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Preliminary Analysis of Lineaments and Engineering Properties of Bedrock, Penobscot Bay Area, Maine

By

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PRELIMINARY ANALYSIS OF LINEAMENTS AND ENGINEERING PROPERTIES OF BEDROCK, PENOBSCOT BAY AREA, MAINE

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ABSTRACT

A remote sensing study of coastal and near coastal Maine was undertaken to identify bedrock features of possible importance to construction. Major lineaments were identified that separate the region into four distinct terrains. Within each terrain, smaller lineaments and other physiographic features show distinctive and consistent patterns, reflecting similarities in bedrock lithology and structure. The major linear features are given the following provisional geographic names:

1. Lewiston line
2. Merrymeeting lineament
3. Dover-Foxcroft line
4. Orland lineament
5. Union lineament

These linear or curvilinear trends are caused by lithologic contrasts, joints, faults, or foliation in the middle and lower Paleozoic phyllites, schists, gneisses, and granite intrusives. Initial field and laboratory results from a pilot study of bedrock engineering conditions indicate that variations in rock strength and fracture spacing are controlled by lithology, intensity of structural deformation, and alteration. At several locations in the study area faults and major joints are alined with a major lineament. Strength anisotropy ratios are as high as 10 in the foliated rocks but near 1 in the granites. The higher compressive strength direction commonly is perpendicular to foliation and to lineament trends which, in turn, are parallel to faults, major joints, or foliation.

Fracture spacing in rocks in the field study area averages 0.5 m for granite and ranges from 0.2 cm to 0.75 m, with an average of 0.15 m, in metamorphic rocks. Diagnostic indications useful for estimating certain construction conditions are shown by point-load and uniaxial compressive strengths. Values for fresh rock range from less than 30 MN/m^2 for weakly bonded phyllite to more than 350 MN/m^2 for dense andesite and metasiltstone. Rock workability is directly related to compressive strength and spacing of joints.

INTRODUCTION

The need to obtain information on the engineering behavior of rocks in coastal or near-coastal Maine arises from increasing development pressures that involve locations for nuclear power reactors, underground chambers for oil storage, and corridors for pipe and electrical transmission lines. Little attention has been given to the general suitability of rock types or structural settings for any of these facilities. In view of the likelihood that coastal Maine may be increasingly utilized to supply electricity and oil to the other New England States, investigation of rock properties is timely.

The first objective of the field studies is to determine what properties of the bedrock are most significant to shallow excavations and to measure those properties. Also, we wanted to find out whether or not a contrast in rock-structure characteristics on and away from lineaments could be expressed as a range of excavation conditions. Because the mass of rock to be characterized is large and includes several lithologies, many measurements were deemed necessary. As much of the data as possible should be gathered in the field. For the initial study reported here, laboratory testing played a secondary, but necessary, role of verifying the results of point-load strength tests made in the field.

The rock properties that we studied are the spacing, orientation, and rank (continuity) of joints, the width and length of fault zones, swell pressure of fault gouge, and the strength of the predominant rock types. Besides these bedrock characteristics, a knowledge of in situ rock stresses is needed to understand seismicity, present-day near-surface coastal bedrock deformations, including rock bursts, and the relationship of stresses to lithology and structure.

In order to first gain general information on the regional structure, major linear features, recognized in Landsat images and RB-57 high-altitude color-infrared photographs, were studied within a coastal strip approximately 40X320 km (Portland to Eastport). Within this broad strip, three study areas were chosen for more detailed work on the basis of expected development, variety of geologic conditions, and the availability of detailed geologic mapping. These areas are the Casco Bay area, the western Penobscot Bay area, and the eastern Penobscot Bay-Ellsworth area (fig. 1). Within these areas we are concentrating work on a few major lineaments, each of which extends through a considerable range of rock types and engineering conditions. Preliminary results from our initial study area, which includes part of one of these features, the Orland lineament, are presented here. An enlarged portion of a Landsat image showing the Orland lineament is shown in figure 2.

ACKNOWLEDGMENTS

The cooperation of R. G. Doyle and W. A. Anderson of the Maine Geological Survey were especially helpful in starting the study. A. M. Hussey and D. R. Wones have generously spent time in the field with us, increasing our knowledge of the coastal bedrock. Uniaxial compressive strength tests were done at the Colorado School of Mines under the supervision of J. F. Abel, Jr.

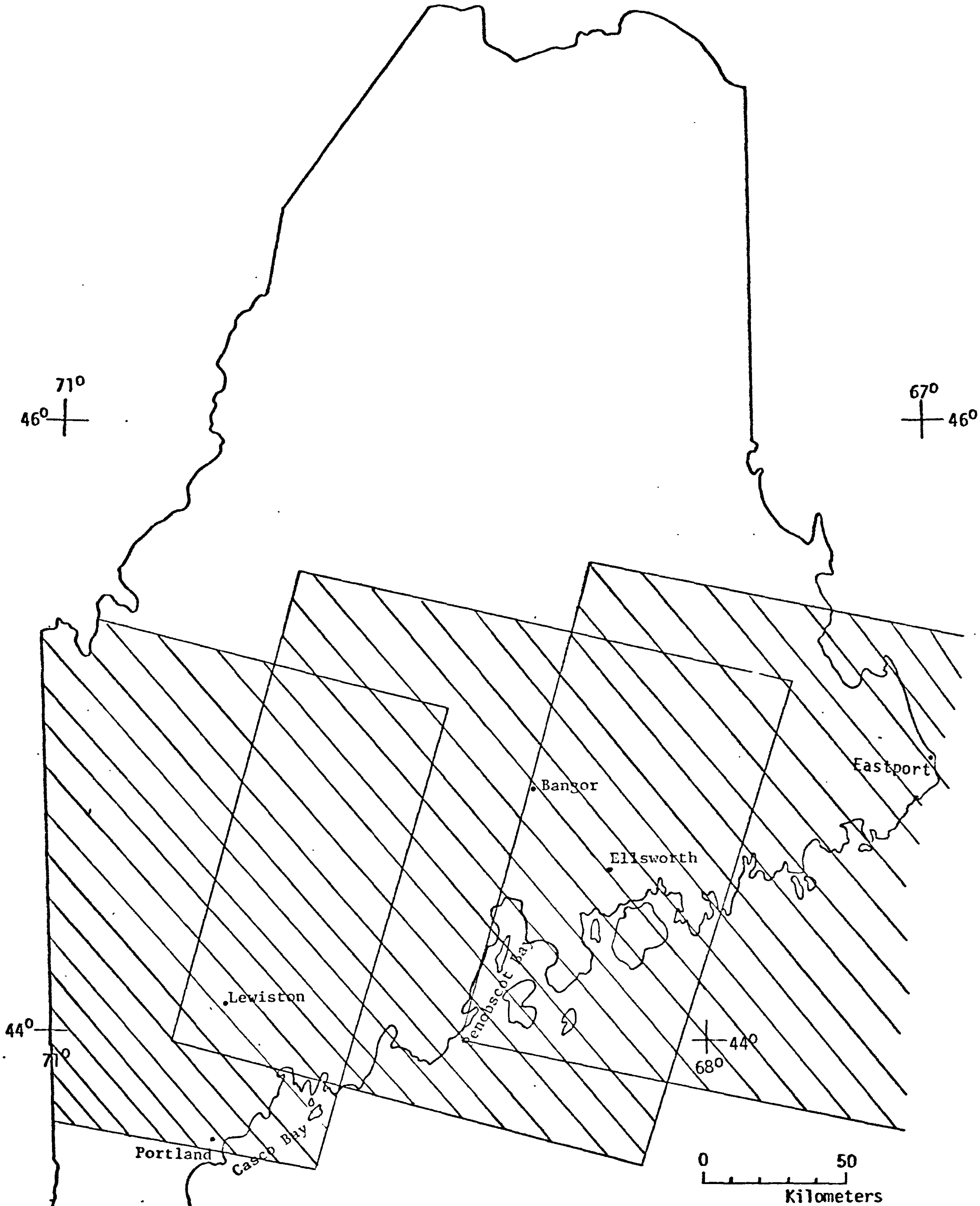

FIGURE 1.--Landsat image coverage of Maine coastal region; pattern shows area covered by three images.

