be stripped away before production of usable slate can begin. Working down dip exposes smaller areas of slate to freezing; once soft slate is frozen it does not split properly. In addition, lateral quarry development necessitates the frequent relocation of aerial trams and other facilities, a slow and costly operation. For similar reasons, new operations seldom are opened in virgin ground. Instead, old quarries are dewatered and reactivated.

Slate usually is raised from the quarry floor to the surface by means of an aerial tram (fig. 3), which also is used to transport workers and equipment into and out of the pit.

Prior to 1926, slate quarries in Pennsylvania extracted large slabs and blocks of slate either by drilling and blasting or by a channeling process. With the channeling process, a row of closely spaced parallel holes was first drilled in the rock bench and then the intervening rib of rock between each pair of holes was broken away to form a continuous slot. The rock then could be freed entirely from the bench by wedging along the cleavage plane. Both methods had disadvantages. Drilling and blasting resulted in excessive fracturing and waste and ragged angular rock surfaces. Channeling was a slow process requiring considerable time to drill and to broach the slate between the holes.

Shortly after 1926, the Bureau assisted the slate industry in introducing the wire saw to facilitate slate extraction. The wire saw consists of an endless three-strand wire rope about 1/4 in. in diameter, which is carried on pulleys from the driving wheel located on the surface near the edge of the quarry to a quarry bench; there it is guided again by anchored pulleys against the rock where a slot in the quarry bench is to be cut (fig. 4). The wire rope is placed in tension, set in motion, and fed with a slurry of sand and water. Compared with older quarrying methods, the wire saw conserved power and labor, lowered costs, reduced waste, and permitted the quarry walls to be cut more smoothly, thereby reducing the hazard of rock falls. The wire saw method continues to be the principal manner by which slate is extracted from the quarries in Pennsylvania.

SLATE PRODUCTION

Roofing continues to constitute the major market for quarried slate, although mill stock, which includes billiard table tops, grave vaults, and architectural items, is an important and growing product. Roofing tiles are used principally in the repair of existing buildings or in the construction of institutional buildings and expensive dwellings. The renovation of historic structures also is an important use of slate roofing tile. The Parsons Brothers Slate Co. has published a handbook fully describing all aspects of roofing slate, roofing alterations, and reroofing (22). Architectural slate consists chiefly of floor tile and facing used for institutional or commercial buildings. Box tile, a slate flooring somewhat thinner gauge than architectural floor tile, is used primarily for residential patios and entrance areas.

The dollar value of all slate produced in the United States from 1890 through 1980 shows an overall increasing trend (fig. 5), reaching a peak in 1980. Roofing slate, as measured in the number of squares produced from 1879 through 1980, reached a peak output during 1900-13. The output generally has declined since then (fig. 6) but shows some signs of stabilizing in the last few years reported.

It has been estimated that almost 85 pct of the slate quarried in Pennsylvania is waste, and most of this material goes to make up the large waste piles that characterize the slate belt. Some waste has been consumed in the manufacturing of lightweight aggregate, roofing granules, fillers, fiberglass, rock wool, and glass ceramics, but the overall consumption of waste for these items remains small. A promising use for waste slate in the manufacturing of a substitute for asbestos was recently investigated by Mackenzie (23), and the results were summarized

FIGURE 3. - Method of hoisting slate slabs to surface.

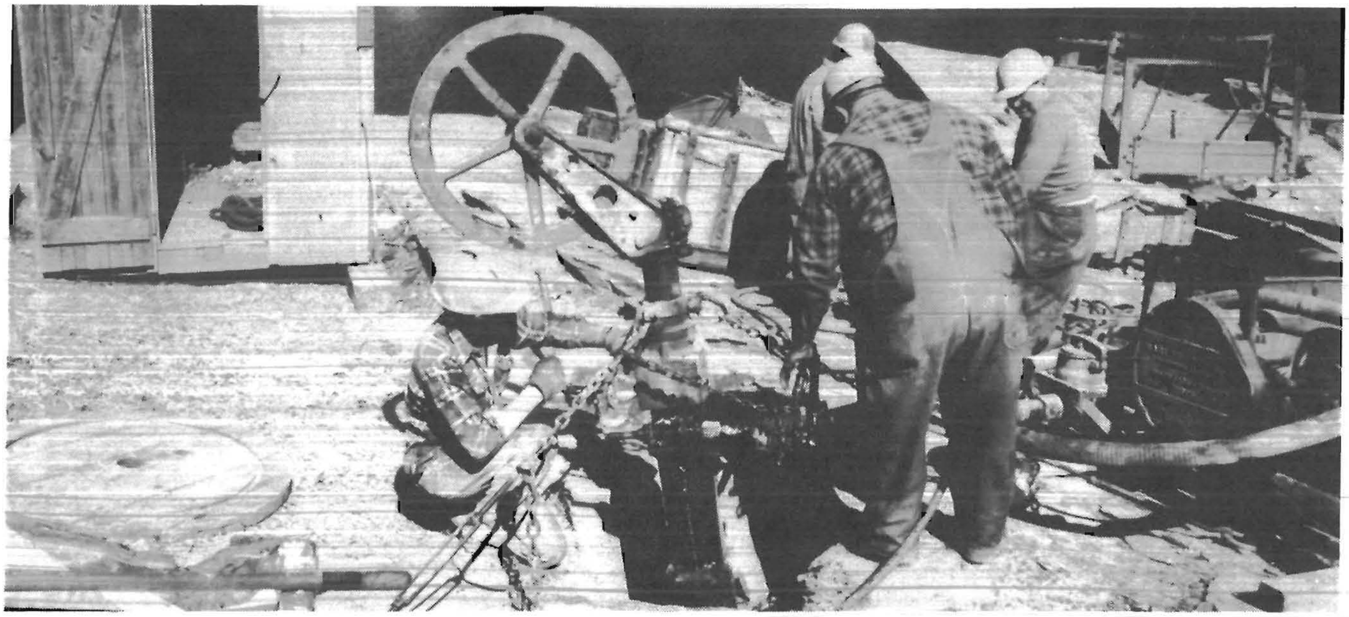


FIGURE 4. - Installing standard and sheave for wire rock-sawing operation.

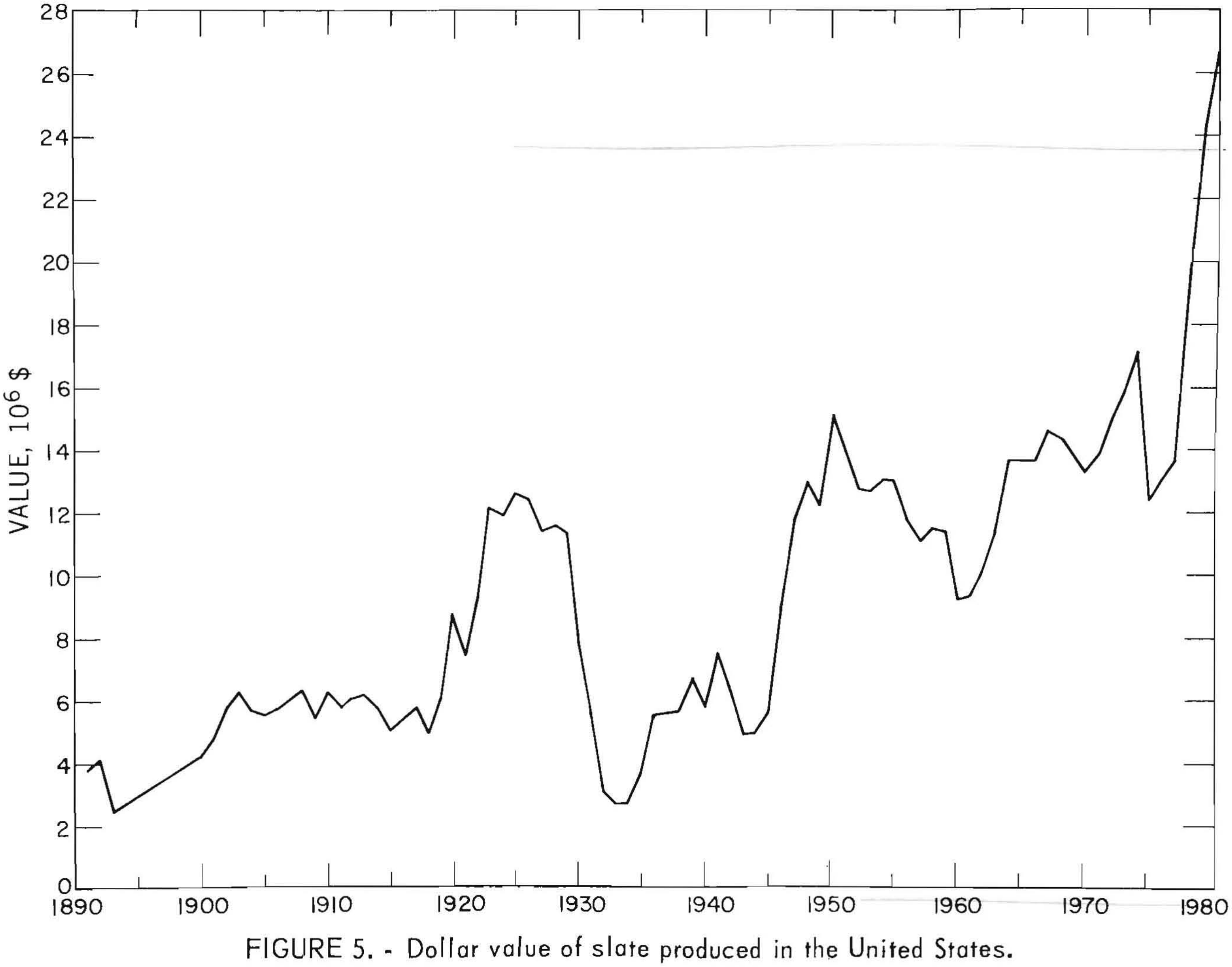


FIGURE 5. - Dollar value of slate produced in the United States.

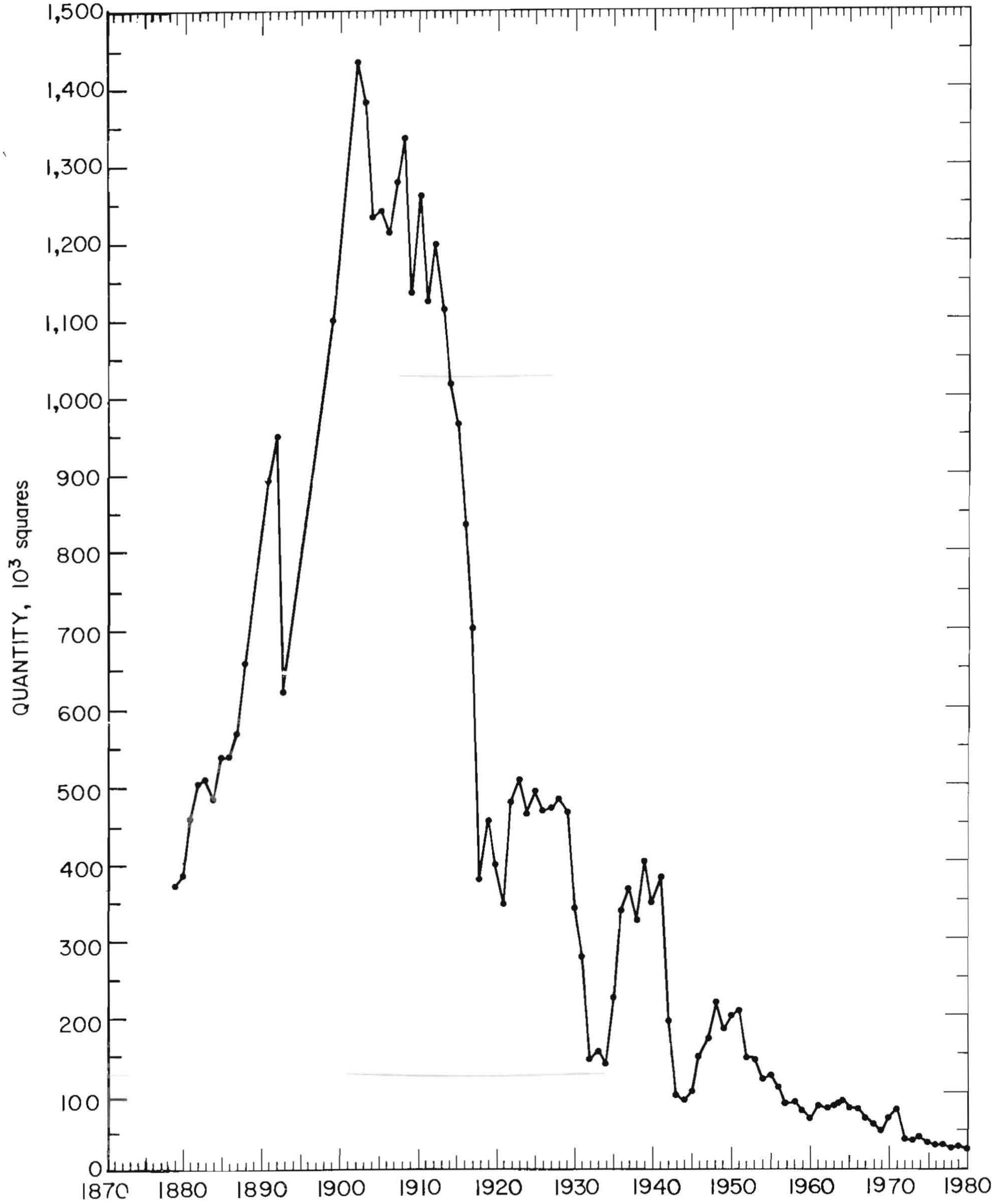


FIGURE 6. - Production of roofing slate in squares.

in Chemical and Engineering News (24). Chrysotile asbestos, used in manufacturing asbestos cement pipe, asbestos cement sheet, and roofing and flooring products, is largely imported from foreign suppliers and, further, is suspected of being a cancer-causing agent, lending urgency to the search for a substitute raw material.

As recently as 1981, the overall demand for slate, except for waste, was greater than the supply [Meade (25)] because of a lack of expansion in production facilities and investment capital, and a resurgence in the use of natural materials. Dickson (26) reviewed the production and marketing of slate, including some new uses, and also reported that interest in higher priced slate products, such as roofing and architectural stock, is increasing again. Some of this increase in demand can be attributed to the renovation of slate roofs on older homes and historic structures.

GEOLOGIC SETTING

The Pen Argyl slate district is located in Northampton County, Pa, about 60 miles north of Philadelphia. The slate occurs in a northeast-trending belt some 6 miles wide that lies along the southeastern foot of Blue Mountain (fig. 7), a northeast-trending ridge of resistant Shawangunk conglomerate of Silurian age. The rocks in the slate belt consist of the Martinsburg Formation of Ordovician age and are bounded on the southeast by the Cambro-Ordovician limestone of the Lehigh Valley. The slate is more resistant than the limestone and forms a low terrace of rolling topography between Blue Mountain and the limestone valley. The Martinsburg Formation originally consisted of clay and silt sediments. According to McBride (27), the formation was deposited in relatively deep water below wave base, as indicated by the absence of crossbedding, channeling, and wave-ripple marks. The clay minerals in the sediments were recrystallized during regional metamorphism and deformation into sericite, chlorite, and quartz. Some carbonate and carbonaceous material also is present in Pen Argyl slate.

