Maine Geological Survey
Studies in Maine Geology: Volume 2
1989

Geologic and Geomechanical Properties of the Mount Waldo Granite, Maine

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ABSTRACT

The Mount Waldo granite in southeastern Maine, although a generally massive rock, has rock-fabric properties which influence the geomechanical behavior of the rock. Strength and deformation properties in the pluton are directional and controlled by joint and microfracture orientations, which are themselves linked to the flow-induced alignment of microcline crystals. Vertical longitudinal and cross joints which formed during cooling of the pluton, as well as much younger, subhorizontal sheeting fractures, are commonly associated with subparallel, discontinuous microfractures. The orthogonality of microfractures (open, healed, and filled) establishes the ease of splitting of the granite. The direction of easiest splitting (rift) is subhorizontal, the direction of second easiest splitting (grain) is parallel to the cross joints, and the direction of least easy splitting (hardway) is parallel to the longitudinal joints and N-S orientation of microcline phenocrysts. These characteristics have permitted the quarrying of very regular blocks that are well suited to the construction of buildings and bridges. Where the alignment of potassium feldspar phenocrysts can be clearly recognized, the direction of most efficient mining can be established. When this relation is disregarded, difficult excavation and uneven breakage may result.

Static and dynamic measurements, made in the field and laboratory, established that structural features are responsible for a marked stiffness anisotropy of the granite. In the central part of the pluton the static Young's modulus in the north-south direction (longitudinal joint orientation) averages 31.1 GPa, in comparison to 20.9 GPa in the east-west direction (cross joint orientation). The stiffer north-south direction parallels the long C-axes of microcline phenocrysts and microfractures that were identified in outcrop, core samples, and thin sections. Young's dynamic moduli, which were derived from downhole seismic measurements and laboratory bulk densities, range from 2.5 to 16.1 GPa, which appears to be anomalously low when compared to laboratory static horizontal values. However, the field seismic values were confirmed by laboratory ultrasonic testing of oriented cores. The field results reflected the presence of closely spaced layers of open horizontal microfractures. Deformation and strength characteristics that are closely tied to fluid inclusion planes, mineral-filled microfractures, and microcline orientation could be extrapolated to greater depths with good hope of success of obtaining similar values.

Fabric and stress relationships suggest that openings should have walls north-south and east-west, with the long axes of underground excavations oriented east-west. Fluid migration in the granite is slow, as indicated by injection tests and by perched water levels in several mountainside quarries, which were observed to lose little water annually, other than through evaporation losses.

INTRODUCTION

Geomechanical studies of the Mount Waldo granite were prompted by the identification of this rock mass as being a potentially suitable host for a shallow underground oil repository (U.S. Department of Energy, 1980). The location of the pluton near a deep-water port, the massiveness, low permeability, and low seismic potential of the pluton, and a relatively high regional water table were favorable factors. However, quarries in similar massive rocks have experienced rockbursts, spalling, and squeezing rock conditions that result in hazardous operating conditions, increased maintenance costs, and in a few cases, abandonment of the facility. Severe rockbursts have been documented in the Mount Waldo granite (Dale, 1907). The geomechanical principles that control these events are poorly understood and warrant investigation so that future structures can be located where hazard-prone rock conditions are minimal, or so that the structures can be designed to accommodate hazardous conditions. Our investigation supplemented previous research on rock stresses in massive igneous rocks conducted by the U.S. Geological Survey (Lee and Nichols, 1972; Varnes, 1970; Lee et al., 1976; Nichols, 1986).

The main objectives of our study were:

1. To investigate the relationships among in-situ stresses, topography, and temperature gradient; and among rock fabric, rock strength, and deformation.

2. To determine the cause of rockbursts and to identify those parts of the granite that are susceptible to such conditions.

3. To evaluate field and laboratory information in terms of the feasibility of construction of underground oil-storage chambers.