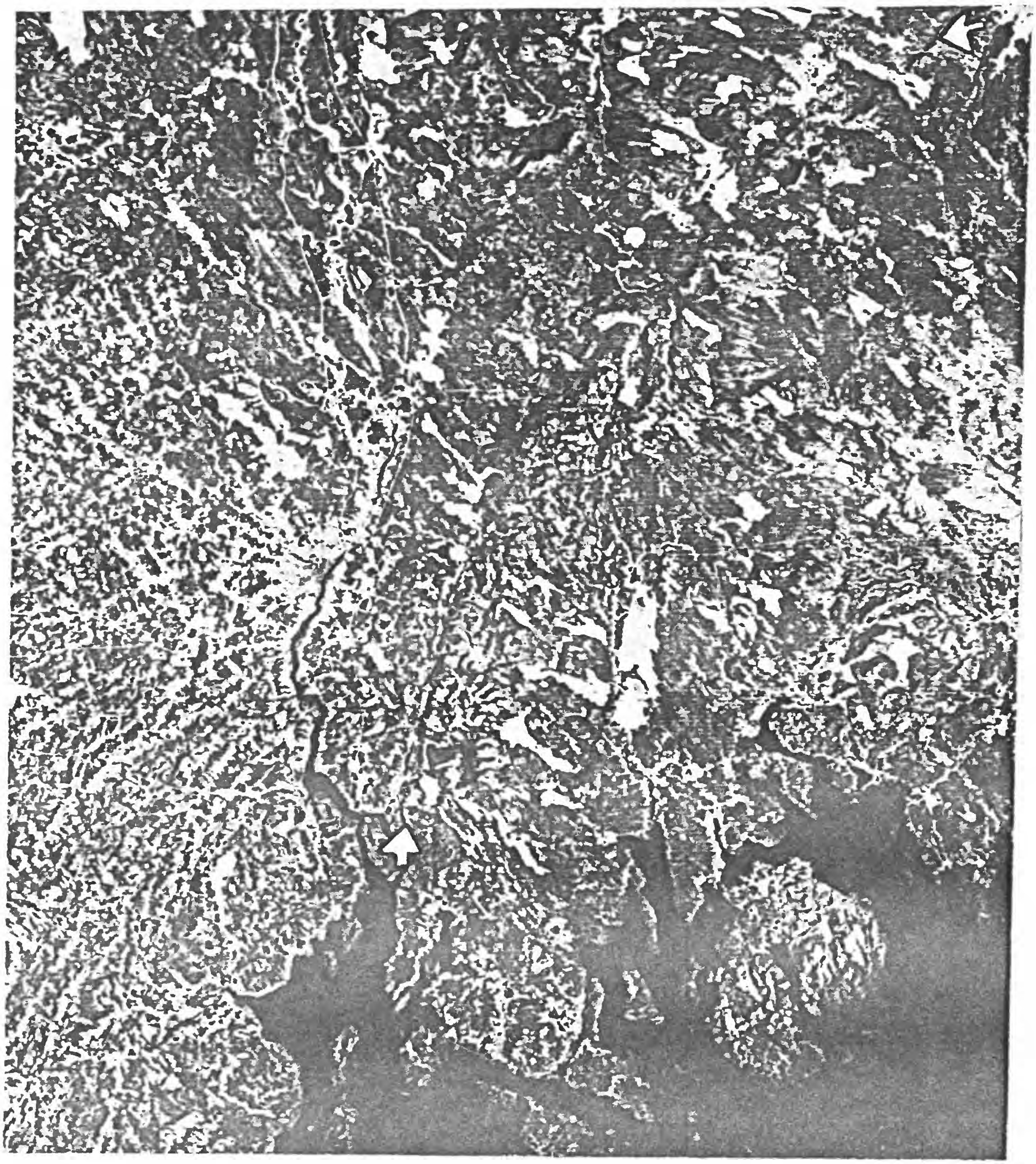

Figure 2.--Enlarged portion of Landsat image showing the Orland lineament.

Scale 0 32 Kilometers

GEOLOGIC SETTING OF COASTAL MAINE

The bedrock of the Maine coast from Portland to Eastport and as far inland as Lewiston and Bangor (fig. 1) consists of folded eugeosynclinal metasedimentary rocks intruded by plutons, most of which are granitic. The region is conveniently divided according to geomorphic characteristics into a generally metasedimentary terrane extending from Portland to Penobscot Bay and a generally granitic terrane extending from Penobscot Bay to Eastport.

From Portland to Penobscot Bay the metasedimentary rocks strike north-northeast and decrease northeastward in regional metamorphic grade, from sillimanite to chlorite (Doyle, 1967). These rocks have been subdivided into two units of Cambrian and Ordovician age, the Rockland and the Penobscot Bay sequences (Osberg, 1974). Predominant lithologies are schist, phyllite, and quartzite. These rocks are in contact to the northwest with Silurian metaflysch deposits that include gneiss and schist. The metaflysch sequence is interrupted by a belt of high-grade metamorphic rocks in the Liberty-Orrington anticline, a large structure that extends northeast from near Portland to Bangor. This structure contains feldspathic and calc-silicate gneisses, schists, and amphibolites, and its core consists of high-grade feldspathic gneisses and schists of Precambrian age (Osberg, 1974). Gneisses in the anticline are of the highest metamorphic grade in the region; they were intruded by postmetamorphic granites in Ordovician time (Stewart, 1974).

All of these units have been progressively folded. The oldest folds are recumbent folds with amplitudes of thousands of meters. These folds have been refolded into isoclinal folds with amplitudes of tens of meters. The Liberty-Orrington anticline is a broad, open fold superimposed on the isoclinally folded section. Open north-trending folds overprint these earlier types. The two earlier fold systems are cut by Devonian plutons (Osberg, 1974).

Southeast of the Orland lineament and between Penobscot Bay and Eastport (fig. 3), there is an extensive plutonic terrane. The country rock here consists chiefly of Cambrian and Ordovician schists (principally the Ellsworth Schist) and minor amphibolite, and quartzite of the Penobscot Bay sequence (Doyle, 1967; Osberg, 1974). Segments of Silurian metaflysch sequence are present in the northern part of this area. These earlier metasedimentary rocks are intruded largely by granites, quartz monzonites, and granodiorites of Devonian age. Mafic and ultramafic plutons of the Bays-of-Maine igneous complex (Chapman, 1962) are prevalent along the coast. The plutons include serpentinites, pyroxenites, and layered gabbros, and are generally of Devonian age. Regional metamorphism in the country rock is of chlorite grade. Around some plutons contact aureoles have significantly overprinted the regional metamorphic facies.

Most faults mapped in the coastal region dip steeply and have strike-slip motion, although horsts and grabens have been identified in some places (Stewart, 1974). Faults range in age from pre-Devonian to possibly post-Triassic (Osberg, 1974). A major fault, the Norumbega fault, shows evidence of 25 km right-lateral displacement (Wones and Stewart, 1976). It crosses the Penobscot River about 15 km south of Bangor and extends northeast as a zone of faulting to the New Brunswick border. According to Wones, not all of the faults are of the same age; some have been active for long periods or were reactivated after earlier movements.