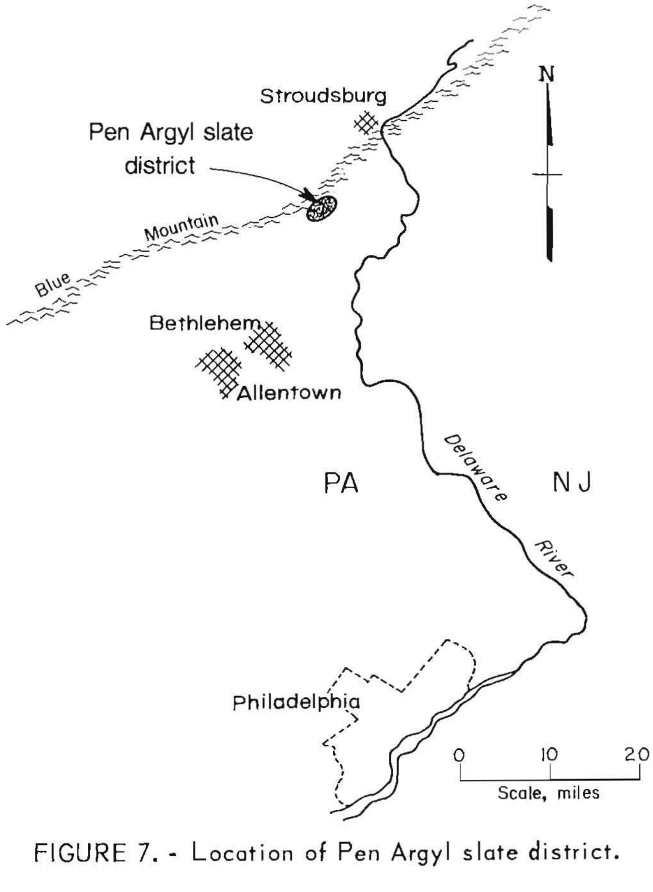


FIGURE 7. - Location of Pen Argyl slate district.

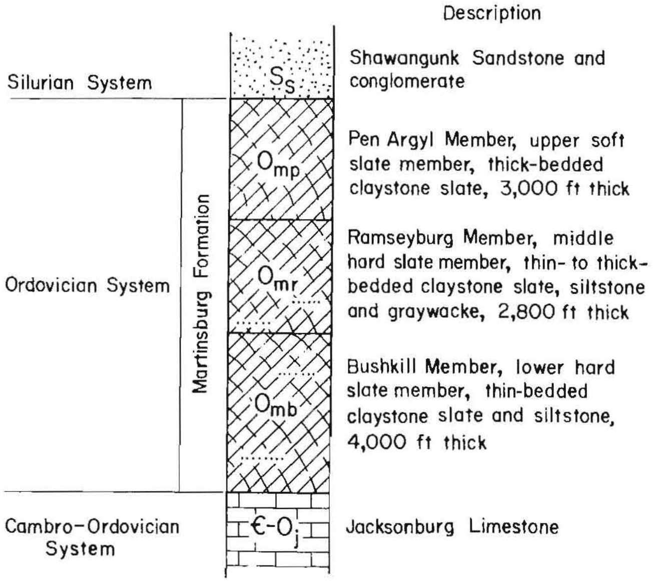


FIGURE 8. - Generalized columnar section of rocks in Pen Argyl slate district.

Drake and Epstein (28) have divided the Martinsburg Formation into three members (fig. 8) to facilitate geologic mapping of the area and to fix the stratigraphic and areal distribution of the commercial slate in the formation (fig. 9). The upper member of the formation, designated as the Pen Argyl Member, includes the principal beds or runs of high-grade commercial slate in the district. The Pen Argyl Member consists chiefly of thick-bedded gray claystone slate with occasional thin beds or "ribbons" of nearly black carbonaceous slate. The upper portion of the middle or Ramseyburg Member of the Martinsburg Formation also has yielded some commercial high-grade slate, but rocks occurring lower in the formation are inferior in quality because of interbedded hard layers of siltstone.

The Martinsburg Formation in this area has been deformed by tectonic forces into highly complicated folds, the formation largely being thrust northwestward into a sequence of overturned to recumbent folds. Beds are inclined at many different angles ranging from horizontal to 90°, and more than 90° or overturned and, therefore, upside down. Quarries developed on steeply dipping beds of high-grade slate are deep and narrow. Continuing to follow a steeply dipping run of slate and quarrying to greater depths eliminates the necessity of removing overburden and weathered shallow slate for lateral expansion of a pit.

A nearly perfect cleavage unrelated to bedding (fig. 10) was formed in the slate belt as a result of the deformation. Faulting also occurred in many directions but is principally parallel to bedding where exposed by quarry openings. These bedding slip faults sometimes are weathered and clayfilled at shallow depths (fig. 11) and are then designated as "rotten ribbons" by quarriers. Many faults are filled with vein quartz and

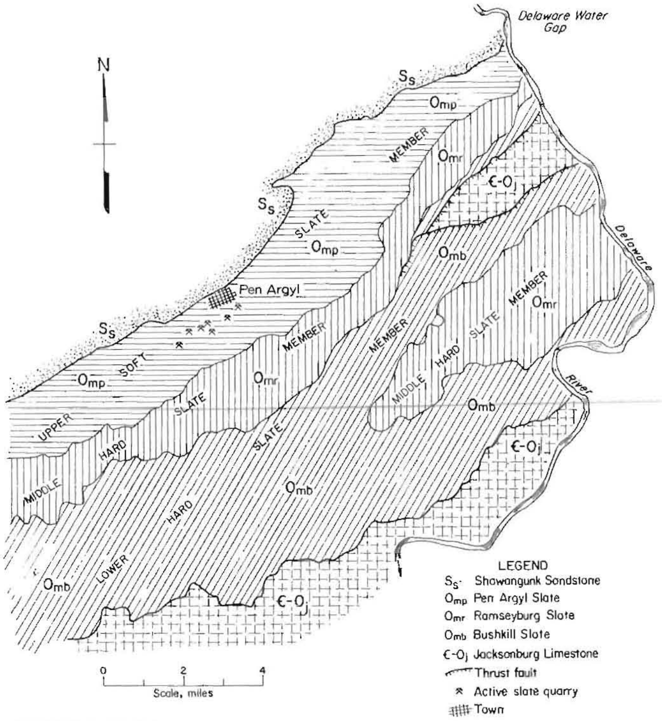


FIGURE 9. · Areal geology of bedrock in Pen Argyl slate district.

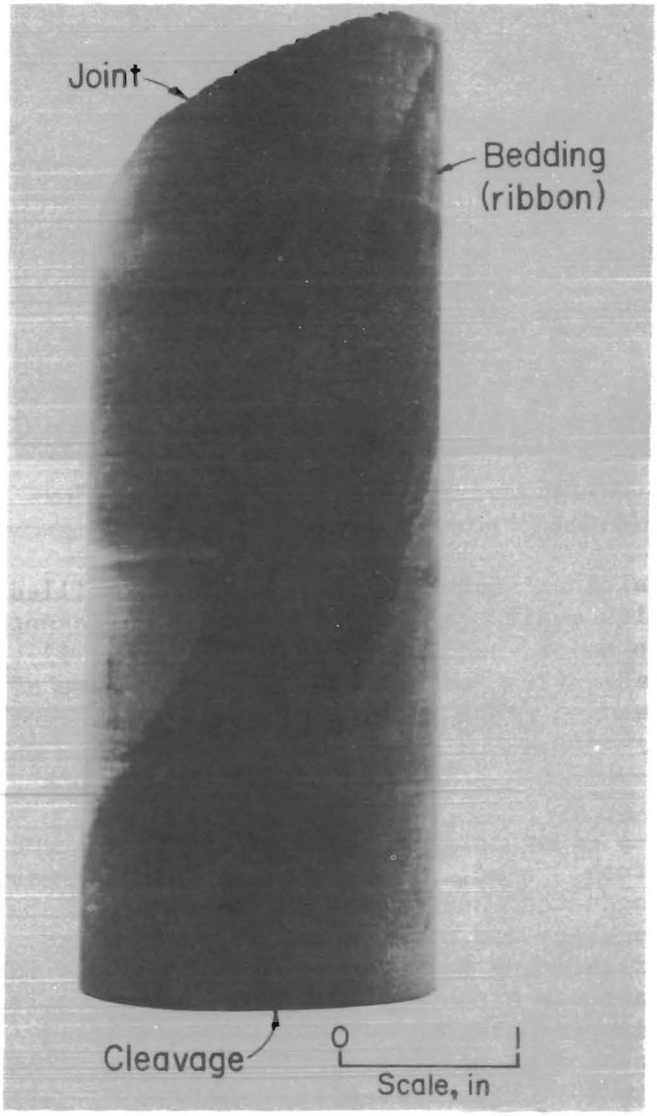


FIGURE 10. - Section of drill core showing bedding, cleavage, and joint.

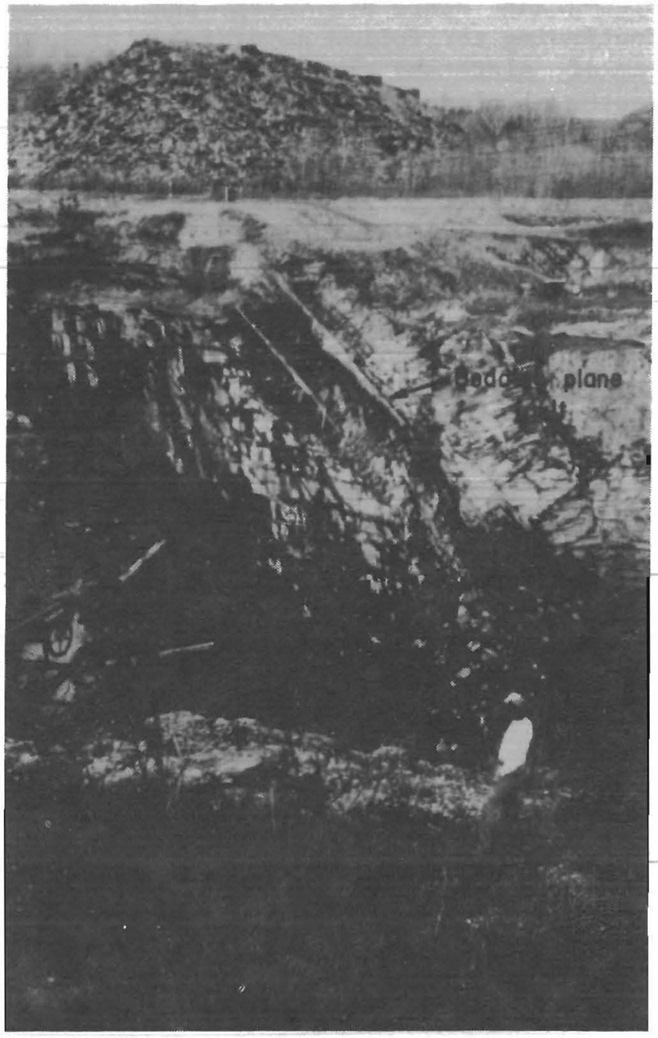


FIGURE 11. Weathered bedding plane fault ("rotten ribbon") in quarry highwall.

calcite. Subsidiary gash veins filled with quartz and calcite occur adjacent to major bedding slip faults (fig. 12). Behre (29) described a special case of bedding plane faults in which the thrust plane is steep but dips nearly parallel to the beds on one limb of a compressed fold. He also describes the gash veins that tend to occur in both walls of the faults. These descriptions compare closely with most of the bedding plane faults observed in the slate quarries. The direction of movement along these faults, but not the amount, is determined by the gash veins. It seems probable that the faults formed while the beds were nearly horizontal and then were compressed further into close folds along with the beds.

Joint sets in the area tend to be locally developed (fig. 13) and for the most part are different from one quarry to the next, probably because of the intense folding, refolding, and localized response of the slate to stresses. There is a tendency toward a northeast strike parallel with the regional structure, while dips are highly variable. Generally, the presence of joints is a disadvantage in quarrying because sufficiently large blocks of high-grade slate cannot be quarried.

Some areas of the slate district are covered by a thin veneer of glacial deposits of both ground and terminal moraine of Pleistocene age and consisting of a mixture of unconsolidated boulders, gravel, sand, and clay. This material is reported to reach a thickness of 50 ft in places, but it seldom exceeds 15 ft in the vicinity of the Pen Argyl quarries where it grades into the underlying broken and weathered slate. Resistivity soundings, reported in a later section, "Geologic Studies for Hazard Detection," confirm this estimate.

QUARRY SAFETY

A study of operational safety in the stone, sand, and gravel industries was conducted under a Bureau contract by Yegulalp and Boshkov (30) for the purpose of defining factors affecting safety in various areas of ground control. Only five injuries were reported for slate dimension stone quarries for 1975-78. The study further revealed that roof fall accidents are the most common ground control accidents in underground stone mining, while falls of face, rib, and highwall occur most commonly in surface stone mining. It is noteworthy that none of the companies quarrying surface crushed stone that were surveyed in this study bolted the pit wall on a regular basis to prevent falling rock, although a number of dimension stone quarries did bolt on a spot basis when necessary.

Accident statistics relating specifically to slate quarries are available,

FIGURE 12. - Gash fractures in lower portion of bedding plane fault.

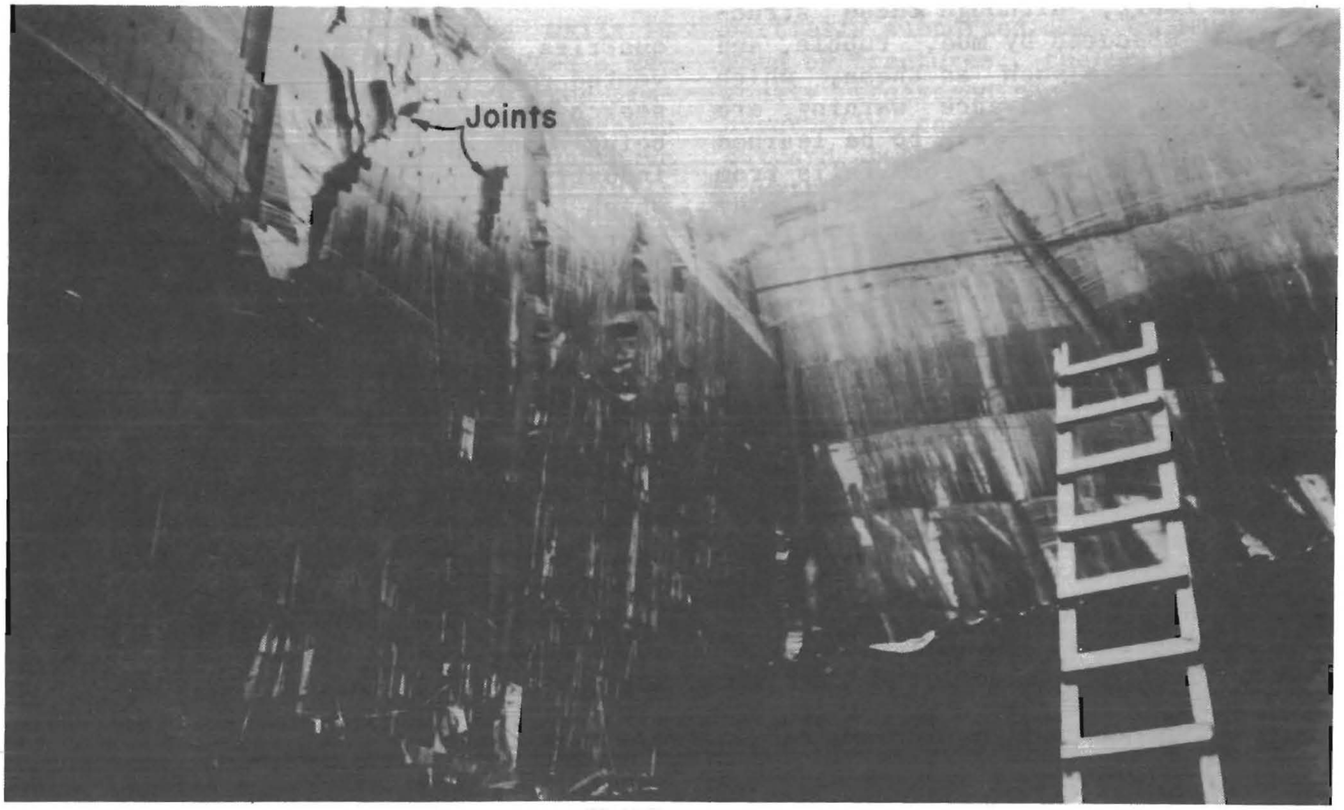


FIGURE 13. - Joints in upper portion of quarry highwall.

but because of the small number of quarries, they do not provide a statistical base concerning causes of accidents. For 1978, 44 slate quarries were operational in the United States, with 312 employees. The Mine Safety and Health Administration (MSHA) (31) reports that, in 1982, there were six injuries and no fatalities related to ground control in dimension slate quarries. Accident and fatality reports for earlier decades are incomplete, but occasional fatalities occurred in the Pennsylvania slate quarries. For example, in 1939, rock falling from a highwall resulted in two fatalities. In 1969, three more deaths resulted from a similar accident. In both of these incidents, the cause of the rock fall was attributed to a rotten ribbon or weathered bedding plane fault (fig. 14) located near the top of a quarry highwall. In 1979, a similar large rock fall occurred unexpectedly from a quarry highwall near Pen Argyl (fig. 15). The fall occurred on a weekend and thus no workers were endangered. It is suspected that the fall was caused by the intersection of a rotten ribbon and a weathered cross joint or transverse fault, although these structures were obscured by mud, rubble, and vegetation. Falls such as these, which occur without any advance warning, are evidence that much is yet to be learned about the exact cause of rock falls from vertical quarry highwalls and methods by which they can be prevented. While it seems clear enough that geologic defects weaken highwalls, methods have yet to be developed to assess the hazard potential of these defects adequately. Precautions such as periodic examination, pinning, and scaling are practiced at some quarries, but this has not entirely prevented rock falls. Currently, little research in ground control technology is being conducted by the dimension stone industry, especially the slate industry, which is struggling to regain what appears to be a market recovering from many depressed years.