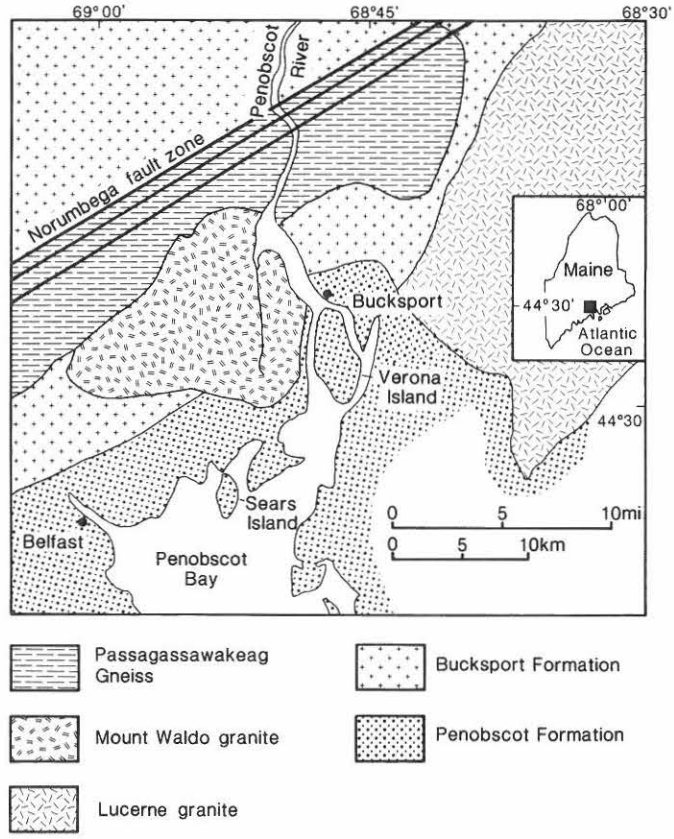

Figure 1. Location map of the Mount Waldo area, Maine, showing generalized geology (modified from Stewart and Wones, 1974.) Passagassawakeag Gneiss = Precambrian, Penobscot Formation = Ordovician, Bucksport Formation = Late Silurian to Early Devonian, Mount Waldo granite = Devonian, and Lucerne granite = Devonian.

GEOLOGIC SETTING

The Mount Waldo granite, located in mid-coastal Maine, is a Devonian age (390 Ma) pluton (Brookins, 1976) that intrudes tightly folded, northeasterly striking Precambrian and lower Paleozoic schists, gneisses, quartzites, and migmatites (Fig. 1). The granite is holocrystalline, light to medium gray, medium- to coarse-grained and porphyritic. It contains perthitic microcline (42%), plagioclase (29%), quartz (25%), and mafics (principally biotite, 4%). At the contact with the metamorphic country rock, the granite is fine- to medium-grained and non-porphyritic with allotriomorphic texture.

In the northwest part of the study area, the Passagassawakeag Gneiss (Bickel, 1971) is the host country rock for the granite and is thought to be of Precambrian age (Wones, 1977). The metamorphic rock is a quartz-feldspar-biotite augen gneiss with less common layers of quartz-muscovite-biotite schist and biotite schist. Mylonitic textures as well as intrusive migmatites are abundant. Several episodes of deformation and regional metamorphism have deformed the gneiss and have produced rocks of the second sillimanite grade. The rock is foliated throughout (Fig. 3); however, gneiss, migmatite, and quartz-biotite-muscovite schist tend to be more massive than the biotite schist. Major joints, N45-55°E, 50-60°NW, are parallel to foliation, and a secondary but strong joint set is oriented N80°W, 75°SW. Sheeting is poorly developed in the gneiss, and commonly only one or two sheets, which are less than 1 m thick, can be recognized.

Faulting affected the region throughout Paleozoic time, and considerable movement took place before the emplacement of the Devonian granite plutons (Wones and Stewart, 1976). The Norumbega fault zone, a major structural feature in northern New England, consists of at least three separate fault traces in a zone approximately 2000 m wide (Wones, 1977) (Fig. 1). The overall motion on the strike-slip fault is right-lateral, and most movement occurred in mid-Paleozoic time. In the study area the fault zone strikes consistently N60°E and dips steeply to the northwest, approximately parallel to the foliation of the gneiss. According to D. R. Wones (pers. commun., 1978), little, if any, Quaternary movement has taken place along the fault.

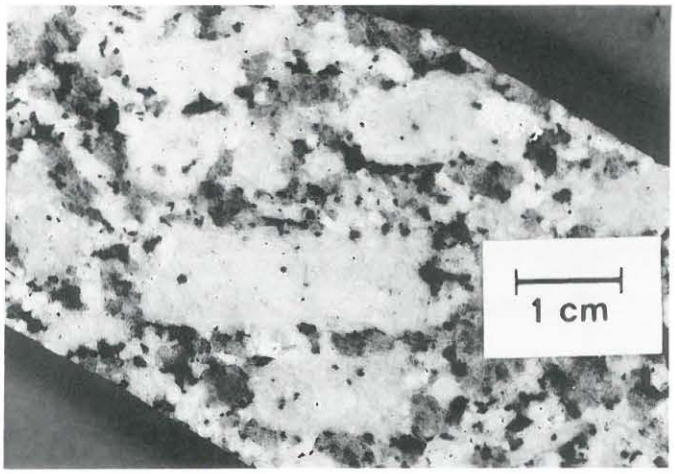

Figure 2. Photograph of sample of Mount Waldo granite from site 7 (Fig. 3) showing alignment of large, light-colored microcline grains.