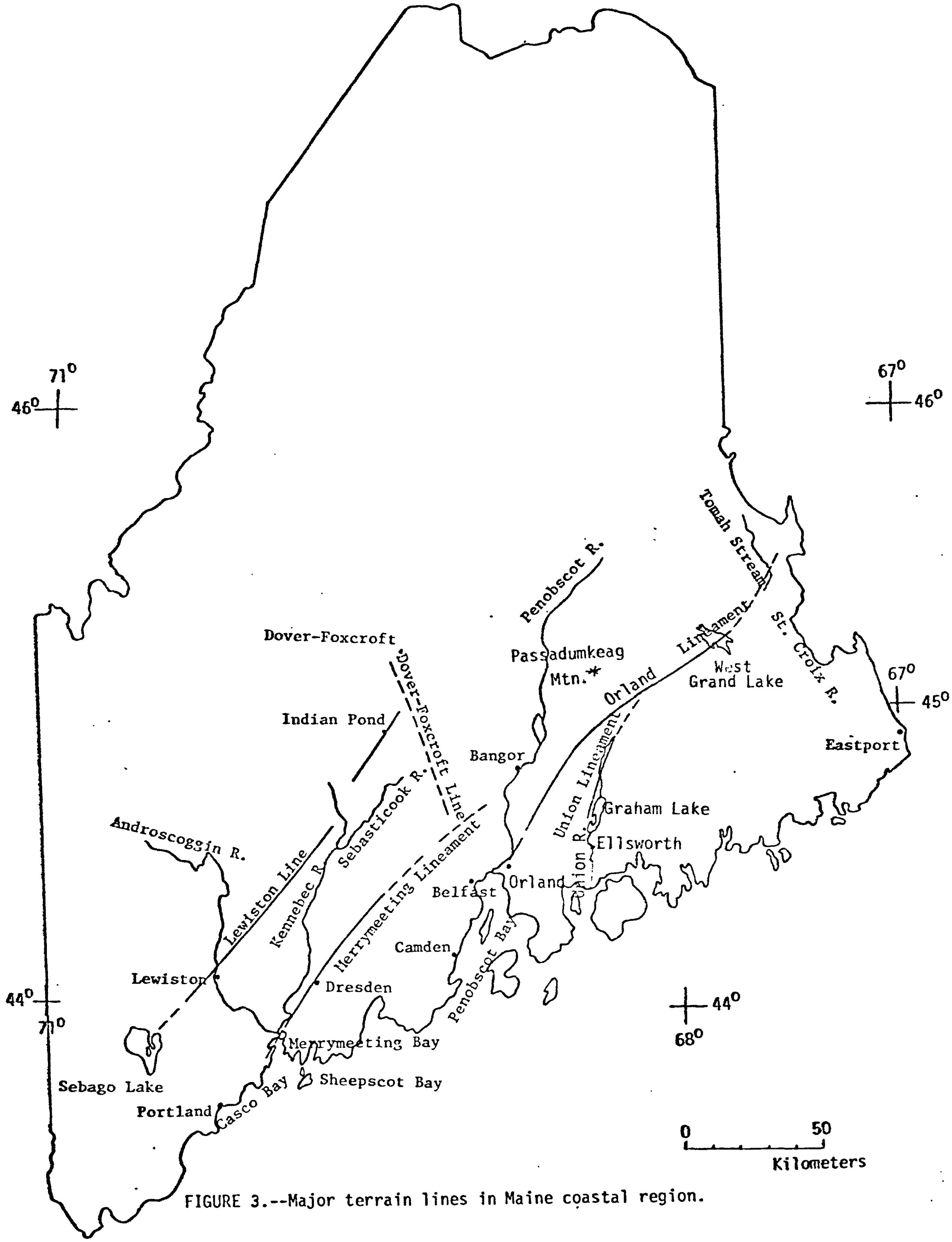

FIGURE 3.--Major terrain lines in Maine coastal region.

TERRAIN PATTERNS AND STRUCTURE OF THE MAINE COASTAL REGION

Four Landsat frames covering the coast of Maine between Portland and Eastport (fig. 1) were studied to obtain data bearing on regional structure. Digitally-processed images were prepared as false-color composite transparencies at a scale of 1:1,000,000; they show the spectral reflectances of surficial materials, vegetation, exposed rock, and water in combined blue, yellow, and red images, one for each spectral band. The patterns visible in the images also reflect terrain irregularities as revealed by shadows related to the sun elevation angle. The spectral (color pattern) and topographic (tone pattern) data in the images thus allow a preliminary analysis to be made of major terrain features. The terrain analysis can then be keyed to mapped geology. Terminology used to designate features observed on the images follows the usage of O'Leary, Friedman, and Pohn (1976).

The topography of coastal Maine has been modified most recently by a succession of ice sheets. The obvious effect has been the scouring and deepening of the coastline and the creation of numerous ponds, lakes, and swamps owing to drainage obstruction by glacial deposits. Abundant outwash and marine sediments from Portland southwestward have greatly obscured preglacial coastal drainage and bedrock contours. In general, however, glaciation has only selectively and locally altered topography; the moving ice served to polish rather than to erode, to accentuate rather than obliterate; areas of resistant crystalline rock are marked by uplands with hummocky drumloidal landforms, rouches moutonnées, and rather large, irregular lakes. Areas of relatively nonresistant rock are the sites of thick glacial deposits, swampy lowlands, and fairly well integrated drainage. Such features are useful for structural interpretation.

The coastal region of Maine can be separated into four distinct terrains. Each terrain is bounded by major lineaments or alinements except for one boundary, which is a flexure axis extending southeast from about 12 km west of Dover-Foxcroft to the vicinity of the northern end of the Merrymeeting lineament (fig. 3). Within each terrain, shorter lineaments and other physiographic features show distinctive and consistent patterns.

REGIONAL LINEAR FEATURES

Three kinds of linear features are recognized in coastal Maine: 1. Lineaments; that is, mappable, simple or composite linear features of a surface--in this case, alined landforms and stream courses whose parts are exposed in a rectilinear or slightly curvilinear relationship and whose patterns differ distinctly from the patterns of adjacent features and presumably reflect subsurface phenomena. 2. Lines, defined by landforms, the precise nature of which is not clear, but having features that are not cultural (though they may be emphasized by culture). 3. Alinements--lines defined by alined geomorphic features, regardless of spacing or presumed genetic association. For this study, the major linear features are given the following provisional geographic names (fig. 3):

1. Lewiston line
2. Merrymeeting lineament
3. Dover-Foxcroft line
4. Orland lineament
5. Union lineament

The terrain blocks between these linear features are characterized by broad uniformities of bedrock lithology and structure. The south-central Maine coastal area includes succession of typically steeply dipping, tightly folded, high-grade metamorphic rocks. Thus, in the area bounded roughly by Portland, Lewiston, Bangor, and Dover-Foxcroft, a pronounced and consistent north-northeast strike is impressed on the landscape. The Orland lineament is a major boundary that separates the high-grade metamorphic rocks to the southwest from the Bays-of-Maine plutons and associated low-grade metamorphic rocks to the northeast.

Lewiston line

The southwesternmost of the major linear features, the Lewiston line, extends northeast from the north side of Sebago Lake, near Lewiston, to the Kennebec River (fig. 3). A shorter segment of this feature, transposed 7.5 km farther west, but parallel to the main trend, extends from north of the Kennebec River to Indian Pond. These two linear features strike N. 35°-40° E. They are defined only locally by landforms recognizable in the Landsat images. The longer line is manifested chiefly by the long shorelines of Messalonskee Lake and Maranacook Lake and the jog in the Androscoggin River north of Auburn (Doyle, 1967). The terrain to the northwest of the line is characterized by a strong north-northwest topographic grain shown by the alinement of small streams and valleys, lakes, and ponds. Southeast of the line the topographic grain, manifested by ridges, valleys, ponds, and small streams, such as tributaries to the Androscoggin and Kennebec Rivers (especially the Sebasticook River), is strongly oriented in a N. 35°-40° E. direction. A few vague linear features have pronounced N. 15° W. trends; a nearly orthogonal northwest trend, less pronounced, is also present.

Along much of its course the Lewiston line follows a major lithologic contact between dominantly calcareous units and intrusive rocks to the northwest, and mainly rocks of detrital origin to the southeast. Location of the line appears to coincide with the southeast side of the core of a steep-sided antiform, according to the preliminary geologic map of Maine (Doyle, 1967).