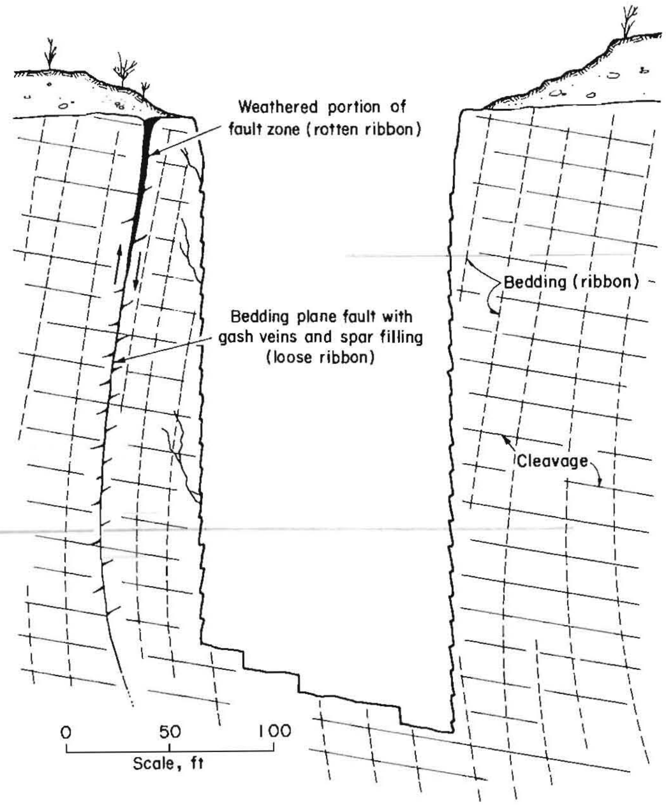


FIGURE 14. - Schematic of a "rotten ribbon" or weathered bedding plane fault.

Specific ground control hazards that are especially troublesome in Pennsylvania slate quarries are described in the following section.

QUARRY HAZARDS

ROCK FALLS

The hazards encountered in Pen Argyl-type slate quarries are somewhat different from those in conventional, shallow rock quarry operations. No blasting is performed, which eliminates the common rock fall problem resulting from highwall breakage. After several decades of wire saw quarrying on a selected "run" of beds, a slate quarry resembles a large shaft more than a conventional quarry. Unlike a shaft, however, the vertical walls of the slate quarry are accessible for examination or scaling only with great difficulty, and any weakness or

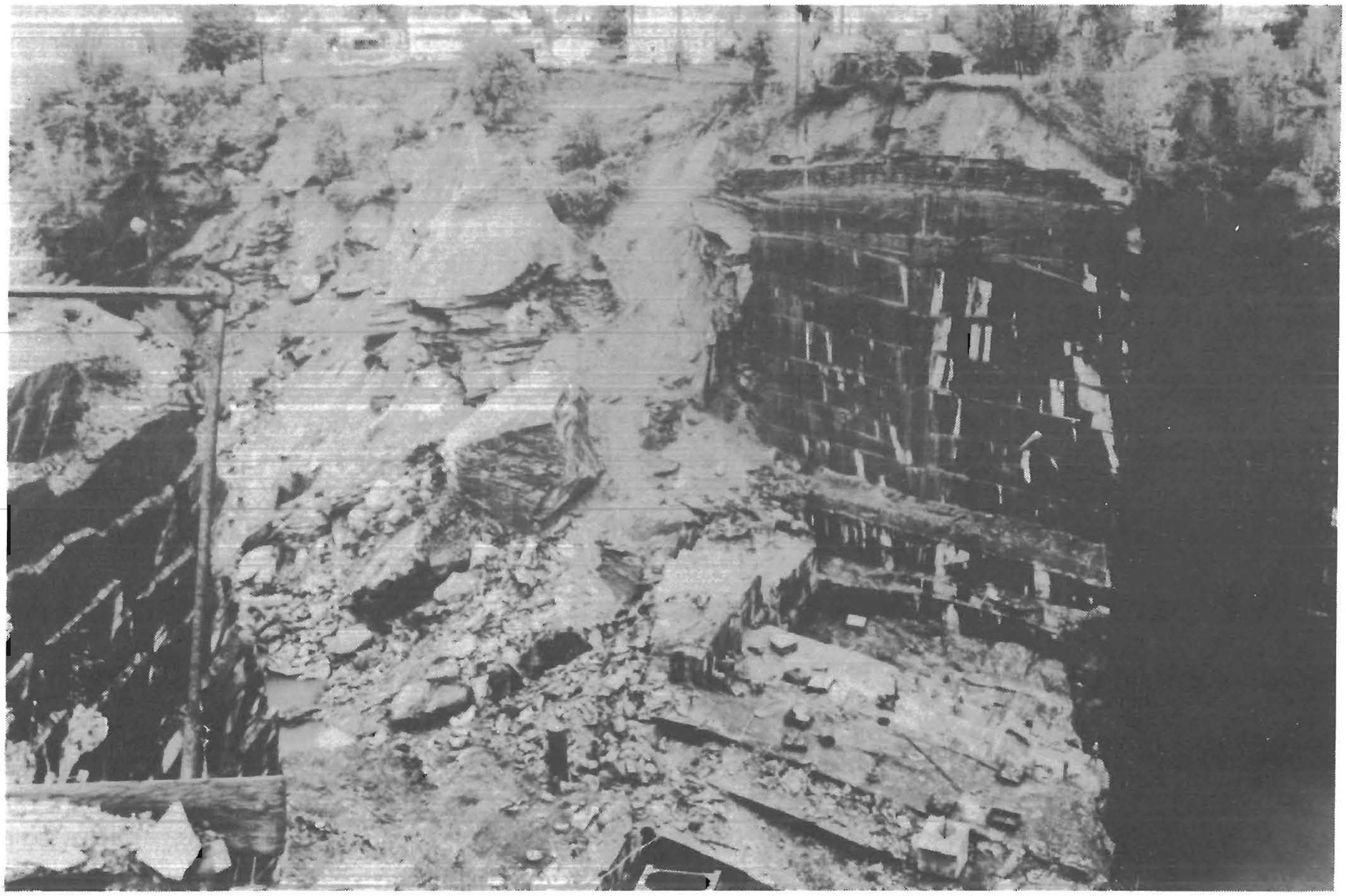


FIGURE 15. - Collapse of quarry highwall adjacent to operating section.

geologic discontinuity in the walls is difficult to detect and constitutes a major hazard to those working on the limited floor space below. For this reason and because of the fatalities that have occurred from time to time, rock falls from the quarry walls can be designated as the principal ground control hazard in slate quarry operations. Most accidents and fatalities have resulted from rather large collapses of a quarry wall rather than the dislodging of a single slab or wedge or rock, and most can be attributed to the presence of a major geologic discontinuity such as a weathered fault zone. The conditions along a fault zone that trigger a highwall collapse can be attributed to several sources. As a quarry is deepened, more of the slate that buttresses the highwalls is removed, and the remaining rock slab between the highwall and fault (fig. 14) is only partially supported and is usually weakened by fractures, thereby becoming virtually freestanding. The forces that eventually cause the highwall to hinge outward, buckle, or collapse can include in situ rock pressures (described in the section "High Stresses"), a hydraulic ram effect from fluid pressure in an open water-filled fault fissure, the formation and expansion of ice in highwall fractures, and the lubrication effect of percolating ground water on the shear strength of any geologic discontinuity. To a large extent, the engineering behavior of slate as a rock mass is governed more by faults or joints than by the cleavage in the Pen Argyl district, which dips at a very low angle. Laboratory tests show only a relatively small difference in physical properties at right angles and parallel to cleavage. Cleavage, however, constitutes a potential plane of weakness and must be given serious consideration in assessing rock fall hazards.

Slope stability studies at the 492-ft (150-m) deep Old Delabole Slate Quarry near Tinagel in North Cornwall, Wales, by Brown, Richards, and Barr (32) also point to the importance of discontinuities such as cleavage, joints, and faults in quarry operations. In particular, a series of failures that occurred in the face of the quarry prompted an investigation of shear strength of discontinuities, with resulting data on the influence of water and surface roughness.

In a related study at the Dinorwic slate quarry, Paterson and Arthur (33) presented portal design and construction methods, including rock bolting, dowels, steel mesh, and sprayed concrete, based on geotechnical information. Joints were identified as major potential planes of failure, and on one occasion they contributed to the complete collapse of a tunnel portal. At the time of the collapse, all the relevant geological information was known, but the interaction of all the adverse factors had not been appreciated fully.

A preliminary study of slate quarry operating experience and the geologic conditions in the Pen Argyl district indicates that, in addition to routine visual examination and scaling of rock on quarry highwalls, some established geologic and engineering methods might be used to detect potential rock fall conditions. These methods include geologic mapping of discontinuities and the use of strain gauges or tiltmeters to detect incipient movement of large wedges of rock near faults and joints. Extended time will be required to assess the practicality of these methods, as quarry development progresses slowly; however, a brief summary of the methods employed and the results obtained could lead to further improvement in quarry safety and hazard detection.

ICE FALLS

The accumulation of ice on quarry highwalls and its dislodgement because of thawing or breaking off under load constitute a serious handicap during winter operations and a hazard to quarry workers from large masses of falling ice.

The ice forms chiefly from water that seeps through cracks in the wall rock near the brink of the quarries. The ice coats virtually every surface in the quarries, the sloping floor becomes slippery and footing is uncertain, cables of various kinds are pulled from the walls by the weight of accumulated ice, and large masses of ice sometimes weighing several hundred pounds form on the quarry walls (figs. 16-18). These ice stalactites are scaled, shattered with shotgun slugs, or sometimes dynamited to avert the danger of their becoming dislodged and falling onto the quarry floor, particularly during the early spring thaw. Since slate dumps and the glacial overburden together constitute aquifers with a sizable storage capacity and since they have been removed to only a few yards from the quarry brinks, water diversion is not easily accomplished. At one quarry, three shallow dewatering wells are located on the side of the quarry and downslope from some large slate dumps. These wells, however, divert only a small portion of the ground water reaching the upper levels of the pit, and ice accumulation in the winter continues to be a severe problem.

Ice control or prevention methods that have been suggested for evaluation include grouting of the quarry walls to reduce seepage, drainage drill holes, the use of a wax emulsion coating on the rock walls to prevent the adherence of ice, and suspended movable chains to break up accumulations of ice at critical areas. To date, only one of these methods, wax emulsion, has been assessed by the Bureau. The wax emulsion failed to substantially reduce ice adhesion in preliminary laboratory tests. Another method, grouting of quarry walls to reduce seepage, could have the adverse effect of increasing to an excessive level the hydraulic head in a water-filled joint or fault. At the present time, ice buildup during the winter continues to be a serious problem.

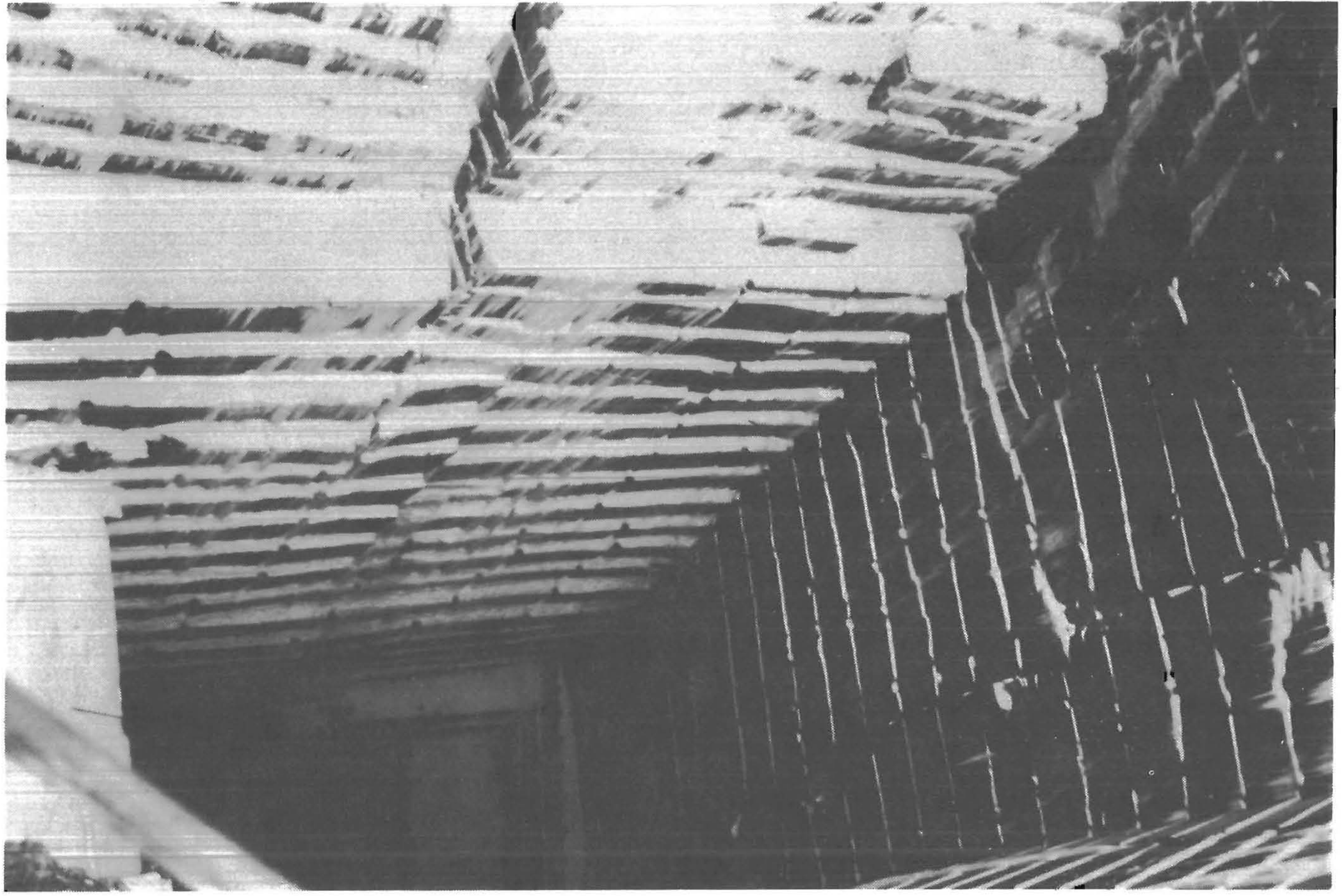


FIGURE 16. - Early stages of ice formation on quarry highwall.

HIGH STRESSES

The closure of 1/4-in vertical rock saw slots and the occurrence of pressure breaks (fig. 19) in the floor of several active Pen Argyl quarries are indications of high horizontal stresses. While slot closures can be controlled by wedging and seldom occur near benches, stresses increasing with depth of operations could lead to severe buckles or failure of highwalls and barrier pillars As used here, "buckles" (popups) describe the heave of flat-lying strata or rock with a pronounced horizontal cleavage, ascribed to load removal from rocks under high horizontal stress. Quarry buckles in Ontario have been described by Adams (34) and Coates (35). Smith (36) and Sbar and Sykes (37) mention buckles at several quarries in upstate New York. These buckles are not entirely unlike the prehistoric stress relief phenomena that occurred because of the unloading of valley floors in the Appalachian plateaus described by Ferguson (38-39).