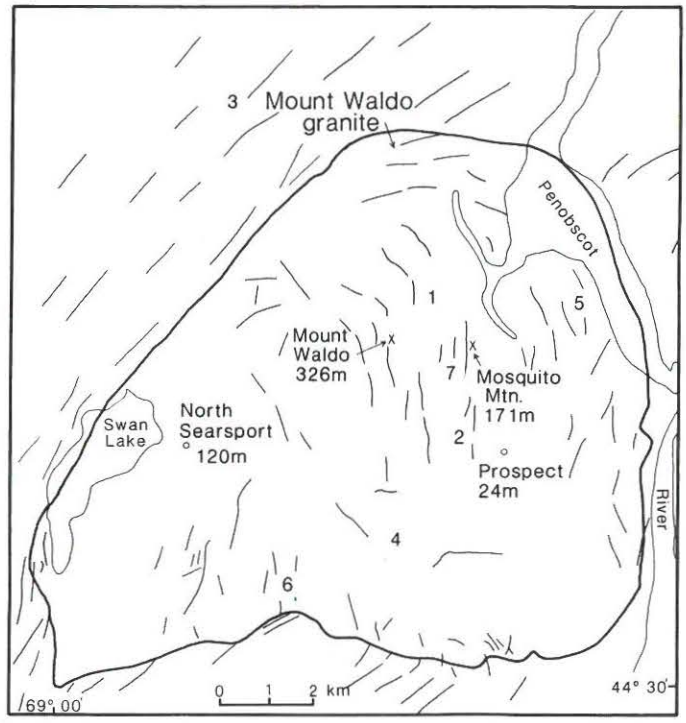

Figure 3. Foliation trend lines of microcline phenocrysts in the Mount Waldo granite and strike of foliation in the country rock. Dips generally exceed 75°. Data in part from Trefethen (1944) and D. R. Wones (unpublished map, 1977). Numbers show location of test sites described in text.

PLUTON GEOMETRY AND EMPLACEMENT

In plan view the granite mass is elongate to the northeast and has a long dimension of approximately 19 km and an exposed area of 170 km^2 (Fig. 1). Sweeney (1976) constructed a three-dimensional model of the pluton based on gravity data and structural features. The body is steep sided, and its horizontal area decreases slightly with depth. Sweeney's model shows that the average thickness of the pluton is less than 7 km; the deepest zone is south and west of the outcrop center. The deep zone ("root zone") is apparently separated into two northeast-trending sections, which may reflect the presence of zones of weakness parallel to the tectonic strike, along which upwelling from a common parent source took place (Sweeney, 1976). Flow may have been from south to north because flow lines, reconstructed from aligned microcline phenocrysts (Fig. 2), trend east-west at the north end of the body, where magma may have been deflected at the north end of the chamber (King, 1977). The general effect of the flow process was to orient the longer C-axes of microcline phenocrysts roughly north-south, which is parallel to the direction of magma movement. The average strike of the long axes of microcline phenocrysts is N5°E, but a range of orientations was measured because local conditions affected grain orientation (Fig. 3). Near the chamber walls where flow was restricted, the orientation of long axes is less well defined than in the center of the mass. Similar conditions in other plutons were recognized by Balk (1937), who distinguished "principal flow" from "local flow."

The Mount Waldo granite was probably intruded along a structurally weak zone in the Passagassawakeag Gneiss at the culmination of regional Acadian thermal and structural events in Maine. Stress conditions during emplacement were probably the same as those that caused the right-lateral faulting that dominated the region throughout middle Paleozoic time and controlled episodic movement along the Norumbega fault zone (Wones and Stewart, 1976).

STRUCTURAL FEATURES OF THE MOUNT WALDO GRANITE

Sheeting

The most conspicuous structural feature of the Mount Waldo and other coastal granites is the pervasive sheeting (exfoliation) which has developed parallel or subparallel to topographic surfaces (Fig. 4). The sheeting is best developed in massive rock and was observed in all exposures of the granite. Sheets are 3-20 cm thick at the surface, typically increasing to 3 m and greater at depths of 7-15 m as seen along quarry walls and in drill cores.