Merrymeeting lineament

The Merrymeeting lineament extends northeast from Merrymeeting Bay past Dresden toward Bangor, subparallel to the Lewiston line (fig. 3). The terrain between these two features is characterized by pronounced northeast linear trends, which are even more strikingly developed southeast of the Merrymeeting lineament, though they gradually diminish to the northeast between Camden and Belfast. From the east side of Merrymeeting Bay north to Dresden, the Merrymeeting lineament follows a mapped fault (Hussey and Pankiwskyj, 1975). Along this stretch it follows the contact between the Paleozoic Cushing and Cape Elizabeth Formations for the distance shown on the Hussey and Pankiwskyj (1975) compilation; it follows an equivalent contact shown on the preliminary geologic map of Maine (Doyle, 1967).

Dover-Foxcroft line

The major northeast-trending strike-controlled landforms characteristic of south-central coastal Maine bend from N. 35°-40° E. to about N. 70° E. near Dover-Foxcroft and die out a short distance farther east. The Dover-Foxcroft line marks the axis of this bend and more or less defines the western edge of the Penobscot River basin, a broad lowland with no pronounced terrain pattern. Drainage tributary to the Penobscot River follows a strong N. 35° W. trend, however. East of Passadumkeag Mountain this trend is reflected in the orientation of lakes in a region of relatively high relief. The line itself strikes about N. 20° W. (fig. 3). Structural or lithologic control of this feature is conjectural, because the area is inadequately mapped.

Orland lineament

The Orland lineament follows a broad curve from the town of Orland, near the head of Penobscot Bay, northeast to at least West Grand Lake; it can be projected less clearly farther northeastward along the northeast-trending reach of Tomah Stream (fig. 3). This lineament helps define the southern edge of the Penobscot River basin. Terrain southeast of this lineament is relatively rugged and set with irregular lakes oriented about N. 35° W. Because bedrock in the Penobscot River basin north of the Orland lineament consists of relatively nonresistant metapelites and calcarenites of low metamorphic grade, a weak terrain pattern is displayed. Bedrock along the northeast coastal district, in Washington and Hancock Counties, is chiefly granitic to gabbroic intrusives with inliers of metavolcanics and metapelites. In Landsat images, this area is markedly distinct from the metasedimentary rock belt to the southwest. This impressive contrast in lithology and structural style greatly accentuates the gross form of the Orland lineament, a feature with major geomorphic significance. Structural data along the greater part of this lineament are presently lacking. However, along the northern edge of the Lucerne pluton, a major fault, corresponding to part of the lineament, has been mapped by D. R. Wones (written commun., 1976). Farther northeast, in the area of Machias Third Lake, a fault along the trace of the lineament is shown on the preliminary geologic map of Maine (Doyle, 1967). The extension of this lineament to the south is not clear, although zones of severe fracturing, discussed later, have been observed by us south and southwest of Orland.

Union lineament

The Union lineament marks the eastern border of the Lucerne pluton and its contact with the Ellsworth Schist and other low-grade metasedimentary rocks. It is this contrast in lithology that apparently gives the lineament its geomorphic character. The Union lineament extends northeastward from the west side of Graham Lake along the west branch of the Union River (fig. 3). At its northern end it merges with the Orland lineament. East of this lineament is a region of moderate relief with numerous small ponds and lakes and swampy ground connected by an irregular network of streams flowing southeastward into a succession of small bays. In this area drainage is "normal"--it follows the regional slope to the southeast and is more or less orthogonal to the coastline with no prominent alinements oblique to the coast.

ENGINEERING GEOLOGY

The preceding analysis of Landsat images was helpful in pinpointing key areas for further study. We are particularly interested in the extent to which the conspicuous linear features on these images represent anomalous geologic conditions produced by joints, faults, or lithologic contrasts, and what changes occur in engineering properties of the bedrock across and along these lineaments. Several bedrock properties are important to construction in crystalline rocks, including mineralogy, fabric, and strength of weathered and fresh rock; spacing, orientation, openness, and extent of joints; extent and mechanical nature (mylonite vs. gouge) of faults and shear zones; and in situ stresses. This report gives a preliminary assessment of engineering properties of bedrock at representative locations in the Penobscot Bay study area and suggests how these properties might affect near-surface construction.

Field investigations in the Penobscot Bay area were made in June, July, and October 1976. Structural data were recorded from 55 outcrops, roadcuts, and quarries; approximately 300 samples were collected and tested. These samples were chosen to represent the range of lithologies in the area in proportion to their abundance, and included fresh and altered material and both fractured and unfractured material.

Rock units

Most of the rock units that crop out in the study area were sampled for strength tests. Unless noted otherwise, the following brief descriptions were furnished by D. R. Wones (written commun., 1976).

Lucerne Granite of Wing, 1958 (Devonian): Coarse-grained, white-weathering granite with 1- to 4-cm euhedral alkali feldspar crystals; subhedral quartz and plagioclase; contains 5-10 percent biotite and uncommon tourmaline. Sparse leucocratic dikes.

Mount Waldo Granite of Brookins, 1974 (Devonian): Medium-grained, pink-to white-weathering granite with common phenocrysts of alkali feldspar; leucocratic dikes very common. Pegmatite pods well developed along southwest border.

Wallamatogus Granite (Sweeney, 1976) (Devonian): Medium-grained, muscovite-bearing, gray-weathering granite. Outer rim contains tabular alkali feldspar phenocrysts 1-2 cm long. Intrudes Bucksport Formation and is intruded by Lucerne Granite.

Stonington Granite of Brookins and Spooner, 1970 (Devonian): Medium-grained, pinkish gray to salmon colored granite. Contains pegmatite pods with 2-4 cm feldspar crystals a few of which have rapakivi texture.

Castine Volcanics (Devonian and Silurian): Includes a variety of lithologies: Volcanic rocks include agglomerates, tuffs, and flows, varying from rhyolite to basalt in composition. Sedimentary rocks include siltstone and mudstone rich in volcanic debris, and some that are calcareous or contain claystone concretions. All units have attained at least chlorite-grade regional metamorphism (Stewart and Wones, 1974).

Bucksport Formation of Wing, 1957 (Silurian and Ordovician): Highly deformed calcareous siltstone, intercalated with black, rusty-weathering phyllite.

Penobscot Formation (Ordovician): Rusty-weathering intercalated siltstone and phyllite; contains abundant pyrite. In southern part of area the formation contains amphibolite layers.

Islesboro Formation (Ordovician? and Cambrian?): Interbedded slate, limestone, quartzite, and quartz conglomerate. South of Islesboro Island, feldspathic greenstones, greenschist, and pillow lavas predominate. The entire sequence is extensively faulted (Stewart, 1974).

Ellsworth Schist (Ordovician? or Upper Cambrian): Polydeformed feldspathic schists. Contains significant amphibolite units to south and east.

Passagassawaukeag Gneiss (Precambrian): Chiefly polydeformed biotite-plagioclase-quartz gneiss with minor intercalated calc-silicate and pelitic beds rich in sillimanite. Also contains disaggregated quartz-plagioclase-biotite migmatitic lenses. Intruded by the Cambrian and Ordovician gneissic granites of the Winterport area (Trefethen, 1944).

Fractures

The orientation and spacing of fractures influence several aspects of engineering behavior of a rock mass. The stability of rock slopes, rock-mass stabilization time, and the magnitude of loads carried by supports in underground openings are all functions of the geometry and distribution of fractures (Schuster and others, 1975; Robinson and others, 1974). Fracture spacing and compressive strength of the rock control the ease of excavation and the type of construction equipment to be used (Bieniawski, 1975).

In this study, fractures are classified as fault zones, major joints, and minor joints.

Fault zones

In terms of engineering behavior, fault zones can be considered to be zones of deformation greater than 1 m wide in which the average dimension of a block of rock is less than 4 cm. Within such zones support requirements for underground excavations are severe and slope deformations are largely independent of structural attitudes. Since block size controls workability, blasting is unnecessary in closely jointed material (Bieniawski, 1975, fig. 7). Figure 4 shows fault zones that we have observed in the field. Most fault zones are vertical, or nearly vertical, and strike north to N. 45° E. Northwest-striking fault zones were mapped near Bucksport and northeast of Orland. Most observed fault zones occur in relatively weak schists and phyllites of the Penobscot and Islesboro Formations, and Ellsworth Schist. The fault zones shown in figure 4 have not been projected beyond their known outcrop locations.