Adams (34), using quarry and buckle dimensions and an adopted value for Young's modulus, estimated that the upper limit of the maximum compressive stress in the McFarland Quarry, Ottowa, Canada, ranges from 1,400 to 4,300 psi (10 to 30 MPa) for the limestone floor after removal of 45 ft of overburden.

Although no buckles were reported, Anderson, Arthur, and Powell (40) conducted measurements of in situ stresses in a tunnel complex being excavated in the main Cambrian slate belt of Dinorwic, Wales, because of the relevance of stresses on the stability of excavations. The results showed a considerable degree of scatter but indicated that the major principal stress of 2,500 psi (17.5 MPa) was about double the vertical or overburden stress and normal to cleavage, which dips 70° southeastward.

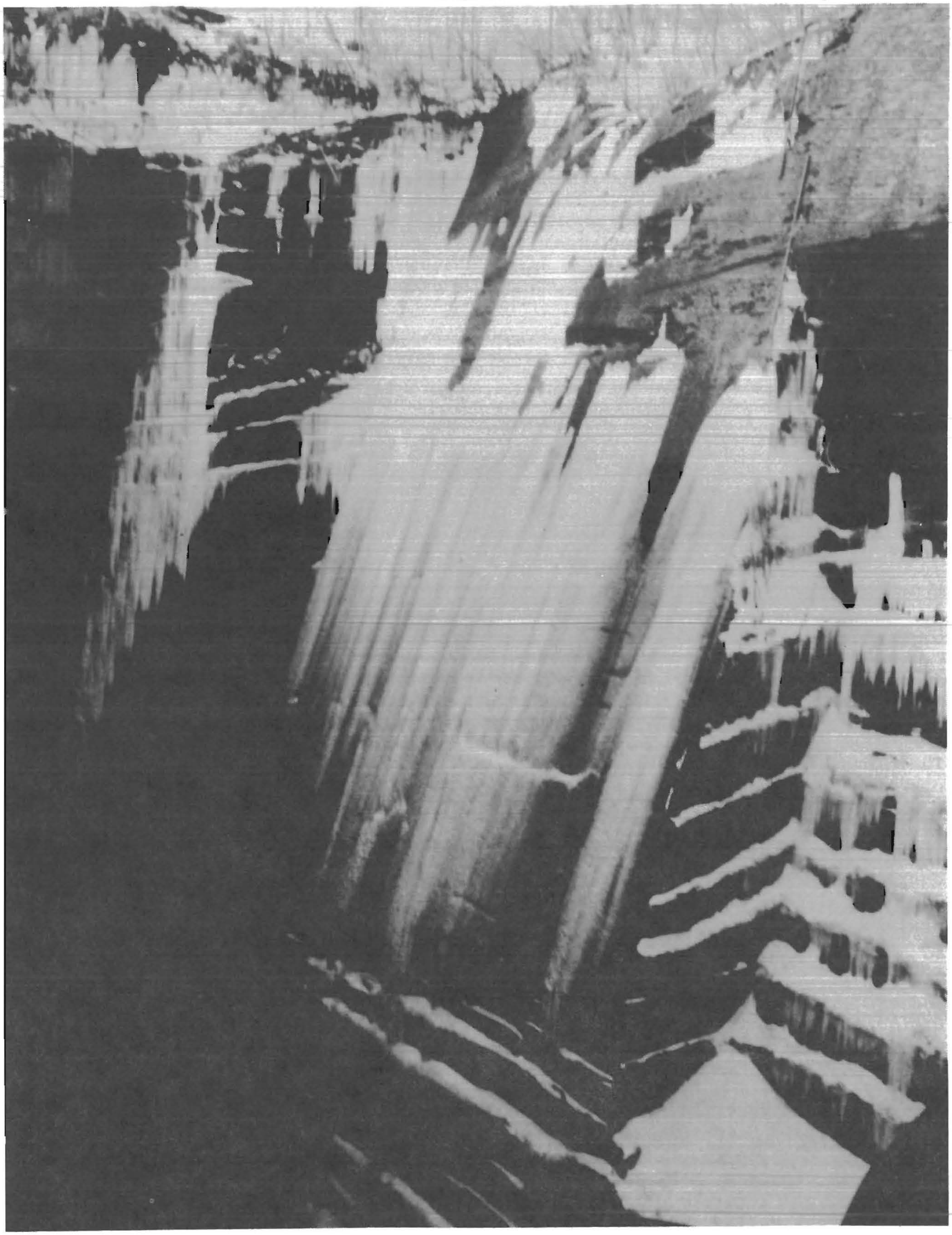


FIGURE 17. - Advanced ice buildup on upper levels of quarry highwall.

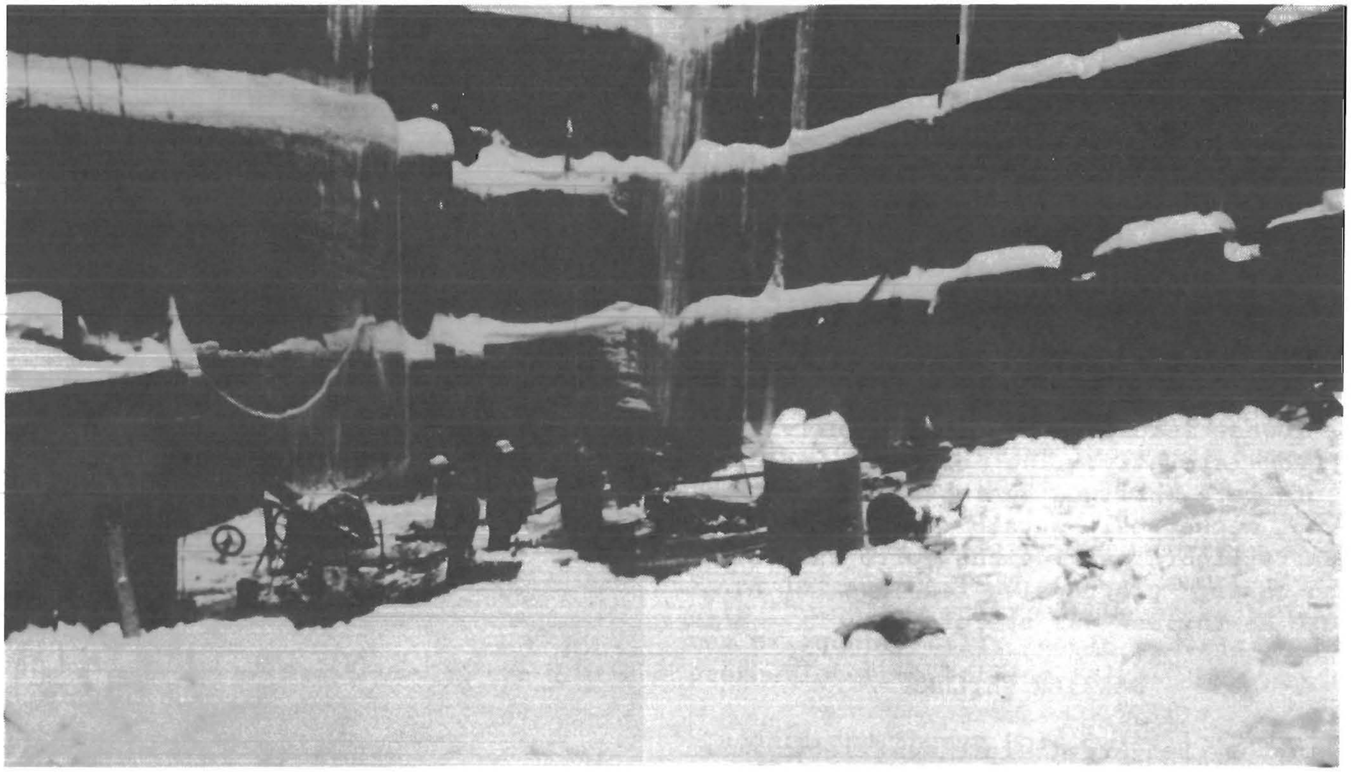


FIGURE 18. - Winter conditions in quarry bottom.

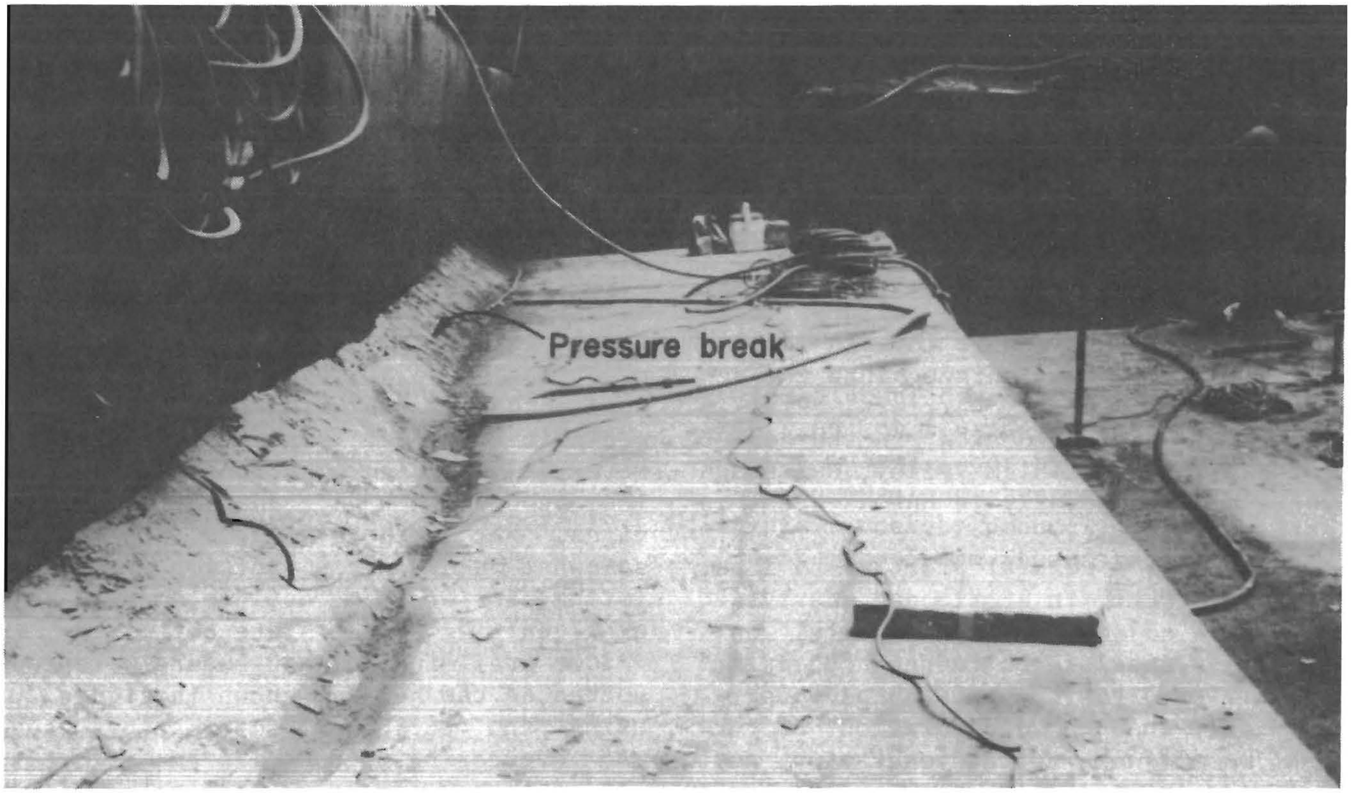


FIGURE 19. - Pressure break across cleavage plane caused by lateral thrust of highwall against bench.

Measurements of rock saw slot closures were attempted at a Pen Argyl quarry for the purpose of estimating stresses and evaluating their role in floor and highwall stability. The maximum slot closure measured was only 0.035 in. This value represents only a small portion of the usual 0.25-in slot closure in the first slot cut, because of interference from nearby wedges in the slot and an existing parallel slot about 72 ft away. Furthermore, the quarry is operated on successive benching levels, and even the sink, or lowest level, is not always fully confined laterally. The closure measurements were obtained by installing a dial-type mechanical strain gauge on the quarry floor astride the wire saw slot and taking progressive readings of closure as the saw was operated.

BARRIER FAILURE

In the Pen Argyl slate district, some active quarries have been developed adjacent to abandoned flooded quarries, from which they are separated by a barrier pillar (fig. 20). Some guidelines for designing coal mine barrier pillars have been available for many years, but they would not be satisfactory for other types of deposits. Existing slate quarry barriers probably were designed on an empirical basis and for limited development only. These should be subject to minute inspection as to adequate size, strength, stress conditions, and geologic defects that could lead to failure. Barrier failure could result in both massive rock falls and water surges into the active quarry. Similar barriers exist in limestone quarries located in the cement district of the Lehigh Valley, although quarry depth generally is not as great as in the slate belt.

While it is a general practice to lower the water level in a flooded quarry to that of an adjacent active quarry, it is not always feasible to inspect an existing barrier from the abandoned quarry, especially when an accumulation of rubbish, metal junk, rotten vegetation, mud, and broken rock obscure the barrier face. Thus, the integrity of the barrier, and even the actual thickness, may be in doubt and should be a serious concern as the depth of operations increases and the barrier is subject to growing pressures from abutments and possible impounded water.

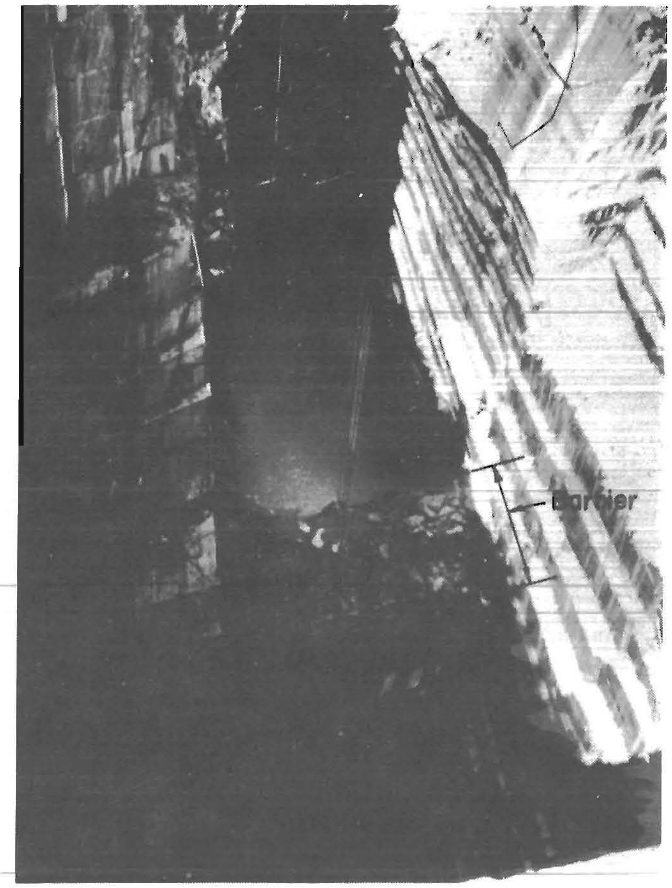


FIGURE 20. - Barrier separating flooded from active quarry.

The integrity of an existing barrier can be explored using many available methods, including core drilling, geologic mapping, stress measurements, referral to design equations, or geophysical probes such as radar or sonic devices. All of these methods are limited somewhat when only a portion of the existing barrier is accessible, as in several quarries of the slate belt.

Some preliminary measurements were conducted on the barrier shown in figure 20, using the borehole deformation gauge and overcoring method, in an effort to estimate the developed stress conditions in the vicinity of the barrier abutment.

Results are discussed in the section "Stress Measurements."

EQUIPMENT

The hazards inherent in working around moving equipment, heavy objects, compressed air, and overhead activity are nearly always present in a quarry operation. Federal safety regulations pertaining to open pit mines such as slate quarries are authorized by the Federal Mine Safety and Health Amendment Act of 1977 and are described in the U.S. Code of Federal Regulations, Title 30, Part 55 (41). Virtually every aspect of extraction and ground control in a slate quarry is interrelated with equipment usage.