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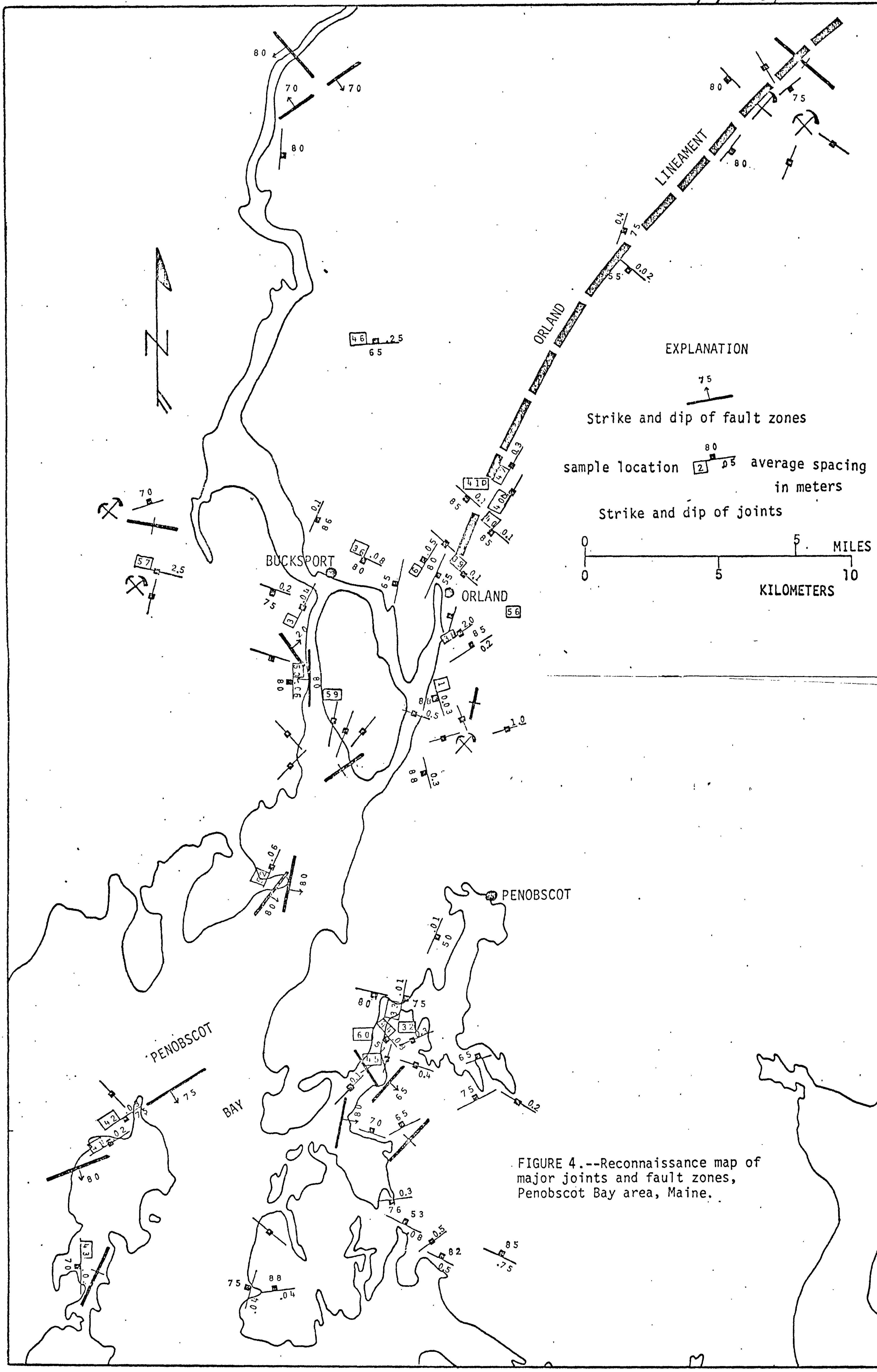

FIGURE 4.--Reconnaissance map of major joints and fault zones, Penobscot Bay area, Maine.

Joints

In the field, joints were recorded as either major or minor joints. Major joints are dominant joints in terms of their extent and repetition, as well as their surface smoothness and planarity. Foliation surfaces with low tensile bond strength commonly form closely spaced major joints, as in the Ellsworth Schist and schists and phyllites of the Penobscot and Islesboro Formations. Minor joints are those fractures that are discontinuous and have irregular surfaces. Most sample sites had one or more major joint sets and several minor joints. Attitudes of major joint sets were plotted on the map (fig. 4) along with the average spacing between the joints and were compiled on a strike-frequency diagram (fig. 5). Figures 4 and 5 illustrate general trends to help understand excavation conditions.

Attitudes and spacing of joints

The attitudes of most major joints that we have observed in the Penobscot Bay area fall into two broad categories: subhorizontal sheeting joints which are best developed in the granites, and vertical or near-vertical joints that pervade all rock types. Sheeting joints generally conform to the surface topography, and the sheets become thicker with depth. The thickness of sheets range from less than 2 cm to more than 10 m. Well-formed sheeting joints were observed at depths of more than 20 m in the Oak Hill quarry, 8 km northwest of Belfast.

The most abundant vertical or near-vertical major joints (23 percent) strike N. 10° E. to N. 30° E. (fig. 5). Other strike-frequency maxima are approximately N. 45° W. (11.7 percent), N. 65° E. (9.1 percent), and N. 65 W. (7.4 percent). At numerous locations, major joints are oriented parallel to faults (fig. 4).

Joints are generally more widely spaced in the granites than in the metamorphic rocks. Spacing of vertical or near-vertical joints in the granite ranges from 0.1 m to 3 m and averages 0.5 m. In the metamorphic rocks, the spacing of vertical or near-vertical joints, which parallel the regional foliation attitude, ranges from 0.2 cm to 0.75 m, and averages 0.15 m. The development of closely spaced, steeply dipping joints is much more pronounced in the schists and phyllites than in the stronger gneisses and metasiltstones.

In the vicinity of Orland, major joints in weakly metamorphosed siltstones of the Penobscot and Bucksport Formations strike northeast, in close alinement with the Orland lineament (fig. 4). Other joints strike perpendicular to this feature so that tabular blocks are formed. Frost heave, running water, gravity, or possibly glacial scouring would act to transport these blocks downslope, developing a valley. Such a process may explain some parts of the coastal lineaments observed on the Landsat images and high-altitude photographs.

Bedrock strength tests

Point-load test

The point-load test has been widely used for several years as a means for preliminary geotechnical classification of rocks (Hiramatsu and Oka, 1966; Broch and Franklin, 1972; Internat. Soc. Rock Mechanics, 1972). Combined with fracture spacing measurements, point-load strength data allow estimates of the relative ease or difficulty of trenching, tunneling, or other types of

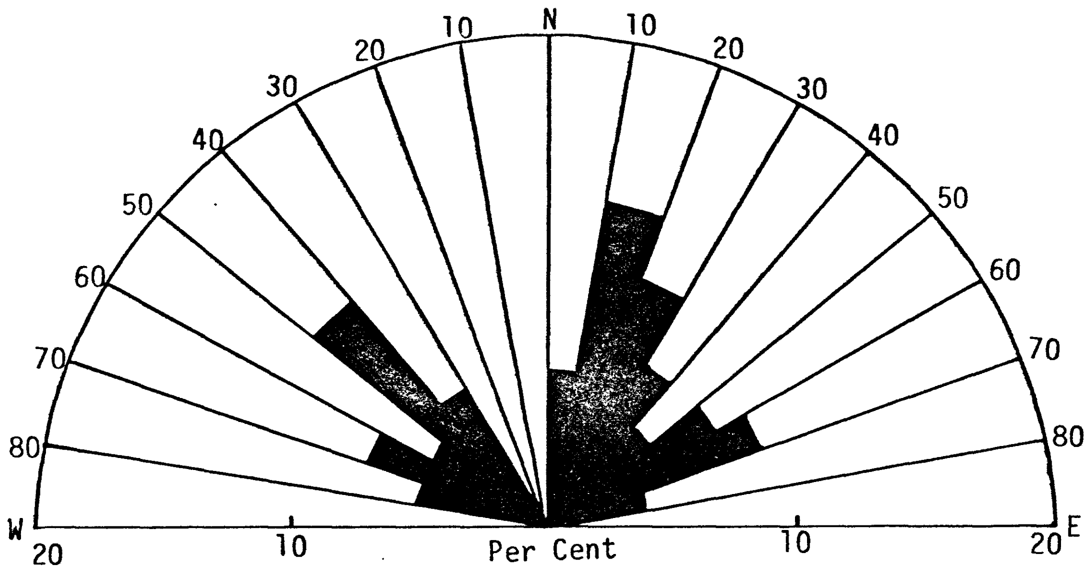

FIGURE 5.--Strike-frequency diagram of 77 major joints from outcrops, quarries, and roadcuts, Penobscot Bay area, Maine.

excavation (Bieniawski, 1975; Muir-Wood, 1972). The property tested is the tensile strength of the rock, and, because most rocks are much weaker in tension than in compression, the equipment can be made lightweight and easily portable. The test is rapid, inexpensive, and sufficiently accurate for most index testing and classification purposes. In essence, it involves compressing a piece of rock between two points until a splitting, tensile failure is produced. The dimensions of the loading points and other details of the apparatus were given by Broch and Franklin (1972). The point-load index is calculated as the ratio of the applied load, P, to the square of the distance, D, between the loading points. This index has been correlated with both the uniaxial tensile strength and the uniaxial compressive strength of rock samples, though the relationship between the point-load index value and the uniaxial compressive strength has been given more attention, mainly because of the predominance of compressive stress in rock mechanics problems. Strength ranges of rock in terms of compressive strength are more widely recognized than are the index values themselves.

The point-load test may be performed on either core or irregular lump samples, although standard deviations are somewhat greater for tests of irregular lumps. The test results reported in table 1 are largely from tabular samples, which help to overcome detrimental shape and size effects. At most of the sample locations, fracture data were also collected. Normally, several pieces of the same material were tested to obtain rough estimates of statistical variation.

Uniaxial compressive strength tests

Table 2 presents the results of 29 uniaxial compressive strength tests on cores from representative rock types from the Penobscot Bay area (fig. 4). The rock types tested include most of those shown in table 1. For some rocks, the core for a uniaxial compression test was taken from the same block from which samples for point-load tests were taken, as noted in the "Remarks" column of table 2.

These tests were considered to be necessary for comparison with the compressive strength values derived from the point-load tests because point-load test results on foliated metamorphic rocks could not be found in the literature. Some workers (Bieniawski, 1975; Broch and Franklin, 1972) have found that a straight-line correlation exists between the uniaxial compressive strength and the point-load index for other rock types, and they recommend discontinuation of uniaxial testing for geotechnical classification. Our results tend to confirm their recommendations. The tests of uniform cylinders as contrasted with those of irregular lump samples increased our confidence in testing the more irregular geometric forms.

Results of strength tests

Test results listed in tables 1 and 2 are in order of decreasing compressive strength of fresh samples loaded perpendicular to layering or fracturing. Several statements can be made regarding rock strength and behavior on the basis of this information. Generally good agreement was obtained between point-load tests of tabular samples and uniaxial compression tests of cylinders. Differences between similarly oriented samples from the same block (for example, samples 40D-1, 40D-2, and 40D-3, table 2) are

Table 1.--Results of point-load strength tests of rock samples, Penobscot Bay area, Maine

Sample No.[1]		Description	Sample condition[2]	Number of samples tested	Loading direction[3]	Point-load index strength, $I_s(50)$, MN/m²	Compressive strength[4] MN/m²	Relative violence of failure[5]	Remarks
60	a	Medium gray, dense andesite of Castine Volcanics.	F	3	Parallel	4.1	98	2	Closely spaced fractures.
	b		F	6	n/a	17.8	427	3	
44B	a	Dark-gray-green andesite of Castine Volcanics; iron-stained fractures.	F	1	Parallel	13.3	319	3	Fractures too widely spaced to influence point-load strength.
	b		F	2	Perpendicular	17.5	420	3	
	c		W	1	Parallel	6.6	158	2	
44A	a	Greenish-gray, fine-grained metasiltstone; platy layering; Penobscot Formation.	F	2	Parallel	3.8	91	2	Layering difficult to recognize in some samples.
	b		F	12	Perpendicular	15.2	364	3	
	c		W	1	Parallel	.68	16	1	
3	a	Brownish-gray, fine-grained metasiltstone, with resinous luster; Penobscot Formation.	F	4	Parallel	4.0	96	2	Old fractures controlled some failures.
	b		F	4	Perpendicular	14.8	355	3	
47	a	Very fine grained metasiltstone of Bucksport Formation; abundant microfractures and shearing.	F	4	Parallel	4.4	106	2	Some failures along preexisting fractures. Some "healed" fractures.
	b		F	5	Perpendicular	13.8	331	3	
46	a	Gray, medium-grained, rusty-weathering, closely fractured Passagassawaukeag Gneiss.	F	4	Parallel	6.0	144	1	Iron-oxide-stained fractures.
	b		F	4	Perpendicular	13.0	312	2	
	c		W	3	Parallel	4.7	113	1	Old fractures controlled some failures.
	d		W	4	Perpendicular	7.0	168	2	
48	a	Light-gray, fine-grained quartzite from breccia zone; very hard.	F	1	60° to layering.	12.8	307	2	No obvious directional weakness.
	b		F	2	Perpendicular	12.6	302	3	
36	a	Fine-grained metasiltstone of Penobscot Formation.	F	15	Parallel	5.8	139	2	Breaks into uniform tabular pieces.
	b		F	13	Perpendicular	12.8	307	3	
39	a	Dark-gray, calcareous, massive metasiltstone of Bucksport Formation.	F	4	Parallel	5.3	127	2	Breaks into uniform blocky pieces.
	b		F	11	Perpendicular	12.1	290	3	
40	a	Gray, fine-grained, sheared, calcareous pelite of Bucksport Formation.	F	2	Parallel	4.2	101	1	Small open fractures.
	b		F	2	Perpendicular	11.4	274	2	
1	a	Light-gray, medium-grained Wallamatogus Granite.	F	12	n/a	10.8	259	3	Moderately weathered. Faintly gneissic.
	b		W	7	----do-------	5.0	120	2	
38	a	----do--------------------------	F	4	----do-------	9.9	238	2	Do.
	b	----do--------------------------	W	3	----do-------	7.2	172	2	Do.
33	a	Gray, sandy phyllite (Ellsworth Schist). Fractured; near fault zone.	F	2	Parallel	4.5	108	2	Fractures reduce strength of larger samples.
	b		F	4	Perpendicular	10.5	252	2	
43	a	Gray-green metasiltstone of Islesboro Formation.	F	2	Parallel	2.3	55	1	Some shearing with slickensides parallel to foliation.
	b		F	7	Perpendicular	10.1	242	2	
56		Light-gray, porphyritic Lucerne Granite.	W	4	n/a	4.8	115	1	Moderately weathered.
57		Light-gray Mt. Waldo Granite----	F	4	----do-------	9.6	230	2	Slightly weathered.
42A	a	Medium-bluish-gray phyllite of Islesboro Formation (includes loc. 45).	F	5	Parallel	1.2	29	1	Loading points push into rock.
	b		F	9	Perpendicular	8.9	213	2	
	c		W	1	Parallel	.5	12	1	Do.
	d		W	1	Perpendicular	2.8	57	2	
40D	a	Purplish-gray, very fine grained, massive, calcareous phyllite of Bucksport Formation; closely spaced, discontinuous, cemented fractures.	F	5	Parallel	4.6	110	2	
	b		F	16	Perpendicular	8.7	209	2	Some violent (3) failures.
41	a	Light-gray phyllite grading to slate of Islesboro Formation.	F	5	Parallel	3.3	79	1	Splits unevenly.
	b		F	8	Perpendicular	8.3	199	2	
50	a	Brown to gray, finely laminated, rusty-weathering schist of Penobscot Formation.	F	13	Parallel	5.3	127	1	Abundant slickensides on foliation surfaces.
	b		F	12	Perpendicular	5.8	139	1	
32	a	Brown, iron-stained, sheared and contorted Ellsworth Schist; in fault zone.	W	6	Parallel	1.6	38	1	Splits easily into thin plates.
	b		W	12	Perpendicular	5.2	125	1	
58	a	Pinkish-gray, porphyritic Stonington Granite; massive.	F	7	n/a	5.1	122	2	Massive, breaks into uniform tabular pieces. Loaded parallel to a fracture.
	b		W	1	Parallel	2.2	53	1	
42B		Buff, fine-grained rhyolite of Islesboro Formation.	F	3	n/a	4.9	118	2	No obvious directional weakness.
52	a	Dark-gray, crenulated, graphitic schist of Penobscot Formation. Rock is soft and layers separate easily.	W	5	Parallel	.5	12	1	Some tests showed a progressive manner of failure.
	b		W	9	Perpendicular	4.7	113	1	