Most equipment currently used in slate quarries in the eastern United States was developed during the first half of this century and is suited to old and well-entrenched extraction procedures. It is commonly agreed that equipment modernization would vastly increase the efficiency of slate extraction and could have a major impact on safety but would require capital expenditure beyond the financial capability of a small industry in which future market trends are indeterminate. Nonetheless, some suggestions for equipment updating are outlined below, along with related modifications in quarry design and operations that might result.

Wire Saw

The drive for the wire saw currently in use is located near the quarry brink, necessitating excess wire length, several pulley arrangements, and the exposure of workers to moving wire under load. This situation could be corrected by moving the wire driving and tensioning mechanism onto the quarry floor and incorporating the components into a more or less self-contained sawing unit. A modification of the standards and sheaves used to direct the wire into cutting slots would be necessary. Any advantages in reducing the length of exposed wire, however, might be lost by the added cost of increased wear on the wire.

An alternative to the above, but one requiring an entirely new design, would be the use of a track-mounted diamond saw, a reciprocating abrasive cutter bar, or a rock chain saw--ideas that have been proposed but not developed specifically for slate. These devices could have self-contained electric or pneumatic power units or could be powered by a separate hydraulic unit.

Any design for a rock-sawing device that would depart radically from those in use might necessitate a somewhat greater offset at the quarry wall on each bench cut in order to provide adequate operating space. This would entail a larger quarry dimension at the surface to provide for a diminishing width further down where the cut could not be made flush with the quarry walls; however, a benching of quarry walls would provide some protection from falling rock.

Standard and Sheave Hole Drill

The electric-powered drills currently in use for coring a 3-ft-diameter hole in which to place the standard and sheave for directing the wire rope for slot cutting are heavy, cumbersome, and difficult to move. It has been suggested that a hydraulic-powered unit would be lighter in weight and easier to move and control, especially if the standard and sheave could be reduced in size so that only an 18- or 24-in-diameter borehole would have to be drilled.

Splitting Wedges

Large blocks of slate that have been sawed free on four sides are separated from the quarry floor by manually driving steel wedges along the nearly horizontal cleavage, thereby producing thick slabs of slate that are then raised to the surface on an aerial tram. Sometimes, shallow, small-diameter holes are first drilled along cleavage to facilitate splitting. A small-diameter tubular hydraulic splitter, activated by a hand pump, has been developed recently, which can be inserted into a shallow drill hole to further facilitate splitting; a few strokes of the pump will free the slab, without the rigorous use of sledgehammers and wedges.

GEOLOGIC STUDIES FOR HAZARD DETECTION

MAPPING

Geologic mapping in the vicinity of the Pen Argyl slate quarries is severely limited by a lack of outcrop, owing to a cover of slate waste piles and glacial moraine. Furthermore, structure is complicated by intense folding so that great care must be exercised in projecting individual structures beyond the exposures in quarry walls. Thus, any effort to map geologic features that might contribute to large falls of rock or collapse of a quarry highwall is usually limited to quarry exposures. Figure 15 illustrates the collapse of a quarry highwall that was attributed to an intersection of at least two planar geologic discontinuities, a weathered bedding slip fault and a transverse joint. The bedding slip fault is an easily recognized feature, but the transverse joint is obscured by weathering and mud, and other factors are suspected of contributing to the highwall failure.

Similar collapses, resulting in fatalities, have occurred in two other quarries where a highwall failure was attributed to geologic structures that weakened the integrity of the wall; such failures indicate the need to recognize, map, and fully assess the effects of geologic discontinuities on highwall stability.

During this investigation, geologic mapping of the trends and character of major structures in several selected quarries was conducted, in an attempt to determine the practicality of locating potentially unstable conditions on the quarry walls. These sites, if successfully identified, could receive special surveillance, instrument monitoring, or remedial measures, in order to provide advance warning or to prevent the occurrence of major falls of rock. However, falls of small rock slabs or fragments that gradually become loosened from the quarry walls require a regular regimen of scaling and are outside the scope of this report.

Figure 21 illustrates the general layout of a group of active quarries in the Pen Argyl district, where geologic mapping of exposed quarry structures was conducted to locate some prominent bedding plane faults, which contribute to the instability of quarry highwalls. These faults were targeted for further study, either by instrument monitoring of strain or by the use of resistivity to detect the extension of the fault beyond the quarry brink. Figure 22 is a transverse profile of the structure in a selected quarry, which illustrates the usually complex relation of cleavage, bedding, and faults. The mapping of bedding slip faults, cause of most large rock falls, was a high priority but was somewhat limited by the virtual inaccessibility of the quarry walls and the lack of outcrop beyond the quarry brink. Nonetheless, most major bedding slip faults were weathered at shallow depths and, therefore, could be identified as loci of potential highwall instability. Figure 11 shows the weathered character of one of the more obvious faults, although some faults showed virtually no evidence of weathering and could be detected (with difficulty) only because of the presence of gash veins, drag, or slickensides.

This brief discussion of geologic mapping demonstrates that the most common cause of highwall failure in the Pen Argyl district, the bedding slip fault, is a mappable feature, especially when weathered. The bedding slip fault therefore provides a target for ground control measures, surveillance, or warning systems based on the detection of incipient movement as described in the section "Strain Gauge Instrumentation." While quarries are usually aware of the hazards of bedding slip faults during development, once these structures are penetrated and exposed in the upper inaccessible portions of a quarry (fig. 23), their presence is easily forgotten; then

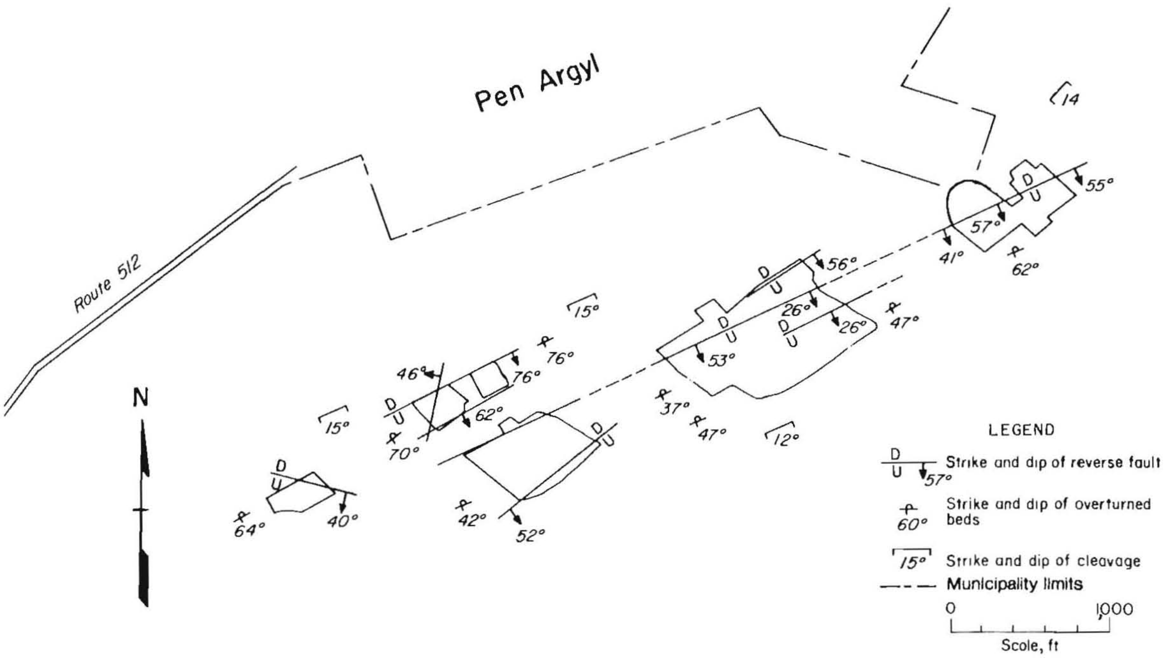


FIGURE 21. - Layout of some active quarries in the Pen Argyl slate district show trend of faulting.

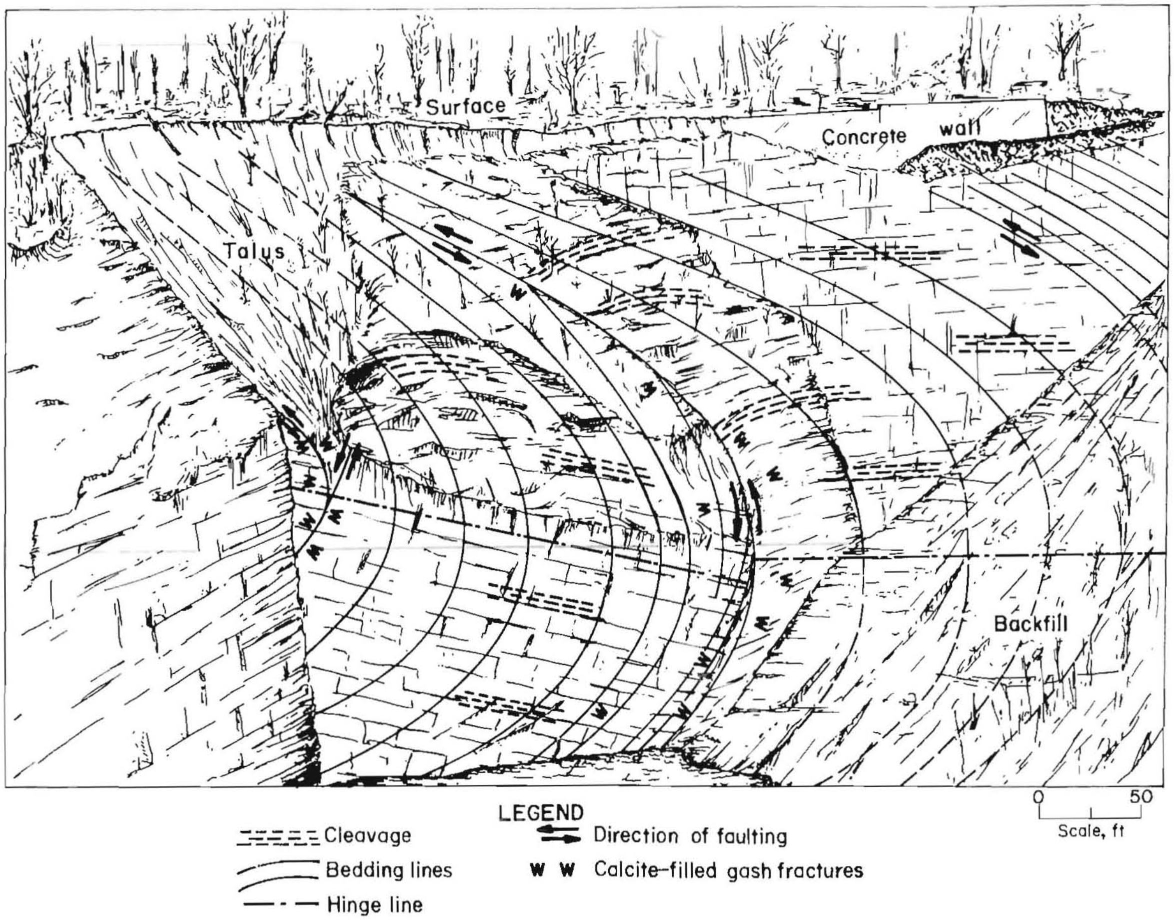


FIGURE 22. - Profile of quarry highwall showing complex geologic structures.

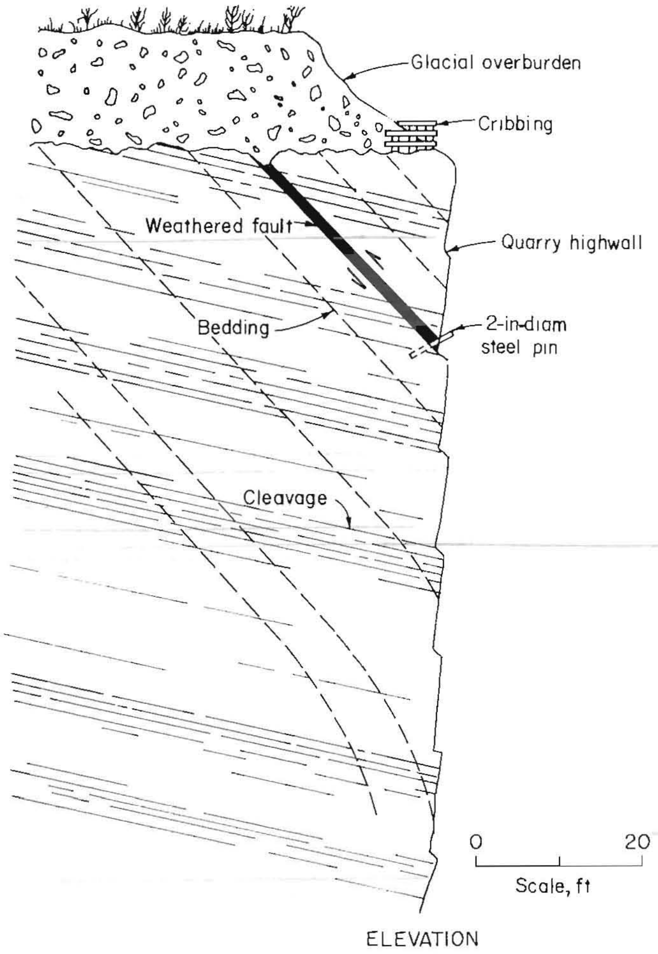


FIGURE 23. - Sketch showing bedding slip fault near brink of quarry.

some method for monitoring the stability of the faulted area is essential.

RESISTIVITY

The use of resistivity traverse measurements to detect fault traces has been tested and found successful in various geological settings [Stahl (42-44), Hubbert and Weller (45), Lee and Hemberger (46).] In Pennsylvania slate quarries, weathered bedding plane faults are a major cause of catastrophic highwall failure; therefore, the use of resistivity traverses to detect concealed faults was explored in that geologic setting. The ability to detect concealed faults with resistivity could promote safer future quarry development.

A study site with minimal surface disturbance between two existing quarries was selected for testing the ability of shallow resistivity equipment to detect bedding plane faults (fig. 24). Three target faults exposed in a quarry's northeast wall (fig. 22) were projected along strike into the study area. The equipment used consisted of a resistivity meter with a power output into the earth of 24 W in short bursts, to attain a depth penetration of 100 ft or less. The Wenner configuration [Wenner (47), Telford (48)], in which four electrodes are arranged in a line at equal distances apart (designated as the A-space), was used for all sounding and traverses in this study.

Resistivity Soundings

Resistivity soundings were conducted to determine an appropriate depth for running the traverse line. Glacial deposits of unsorted sand, silt, and gravel with some associated boulders seldom exceed 15 ft in thickness in the Pen Argyl area but can vary considerably. Therefore, it was necessary to conduct depth soundings to determine an appropriate electrode spacing for traversing. An electrode spacing too large can mask the presence of faults, while an electrode spacing too small may not penetrate the glacial cover and reach the target depth.

The empirical cumulative resistivity plot [Moore (49-50), Mooney (51)] and actual value plot [Telford (48), Mooney (51)] using both logarithmic and linear axes were used for interpretation during this study. These two methods, while not the most widely accepted for accuracy among experts, are the easiest interpretative plots.