[1]Location of samples is shown in figure 4.
[2]F, fresh; W, weathered or altered.
[3]Parallel or perpendicular to foliation or fractures. n/a indicates no obvious directional weakness.
[4]Compressive strength equals $I_s(50)$ times 24 (Bieniawski, 1975). 1 MN/m² equals 145 lb/in².
[5]1, quiet; 2, audible; 3, loud, violent.

Table 2.--Results of uniaxial compressive strength tests of rock core samples, Penobscot Bay area, Maine

Sample No.[1]	Description	Sample condition[2]	Loading direction[3]	Uniaxial compressive strength[4] (MN/m^2)	Remarks
48A	Light-gray to brown, fine-grained quartzite from breccia zone; very hard.	F	Perpendicular	336	Closed fractures 10° to loading direction; similar to 48 a and 48 b, table 1.
48B		F	60° to fracture	152	Closed fractures; perpendicular to 48A.
43A 1	Gray-green metasiltstone from Islesboro Formation.	F	Perpendicular	302	Similar to sample 43 b, table 1.
42D 1	Gray, fine-grained, massive, calcareous metasiltstone from Islesboro Formation.	F	----do---------	228	
40D 1	Purplish-gray, very fine grained, calcareous	F	Parallel	146	Calcite-filled vertical fractures.
40D 2	phyllite of Bucksport Formation; closely	F	Perpendicular	213	Similar to sample 40D b, table 1.
40D 3	spaced, discontinuous, cemented fractures.	F	60° to fracture	126	Closed fractures 60° to loading direction.
1A 1	Light-gray, medium-grained Wallamatogus	F	n/a	151	Samples 1A 1 and 1A 2 from same block.
1A 2	Granite; some weathering.	F	n/a	152	Samples 1A 1 through 1A 4 and 1A 8 are similar
1A 3		F	n/a	176	to samples 1 a, 1 b, 38 a, and 38 b, table 1.
1A 4		F	n/a	148	
1A 8		F	n/a	138	
44A	Gray, fine-grained schist of Penobscot	F	Parallel	62	Similar to sample 59C below, but unweathered.
44C	Formation.	W	Perpendicular	166	
38A	Light-gray, medium-grained Wallamatogus Granite--	W	n/a	145	Feldspars slightly altered. Similar to 38 b, table 1.
42F 1	Buff, fine-grained rhyolite of Islesboro Formation.	F	n/a	98	42F 1 is perpendicular to 42F 2. Same as 42B, table 1.
42F 2		F	n/a	53	
3A	Gray, fine-grained metasiltstone of Penobscot Formation.	F	Perpendicular	61	Failed along weathered fractures 45° to loading direction. Similar to 3 a and 3 b, table 1.
41A	Light-gray phyllite grading to slate of Islesboro Formation.	F	Parallel	56	Two vertical closed fractures the entire core length.
41B		F	----do---------	35	Both samples are similar to sample 41 a, table 1.
42B 1	Light-gray phyllite grading to slate of Islesboro Formation.	F	----do---------	54	Vertical open fracture throughout length of core. Similar to sample 41 a, table 1.
59A	Medium-grained, rusty-weathering schist of	W	Perpendicular	37	Weathered fractures 30° to loading direction.
59B	Penobscot Formation.	W	----do---------	44	Failed along fracture.
59C		W	Parallel	25	Failed along weathered fracture 60° to loading direction.
59D		W	----do---------	6	Do.
46A 1	Gray, medium-grained, rusty-weathering, closely fractured Passagassawaukeag Gneiss.	W	----do---------	38	Failed along old rusty fractures; more fractured than 46 c, table 1.
46A 2		W	----do---------	12	Do.
42A 1	Medium-bluish-gray phyllite of Islesboro Formation.	F	----do---------	14	Vertical closed fractures; similar to 42A a, table 1.
42A 2		F	----do---------	16	Fractures 75° to loading direction; similar to 42A a, table 1.

[1]Location of samples is shown in figure 4.

[2]F, fresh; W, weathered or altered.

[3]Parallel or perpendicular to foliation or fractures. n/a indicates no obvious directional weakness.

[4]1 MN/m^2 equals 145 lbs/in^2. Testing performed in accordance with ASTM Designation D-2938-71a, 1975 edition.

probably as significant as variations between the two types of tests (for example, 40D-b, table 1, and 40D-2, table 2). Some individual test results were influenced by fractures. Unhealed fractures oriented at small angles to the loading direction were the main causes of strength variations among similar samples.

Relation of lithology to compressive strength

The amount of data collected so far is insufficient to categorize any of the mapped formations as engineering units on the basis of physical properties of the rocks. It is doubtful, however, that additional information would accomplish such an objective. For the metamorphic rocks, the intraformational strength variations are as great or greater than the interformational strength variations. For example, the compressive strength of fresh rock perpendicular to layering within the Penobscot Formation in the study area ranged from 113 MN/m^2 to 364 MN/m^2 (1 MN/m^2 = 145 lb/in^2), nearly the range of all rocks tested. Strength, as well as engineering rock units, is controlled by lithology, fabric, and structure. Rocks of the existing metamorphic formational units are simply too heterogeneous in these characteristics.

It is possible to separate lithologies into three broad groups--though there is considerable overlap between the groups--on the basis of the information in tables 1 and 2. The andesites of the Castine Volcanics, the metasiltstones of the Bucksport and Penobscot Formations, and fine-grained quartzites have compressive strengths ranging from 240 MN/m^2 to 427 MN/m^2. The granites range from 122 MN/m^2 to 259 MN/m^2. Phyllites and schists of the Ellsworth, Islesboro, Penobscot, and Bucksport range from 14 MN/m^2 to 252 MN/m^2.

The strength of rocks in the study area is influenced by planar features such as foliation, cleavage, and fractures. A knowledge of any significant directional control of strength is useful in assessing workability of the rock and in anticipating potentially severe conditions in the walls of excavations.

The ratio of the strength perpendicular to a discontinuity (such as foliation) to the strength parallel to a discontinuity is the anisotropy index. For the metamorphic rocks, the anisotropy index ranged from 1.1 to 9.4. The lower index values correspond to metasiltstones and gneisses with high tensile bond strength, whereas the high index values correspond to phyllites and schists with weakly bonded layers. The effect of a high anisotropy index would be most severe for slopes and walls oriented approximately parallel to the planar weakness and dipping toward the excavated surface.

Strength reduction due to alteration

Alteration includes the effects of such strength-reducing processes as weathering, micro-fracturing, and, in some cases, metamorphism and mineralization. Thus the effects of alteration may be near-surface (weathering) or may extend to depth (steeply dipping fracture zones). The few tests made on fresh and altered rock taken from the same outcrop indicate strength reductions of 20 percent (gneiss) to more than 300 percent (phyllite and granite). Knowledge of the extent of alteration and the predominant rock types would be useful in evaluating costs of surface or near-surface construction in rock.