The cumulative and actual value plots can give adequate depth determinations without excessive interpretative time when the user has a good understanding of the local geology [Telford (48), Mooney (51)]. Examination of published geologic information on the Pen Argyl area and direct observation established the presence of glacial cover, and discussions with the quarry operator and examination of existing quarries indicated a decreasingly weathered zone of slate extending

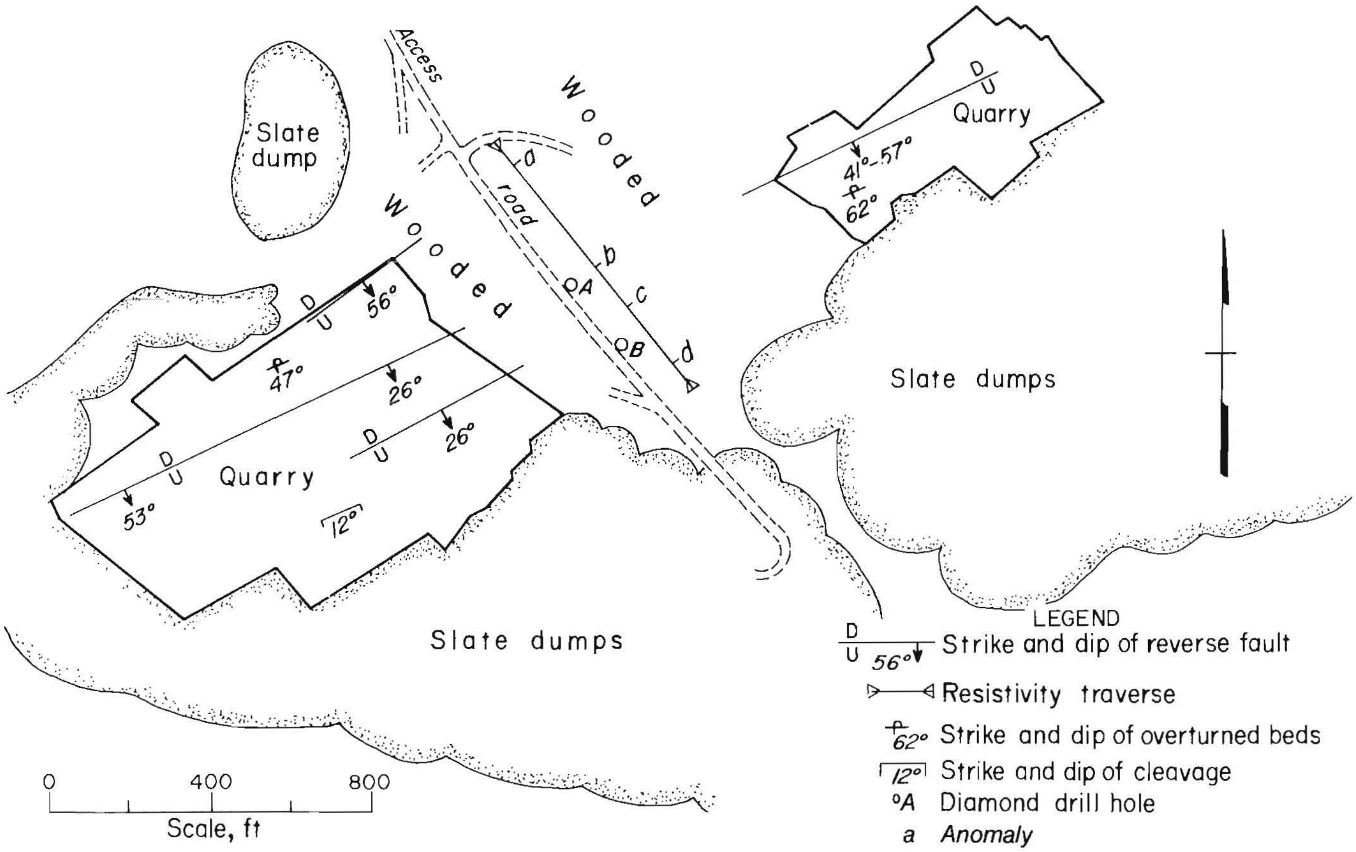


FIGURE 24. - Location of resistivity traverse between two active quarries.

from the glacial mix and slate contact to a thickness of 20 to 30 ft in most areas.

Figure 25 shows two sounding curves from the study area, with both cumulative and actual value plots of the data along linear axes. Figure 26 presents the actual value data plotted equally spaced on double log scales. The soundings were only of limited success in determining accurately the depth of weathered bedrock; however, reasonably accurate estimations of depth of glacial cover were obtained. The cumulative curve in figure 25 breaks at approximately 10 ft and 29 ft. The actual value curve in figure 25 breaks at approximately 8 ft and 51 ft. The double log plot of actual values in figure 26 breaks at approximately 8 ft and 45 ft. Correlation among the three curves for depth of glacial cover (indicated by the first break) is fairly good: 8, 8, and 10 ft. However, a wide variation exists in the second break: 29, 45, and 51 ft. This variation among the three methods of plotting may indicate the lack of a well-defined interface between weathered and unweathered slate. The three curves may be emphasizing different levels of weathering within the gradually changing slate.

Since the target faults should be detectable within the weathered slate zone, a clear determination of its thickness was unnecessary. Probing beneath the glacial cover was the only required certainty. With soundings indicating a maximum 10 ft of glacial cover, an electrode spacing (A-spacing) of two times the target depth, 20 ft, was chosen for traversing.

Resistivity Traverses

After the soundings were completed, a traverse line through the study area was laid out. The three projected faults fell within the traverse line (fig. 24). The traverse was begun from the north and ran S. 40° E., parallel to the road, using a 20-ft A-space and 10-ft steps. The results of the traverse measurements are shown in figure 27.

Four anomalous peaks or depressions are evident at points *a*, *b*, *c*, and *d*. When placed on profile (fig. 28), the fault projections-traverse line intersections and anomaly locations indicate a strong correlation. The fourth anomaly point, *d*, falls outside the visible quarry boundry in figure 28 but also indicates a buried fault trace.

Structure in the traverse area and possible fault zones indicated by corehole data also correlate with the resistivity anomaly locations. Corehole *A* appears slightly misplaced, causing an absence of evidence for fault presence at anomaly *b*. However, evidence that the bottom of corehole *A* approaches the approximate location of the anomaly *a* fault is indicated by the presence of massive spar and disruption of the slate near the bottom of hole *A*. The calcite spar associated with the anomaly *a* fault projection can be seen in figure 22, a sketch of the quarry's northeast wall.

Faults indicated by resistivity anomalies at points *b* and *c* are supported by corehole *B*. In corehole *B*, anomaly *c* is indicated by a sheared, chloritized zone separating highly ribboned, siliceous slate from normal slate. Presence of a fault at anomaly *b* is supported by the presence of spar in hole *B* approximately 160 ft below the surface. A projection of spar occurrence to the surface along bedding intersects both the resistivity anomaly point *b* and the fault projection on the map view.

All the available evidence in this study indicates that resistivity is an effective method of detecting bedding faults in the Pennsylvania slate belt. The use of resistivity traversing to detect faults yielded more promising results with less difficulty in interpretation than did sounding curve interpretations in determining layering. Strong correlation among fault projections, corehole data, and resistivity anomaly locations support this conclusion. However, interpretation of both the resistivity and corehole data was greatly enhanced by the outcrop information available in adjacent quarries. In areas of more restricted outcrop information, resistivity interpretation may be more difficult, but when pronounced anomalies are found, similar to those in figure 27,

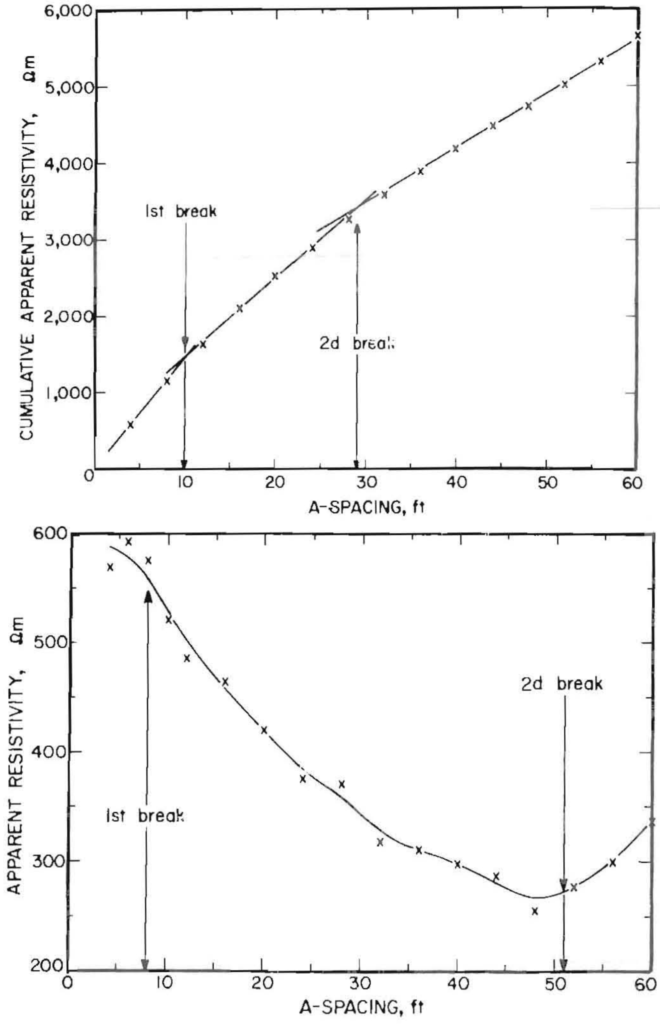


FIGURE 25. - Resistivity sounding curve, cumulative plot (top) and linear plot (bottom).

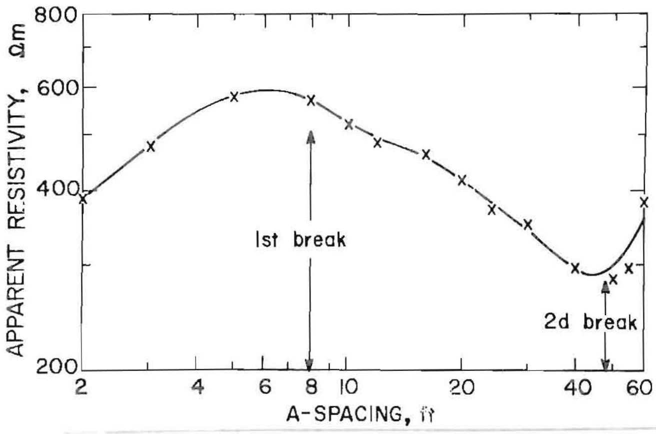


FIGURE 26. - Resistivity sounding curve, double log plot.

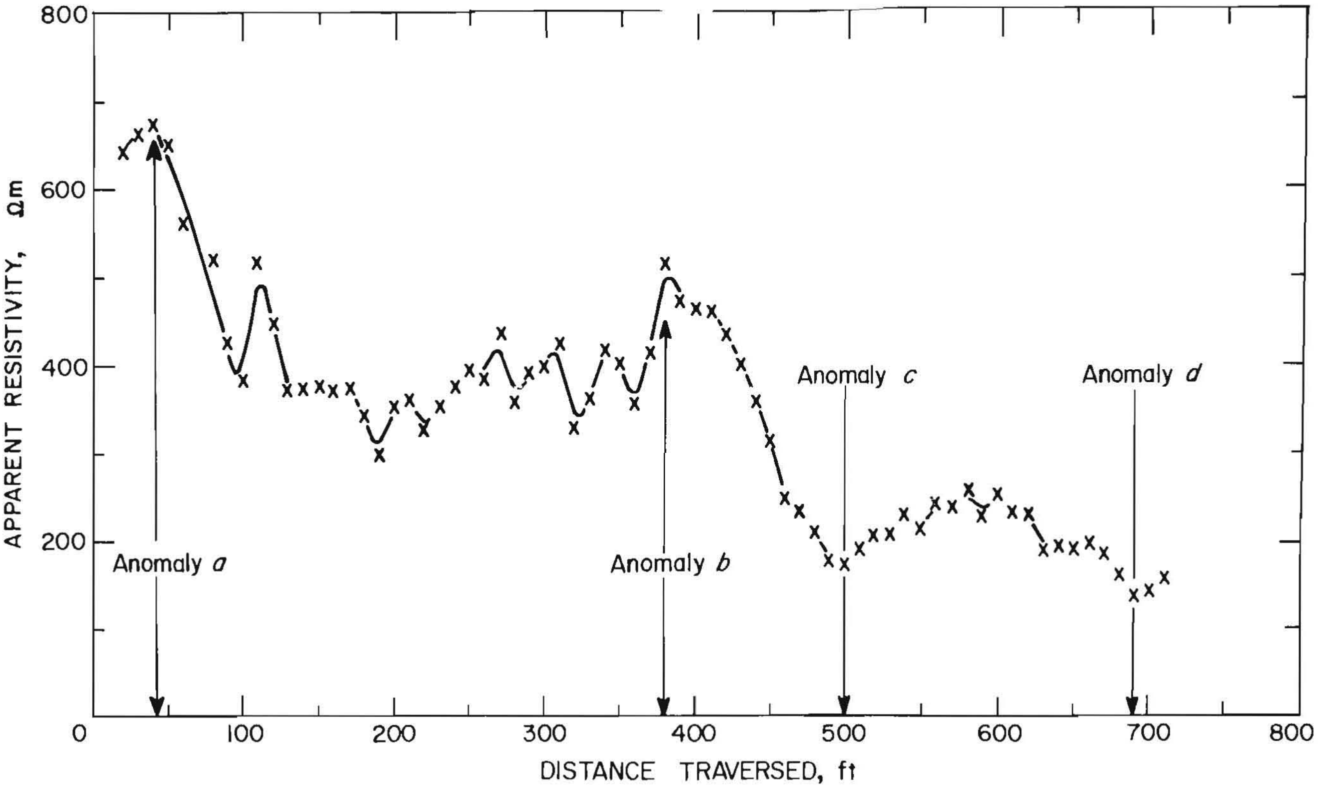


FIGURE 27. - Apparent resistivity traverse plot.

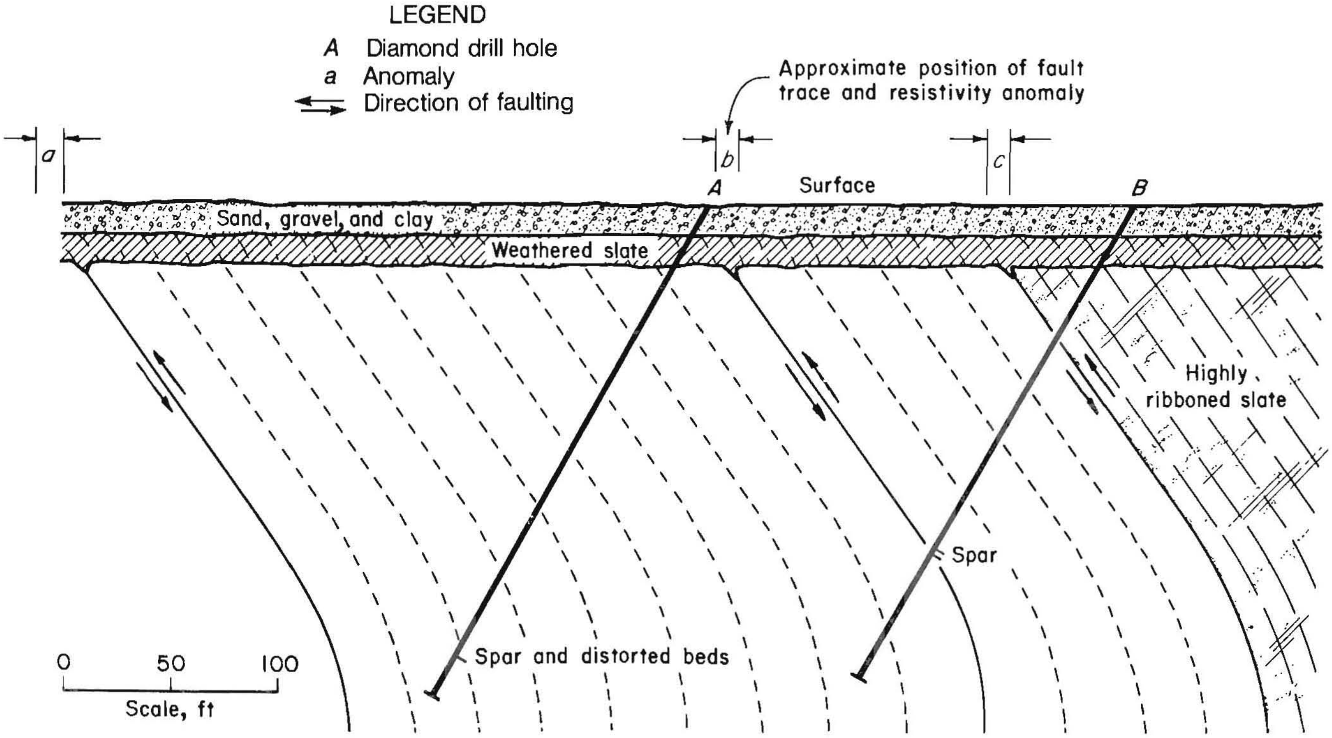


FIGURE 28. - Profile showing relation of resistivity anomalies to buried fault traces.

fault presence should be suspected and investigated further.