Brittle behavior and rock bursts

The manner in which rocks deform and fail governs their potential for destructive rock bursts. Such rock failures have been numerous in coastal Maine granite quarries as a result of quarrying operations (Dale, 1907; Feld, 1966), and hazardous deformations might also occur during other types of surface or subsurface excavation. Experience indicates that these explosive rock failures largely depend upon the ability of the rock to store and release strain energy. Favorable conditions for rockbursts in crystalline rocks include strong, brittle, relatively unfractured rock, high horizontal stresses, and changes in the stress equilibrium state caused by excavation or solar heating. The manner in which rock is quarried may create large stress concentrations, leading to rock failure. Table 1 shows in a simple way how the various rock types in the study area behaved during tensile failure. Most of the lower grade metamorphic rocks (slates, phyllites, and schists) failed relatively slowly in a quiet ductile manner, whereas the higher grade gneisses and metasiltstones as well as andesite, quartzite, and fresh granite samples failed abruptly and explosively. Because fracture spacing is generally much closer and strengths are lower in the lower grade metamorphic rocks than in the granites, actual rock-burst conditions may be less likely in the lower grade metamorphic rocks than in the granitic rocks. Future work will deal with this problem, including microseismic effects, in more detail.

Relation of rock strength and structure to excavation

By combining the data on fracture spacing (fig. 4) and compressive strength (table 1), a practical guide to estimating the workability of the rock mass can be constructed (fig. 6). Additional data would more closely characterize the rock mass in the study area. For instance, badly decomposed rocks, some of which could be shoveled by hand, were not selected, as they are impractical for testing. Therefore, there are no data points within the "dig" category on figure 6. Such rock materials are shallow-weathering products or the result of intense mechanical deformation which extends to depth. These conditions are estimated to represent as much as 10 percent of the rock mass to a depth of 30 m. Otherwise, the range of bedrock workability is thought to be adequately represent. The objective here is to present excavation conditions at selected locations that also are representative of the study area.

The sample numbers in tables 1 and 2 correspond to the location numbers in figure 4. Several examples have been plotted on the graph (fig. 6). To illustrate the influence of the pronounced anisotropy of the metamorphic rocks on workability, strength values perpendicular and parallel to layering are given. All of the granitic rocks examined so far, even where moderately weathered, would fall in the "blast to fracture" category.

CONCLUSIONS

The linear features we observed on high-altitude images of coastal Maine are caused by lithologic contrasts, faults, and joints, features that are important to the preliminary planning of rock-construction projects. Field observations are required to confirm image interpretations and to provide quantitative data on fracture spacing and orientation, alteration, and the

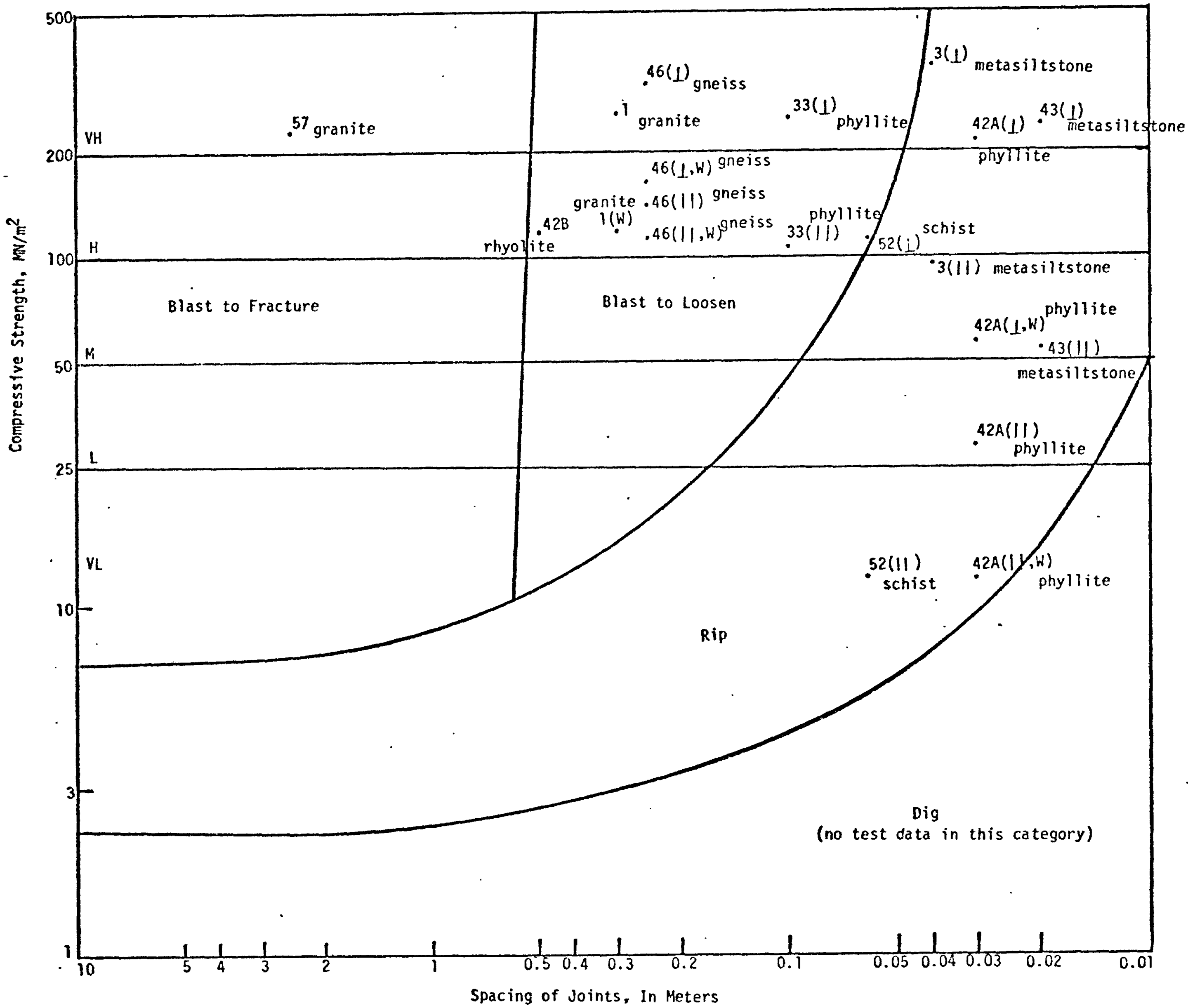

FIGURE 6.--Diagram showing workability of rock with examples from Penobscot Bay area, Maine (modified from Bieniawski, 1975, fig. 7). VH, very high strength; H, high strength; M, medium strength; L, low strength; VL, very low strength; (⊥), tested perpendicular to layering; (||), tested parallel to layering; (W), weathered. Data points are from table 1.

nature of faults. Some fault zones that were observed in the field could not be identified on the images because of a lack of sufficient topographic relief and the small scale of the images. One mode of lineament development appears to be the downslope movement of tabular blocks of foliated metamorphic rocks which are formed by jointing that is parallel and perpendicular to the lineament. The manner in which the joints form and their orientation is suggested by the high strength anisotropy ratios, indicating preferred weakness planes.

The types of field observations and test results presented here are applicable for the preliminary planning of many rock-construction projects. Such projects include shallow pipelines and oil-storage facilities, foundation conditions, underground waste disposal, and the excavation of deep water ports. Further, knowledge of the compressive strength of rock is necessary in estimating explosive requirements for blasting, the selection of drill bits, and in the design of cutters for boring machines. As in most classification schemes, the control of strength and fracturing on ease of excavation should be compared with actual field experience.

Satisfactory agreement between compressive strengths determined by point-loading and laboratory uniaxial tests increased our confidence in the field use of the point-load test. It would appear that quantitative ranges of rock conditions in other areas can also be estimated from simple field measurements, and the number of tests can be increased for more detailed site appraisals.

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