CORE DRILLING

Core drilling is virtually the only practical method of directly obtaining subsurface information and samples of bedrock for study purposes. According to Behre (14), "Core drilling is the only method by which the slate operator, no matter how experienced, may assure himself of the favorableness of stratigraphic and structural conditions before opening." In the Slatington district, about 22 miles southwest of Pen Argyl, where close folding makes the subsurface structure very irregular, core drilling is more generally practiced than elsewhere in the Pennsylvania slate district. Drilling also gives an indication of the thickness of unconsolidated material and weathered and stained bedrock that must be removed before commercial-quality slate can be recovered. The sampling area of drill core is very small, about 3 in^2, and critical geologic structures nearby can be entirely missed in drilling. Sometimes, minor features observed in the core can be extrapolated to extend coverage by inference, or the results of resistivity traverses and soundings can be used both to site drill holes in the optimum location and to provide indirect information on the subsurface between drill holes.

The core drilling equipment used in this study consisted of a skid-mounted rig capable of drilling both vertical and angle holes. The 2-in-diam core was adequate in size for detecting geologic structures and slate quality. The only drilling problem encountered was due to hole collapse while an attempt was being made to set casing through unconsolidated glacial material and into bedrock.

For the purposes of the current study, core drilling information was used to locate weathered fractures and bedding plane faults, which severely weaken quarry highwalls, and to confirm the effectiveness of the surface resistivity surveys. The bedding plane faults are easily detected in drill core when they are heavily weathered or filled with spar, but some problems were encountered in trying to orientate the core if it turned in pulling. Figure 28 illustrates the probable structure in the vicinity of the cored drill holes. The bedding plane faults located in drill hole *B* occur nearly along strike of faults exposed in a nearby quarry and probably would be troublesome during expansion of the existing quarry.

Behre (14) discusses the manner in which geologic work, and in particular core drilling, can be used to control the opening and operation of a slate quarry. This work has almost always been concerned only with identifying and following high-quality beds and avoiding heavily ribboned rock. In the future, core drilling should also be used to assess the competence of wall rock in a proposed quarry site, as a more scientific approach to ground control is essential in sound quarry valuation. Roberston (52) also stresses the importance of adequate core drilling to define the geologic parameters necessary for quarry planning and equipment selection.

STRESS MEASUREMENTS

The magnitude and direction of the secondary principal stresses present in the highwalls and floor of a quarry in the study site were determined using the Bureau's borehole deformation gauge [Hooker, Aggson, and Bickel (53), Merrill and Peterson (54), Merrill (55)]. The quarry was adjacent to abandoned workings approximately 540 ft below the surface. The stress values measured at various times in the quarry were consistent but were of a much lower magnitude horizontally than might be expected in this region, based on current literature [Sbar and Sykes (37), Hooker (56)].

Figure 29 shows the measurements obtained at depths of about 24 in beneath exposed quarry surfaces. Theoretical values calculated for expected vertical and horizontal stress in gravity-loaded rock strata are 550 and 103 psi, respectively. Stress values determined by overcoring measurements, as shown in figure 29, are all well above the theoretical values: an average maximum 1,203 psi

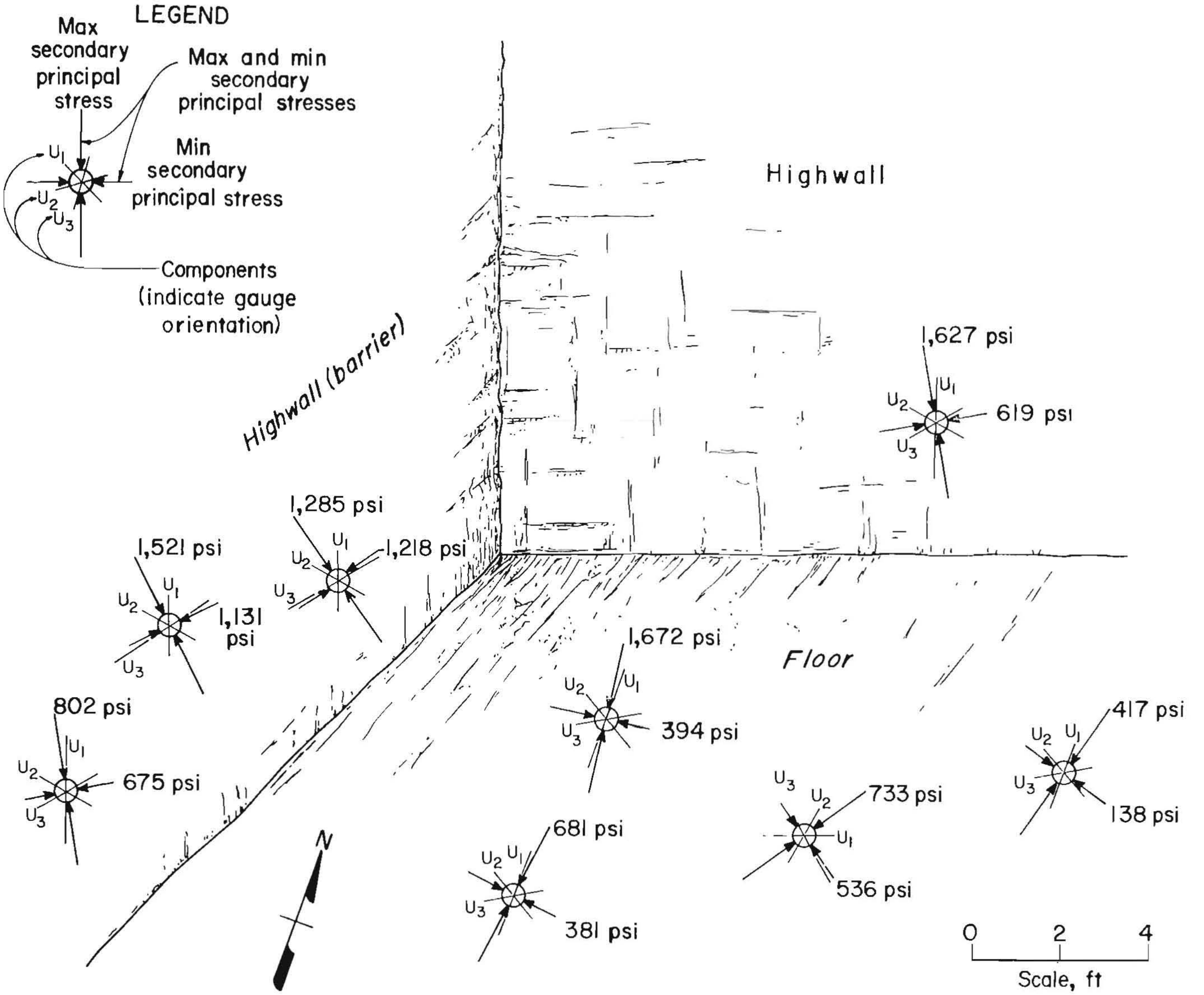


FIGURE 29. - Diagram of quarry stresses.

and minimum 1,008 psi, in the barrier highwall; an average maximum 1,627 psi and minimum 619 psi, in the quarry highwall; and an average maximum 876 psi and minimum 362 psi, in the floor. All these measured stress values are compressive.

While there are no comparable values in the literature for vertical stress measurements in this vicinity, horizontal stresses have been measured. Sbar and Sykes (37) and Hooker and Johnson (56-57) note generally high horizontal stresses in this area. The measured average maximum horizontal stress in this quarry is not excessive (876 psi), but it does indicate pressure influence other than gravity. The highwall maximum stress in a nearly vertical direction is generally higher than the horizontal maximum stress in the floor.

The stress measurements are affected by their proximity to the corner of the quarry. As the measurement points move outward from the corner in the floor and in the barrier highwall, the stresses tend to decrease in magnitude and change slightly in orientation. The compressive strength of the slate, 17,200 psi parallel to cleavage and 24,700 psi perpendicular to cleavage, indicates that in the absence of any weakening geologic structures (i.e., faults, joints, fractures) the slate should not be approaching stress-induced failure.

STRAIN GAUGE INSTRUMENTATION

An electromagnetic strain gauge system was tested as an early warning device for hazardous highwall conditions (i.e., joints, fractures, faults) by detecting incipient movement. The strain gauge system is capable of detecting small changes in spacing between adjacent sensor pairs mounted securely on opposite sides of a suspected plane of weakness. Strain sensor pairs were installed in three active quarries (shown in figure 21) to evaluate their monitoring capabilities under varying geologic and weather exposure conditions.

The first pair was installed on either side of a fault diagonally cutting the top edge of a free-standing highwall. A second pair was installed on a highwall and a subparallel slab separated from the highwall by a joint. The third pair was installed above and below a fracture that created on overhanging wedge on a bench above the quarry floor. All of the sensors were secured to the slate surfaces with specially designed acrylic brackets to maintain the most sensitive parallel sensor position. The gauges were wired with coaxial cable to easily accessible areas for either continuous monitoring with strip chart recorders or occasional direct manual readings.

Experience with the strain gauge monitoring system quickly showed that the effects of weather on installations and wiring would be difficult to control or prevent. Operation during summer months was quite satisfactory. However, the onset of fall and winter months presented many problems. High winds on exposed quarry faces continually flexed the coaxial cables, creating breakages and affecting the small electric current flow from sensors through the cable and connections to the recorder, often creating spurious fluctuations in the output. Ice accumulations in winter often overcame the strength of both the cable and connections, resulting in breakages and the loss of much important winter data.

The use of strain gauges to monitor highwall discontinuities that might pose a hazard to workers should not be discounted because of the problems encountered during this study. Improved installations and active involvement by actual quarry operators in maintaining a monitoring system and collecting data may alleviate some of the above difficulties. The use of conduit to protect instrument wiring and frequent inspection of the installation by operating personnel should contribute to more trouble-free monitoring.

During periods of accurate data collection, no discernible rock movement was detected. Two of the sensors mounted in full southern exposures exhibited diurnal fluctuations during continuous recording. The gauge spacings fluctuated ±0.008 in from the baseline in 24-h periods, giving an indication of gauge sensitivity. Changes on the order of 0.125 to 0.25 in were determined to indicate real movement. No actual occurrence of this magnitude was detected at any of the three stations.

ROCK BOLTING TESTING

The practice of using bolts to secure rock that is weak or may become dislodged is commonplace in underground mines and some open pits but virtually unknown in slate quarrying. Instead, loose slabs in quarry highwalls that cannot be scaled are supported by steel pins inserted into downward-sloping holes drilled in the highwall (fig. 30).

In contrast to pinning, a rockbolt is anchored, either by a mechanical wedge-like expansion shell attachment on one end (figs. 31-32) or a resin grout. The mechanical bolt is placed in tension, as are some versions of the resin-anchored bolt, thus exerting a positive stabilizing force against the rock surface, whereas the pin is merely a passive form of support largely resisting the shearing force of gravity in a highwall.

Because of the extremely limited experience with rock bolting in the slate belt, several tests were conducted in a Pen Argyl quarry to determine the anchorage capacity and tension bleedoff of both mechanical and resin-anchored rockbolts. The results demonstrated that in slate rockbolts of both types have a high anchorage capacity.

All bolts were tested in a quarry highwall where cleavage is nearly horizontal and the bedding steeply dipping. The bolts were installed horizontally and perpendicular to bedding. After the bolts were installed, tension was applied using a pulling collar and hydraulic ram. Tension was measured both with an electronic transducer and compatible indicator and with a calibrated pressure gauge on the hydraulic ram. Strain or bolthead displacement was measured directly with a mechanical dial strain gauge. The setup for these procedures is illustrated in figures 33 and 34.

The mechanical bolts were 48 in long, 5/8 in. in diameter, with a bail-type four-leaf expansion shell, and were installed in a 1-3/8-in-diameter hole. The resin-anchored bolts consisted of rebar, 48 in long, 3/4 in. in diameter, anchored with 24 in of resin, and were installed in a 1-in-diameter hole. The head of the resin-anchored bolt consisted of a shear pin nut by which the rebar could be

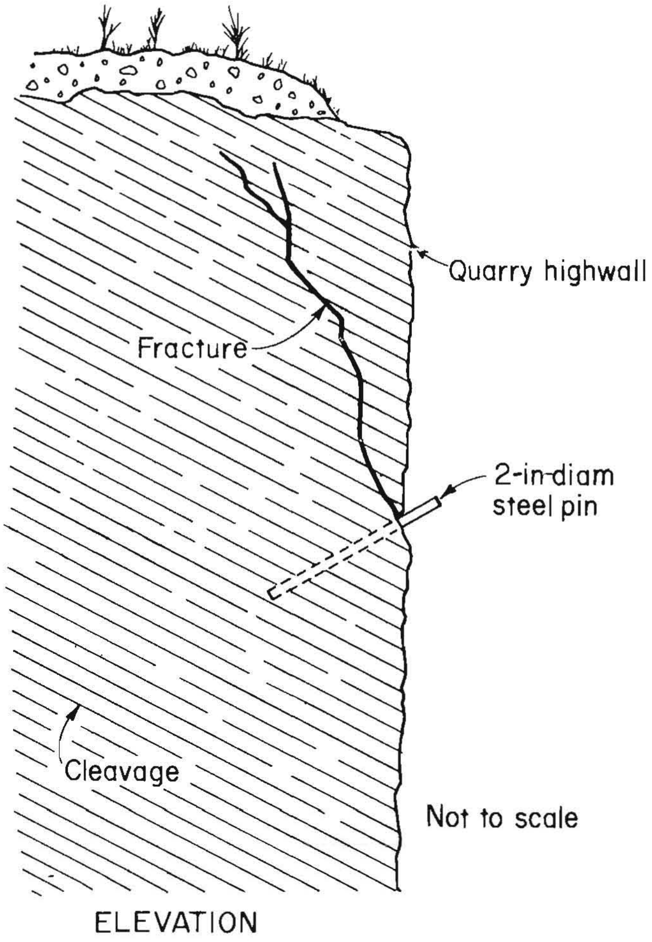


FIGURE 30. - Common method of securing fractured rock on quarry highwall with steel pins.

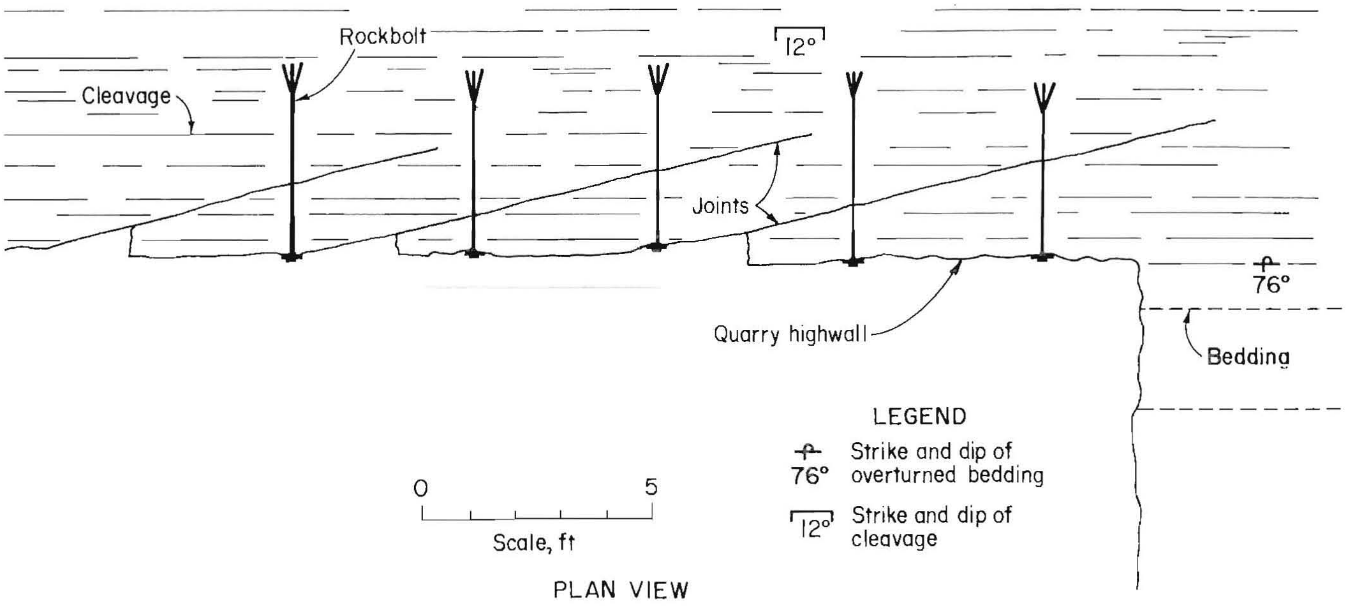


FIGURE 31. - Use of anchored mechanical bolts in tension to secure jointed rock.

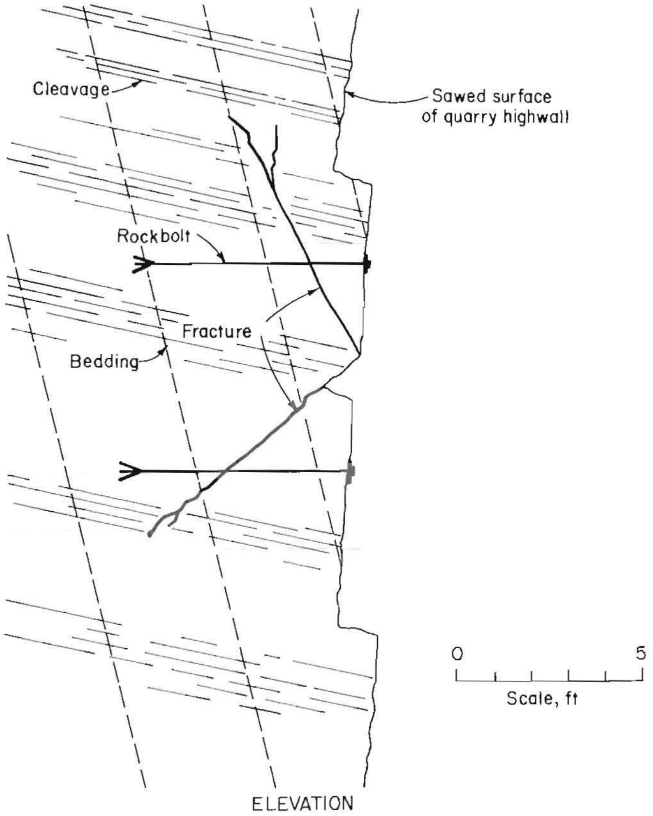


FIGURE 32. - Use of anchored mechanical bolts in tension to secure fractured rock in quarry highwall.

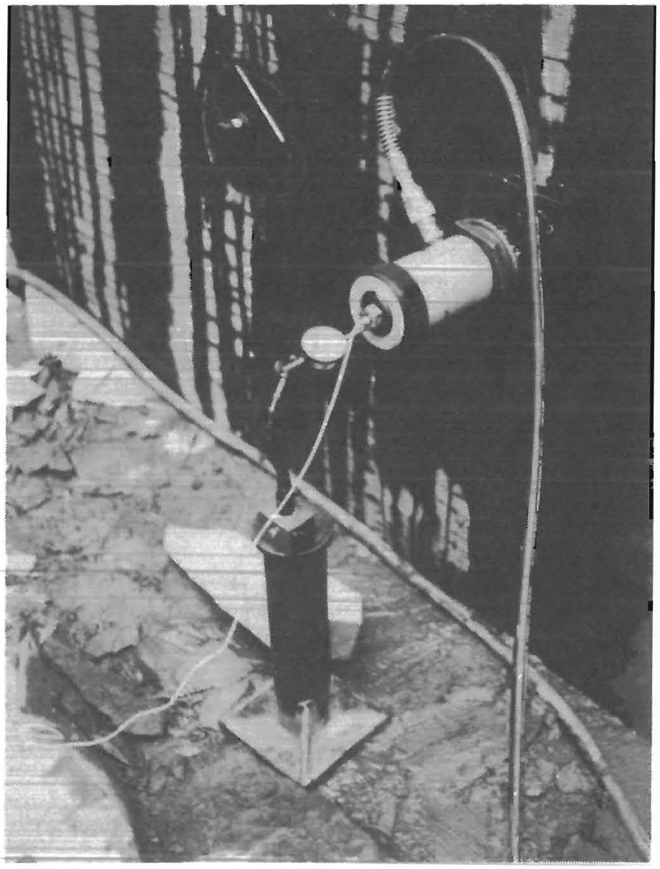


FIGURE 33. - Setup for rockbolt pull test.

rotated to mix the resin; after hardening of the resin, the nut could be rotated further to shear the pin, tighten the nut, and put the rebar in tension.

For the pull test, after each bolt was pretensioned to a 1,000-lb load with a hand torque wrench, the load on the hydraulic ram was increased in 1,000-lb increments, while the bolthead displacement was recorded at each increment until the anchorage capacity was exceeded.

Four representative load-displacement curves for the mechanical bolts tested are illustrated in figure 35; the distinctive portions of a curve are labeled on the top-left panel. Anchorage capacity ranged from 14,500 to 16,600 lb. Displacement ranged from 0.019 to 0.025 in per 1,000-lb load.

Tension bleedoff on four mechanical bolts is shown in figure 36, which indicates that losses of 700 to 2,000 lb tension occurred within 24 h after installation and additional losses of 300 to 900 lb occurred over the following 36 days. About 6 weeks later, hole 3 showed an unexplained increase in tension of about 1,200 lb.

Four load-displacement curves for resin-anchored bolts are illustrated in figure 37. Three of the bolts showed only 0.115 in displacement or less, even under 20,000 lb load. The fourth bolt (No. 2) began to fail at slightly over 20,000 lb. Probably a third of the total displacement is accounted for by bolt stretch and the remainder by actual anchorage displacement.

SUMMARY AND CONCLUSIONS

An investigation was conducted of the slate quarrying operations in eastern Pennsylvania to determine the nature of ground control hazards and geotechnical

FIGURE 34. - Measuring rockbolt tension bleedoff.

methods by which these hazards might be reduced. The study was somewhat handicapped by the inaccessibility of quarry highwalls, the absence of outcrop outside the quarry walls, and the severity of winter weather, which disrupted instrumentation. Nonetheless, the geologic character of the quarry operations was examined, and specific ground control hazards were identified. Several geotechnical methods were employed to detect these hazards, and rockbolts were assessed as to their anchorage capacity in slate.

The principal ground control hazards that were identified as a result of this study and from the history of accidents that have occurred over many years of operations are as follows:

1. Collapse of highwall, or portion thereof, weakened by bedding plane faults and fractures. The presence of spar, water, and weathered material in the fault planes greatly increases the probability of highwall failure.
2. Falls of large ice accumulations from highwalls, especially during the spring thaw.

Highwall collapse is the foremost cause of injuries and fatalities in quarries. Major highwall failures have occurred infrequently, but without warning or any obvious antecedent events. They have occurred, however, in proximity to known or suspected geologic discontinuities, and have sometimes been facilitated by a highwall overhang or lack of artificial restraint. It is essential to identify

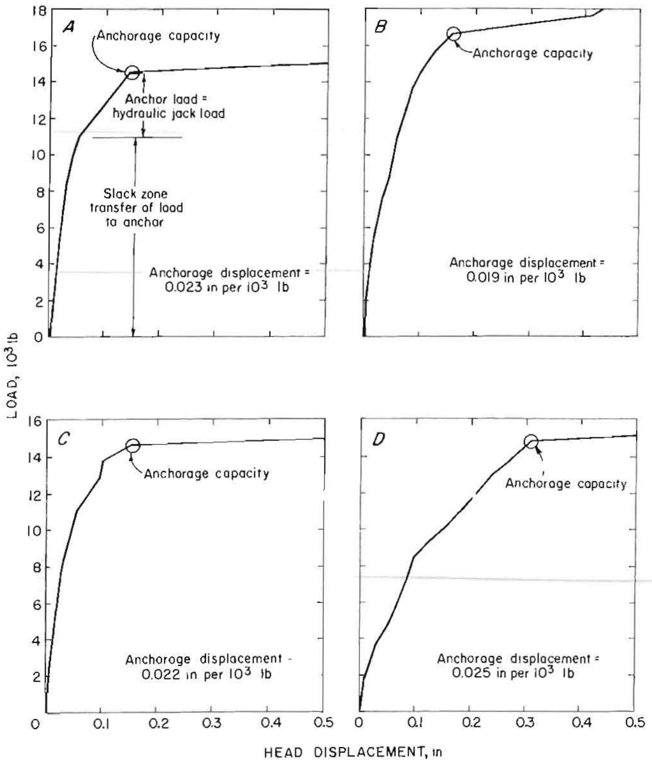


FIGURE 35. - Representative load-displacement curves for mechanical bolts.

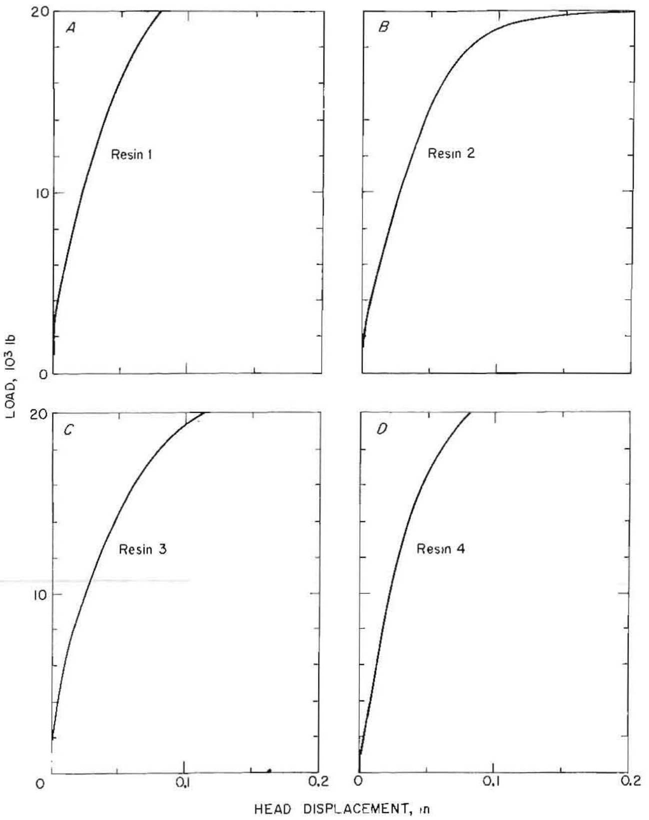


FIGURE 37. - Representative load-displacement curves for full-column resin-anchored bolts, using pull tests.

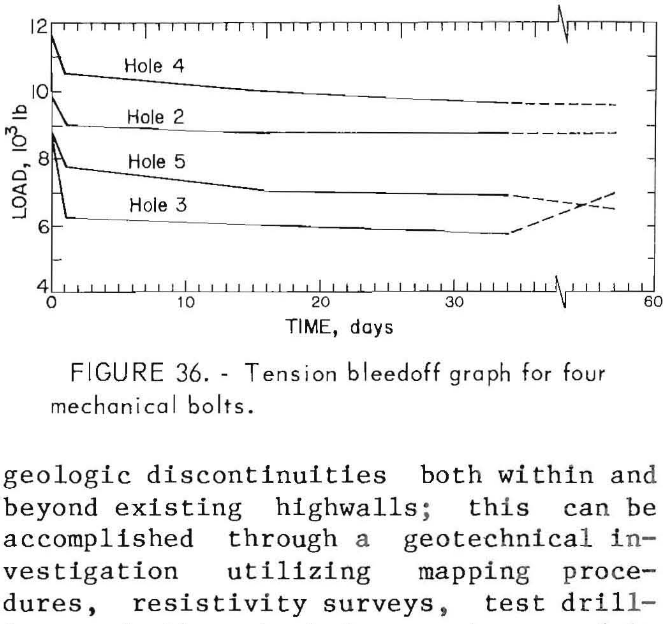


FIGURE 36. - Tension bleedoff graph for four mechanical bolts.

geologic discontinuities both within and beyond existing highwalls; this can be accomplished through a geotechnical investigation utilizing mapping procedures, resistivity surveys, test drilling, and other techniques not covered in this report. Once hazardous conditions are identified, instrumentation such as strain gauges to measure the movement of loose rock masses or tension-load indicators on rockbolts can be useful in detecting incipient movement and antecedent events that could warn of impending failure.

The in situ stress field in a quarry could be a factor in the instability. Lateral rock pressures are manifest in the quarry floors as slot closure and the so-called pressure breaks during extraction of slate. Although stress measurements were conducted in two quarries, a full assessment of their significance must await additional measurements and the development of an appropriate finite element analysis, a procedure by which stresses are calculated for the individual elements of a continuous medium.

The season for ice falls is limited and can be anticipated, and some precautions can be exercised. However, injuries from falls of ice occur almost annually, and a fatality occurred as recently as 1984. Water diversion is basic to the prevention of ice accumulation and can be accomplished only through determining the courses that the water follows in reaching the brink and upper reaches of the quarry highwall. Once these courses are established through a hydrologic study, the water inflow can be reduced at least partially through the use of diversion ditches and drains, dewatering wells, surface barriers, or grouting. Unless water diversion is accomplished, expedient ice control measures will be largely ineffective in preventing ice falls.

Slate quarrying operations in eastern Pennsylvania are unique, mostly old, and tradition bound, and a modest increase in the level of geotechnology could lead to a substantial reduction in potential ground control hazards. New quarries especially should be planned to take advantage of improved methods of site investigation, quarry design, and hazard detection. Modern slate extraction devices such as rock chain saws, jet cutting, or hydraulic splitting, to name a few, should lead to reduced hazards, reduced waste product, and an increase in productivity. This will require support from outside the industry and a more concerted effort from the industry.

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APPENDIX.--GLOSSARY OF QUARRY WORKERS' TERMS

Broach.--Break and remove the narrow rib of rock between closely spaced parallel drill holes.

Channeling (Drilling and Broaching).--Cutting a narrow channel or slot by drilling closely spaced parallel holes and then broaching the intervening rock.

Eighter.--A block of slate sculped and split to a thickness equal to eight roofing slates each 3/16 in. in thickness.

Grit.--A bed consisting of soft slate mixed with a high percentage of abrasive, fine-grained quartz sand.

Hard Roll (Hard End).--A thin, hard siliceous bed of slate.

Loose (Silver) Ribbon.--A very thin bedding plane layer of calcite, usually indicating movement along bedding.

Pressure Break.--An irregular fracture that develops in a bench of slate during extraction. The fracture trends across cleavage and bedding and is attributed to abutment pressure from an adjacent bench or quarry wall.

Ribbon.--A dark-colored thin bed of slate, usually high in carbonaceous material.

Rotten Ribbon.--A highly weathered bedding plane fault.

Run.--A particular group or sequence of beds usually characterized by predominantly thick beds of pure, soft commercial slate, and commonly given romantic names such as Acme, Phoenix, Diamond, and Albion.

Sculp.--Break slate along a cross grain perpendicular to both cleavage and bedding.

Sink.--The lowermost level in a benched quarry. A sump.

Slate.--A fine-grained metamorphic rock with a pronounced fissility along planes independent of original bedding.

Soft Slate.--A smooth, even-textured, light-colored, thick-bedded slate consisting of very fine-grained sericite, quartz, and chlorite, as opposed to hard slate, which is more siliceous and calcareous.

Spar.--Vein-filling material of calcite and quartz.

Square.--Sufficient roofing slate to cover 100 ft^2 with a 3-in overlap, and weighing about 650 lb.

Wedging.--Splitting of stone by driving wedges into planes of weakness.

Wire Saw Method.--A method of cutting stone by immersing a twisted, multistrand, tensioned wire in a slurry of abrasive material and then passing it over the stone.

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