The sheeting fractures pass through vertical diabase dikes that are the youngest (200 Ma; McHone, 1978) igneous rocks in the region. On the basis of age and topographic relations, the sheeting probably did not result from shrinkage associated with cooling of the magma. Such fractures would seem to belong to the general category of "unloading fractures" that typically appear suddenly after the release of confining pressure (Ollier, 1969). In the gneiss, however, deformation from unloading presumably took place along abundant preexisting joint and

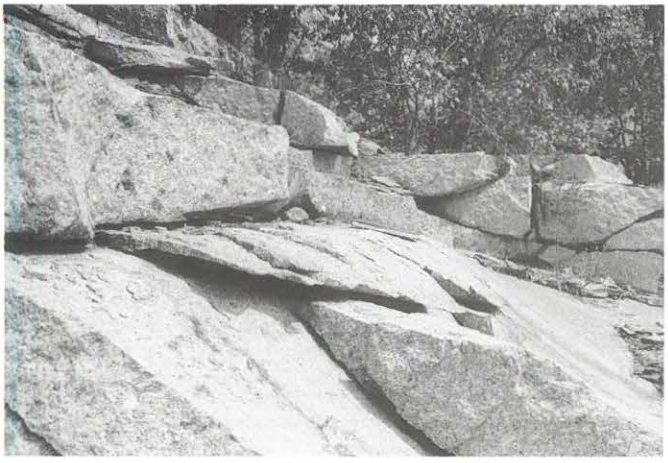

Figure 4. Development of sheeting in the Mount Waldo granite. Fractures closely reflect changes in topographic slope. Notebook is 21 cm long.

Figure 5. Subhorizontal shear zone in the Mount Waldo granite near site 1.

foliation surfaces. In the study area we have observed sheeting to depths of 30 m in the granite (where it shows slight alteration), but it may extend deeper as it does in granitic rocks elsewhere in New England. Local subhorizontal shear zones are closely associated with upper levels of sheeting (Fig. 5). These shear zones consist of closely spaced, en-echelon fractures that are oblique to the bounding sheets and that contain sand- to clay-size gouge material. These fracture features probably formed at locations of shear stress concentrations.

Joints and Dikes

A relationship between joint attitudes and feldspar phenocryst alignment has been reported in massive igneous rocks (Balk, 1937; Hutchinson, 1956). Primary cooling joints in the Mount Waldo pluton are at high angles (cross joints) and parallel (longitudinal joints) to the microcline lineation and are consistently vertical or near vertical (Figs. 3, 6, and 7). The cross and longitudinal joints strike approximately east-west and north-south, respectively, except near the boundaries of the pluton where flow was less regular (Fig. 7). The primary joints commonly are spaced 1-2 m apart. The cross joints acted as hosts for the widespread intrusion of aplite dikes during Late Devonian and/or Early Mississippian time (362 Ma; author's unpublished data). Aplite dikes pervaded the adjacent country rocks to a lesser extent (Fig. 8). In Late Triassic and Early Jurassic time (225-200 Ma; McHone, 1978), a few cross joints were again opened and diabase dikes were emplaced. However, these diabase dikes are rare, even though they extend several kilometers along strike.

Renewed regional east-west compression in post-Mississippian time caused right-lateral displacement on the nearby Norumbega fault and probably produced the infrequent northeast- and northwest-striking conjugate shear fractures in the Mount Waldo granite pluton (Wones and Stewart, 1976). Diabase dikes reportedly have been offset along a northeast-striking vertical fracture 50 km southeast of the study area, suggesting that the shear displacements may be less than 225-200 Ma (Westerman, 1981). A few of the northeast-striking fractures form gouge zones, but both the gouge zones and individual conjugate shear fractures are discontinuous and less numerous than the primary cooling fractures.

Microfractures

The pluton contains abundant discontinuous microfractures (open, healed, and mineral-filled) that are oriented in three different directions, approximately perpendicular to each other. The microfractures are oriented (1) parallel to the cross joints, (2) parallel to the longitudinal joints, and (3) parallel to the sheeting fractures (Figs. 7, 8, 9, and 10).

The open microfractures have surfaces with no mineral deposition. Numerous fluid inclusion planes (or bubble trails) are healed microfractures that have been resealed within a grain by the same optically continuous mineral. Filled microfractures contain primary and/or secondary alteration minerals that are unlike the host grain.

The majority of microfractures that were observed are open and are contained within, or transgranular through, clusters of quartz grains (Fig. 10a). Most of the open microfractures are horizontal or subhorizontal and appear to be related to the young sheeting fractures. The density of open microfractures increases as a sheeting fracture is approached. Many of the open microfractures are vertical and parallel fluid inclusion planes, or are regenerated along these bubble trails, which indicates a weakness along resealed fractures (Fig. 10b). Where the sheeting follows changes in topography, many microfractures and fluid inclusion planes persist in the horizontal plane.

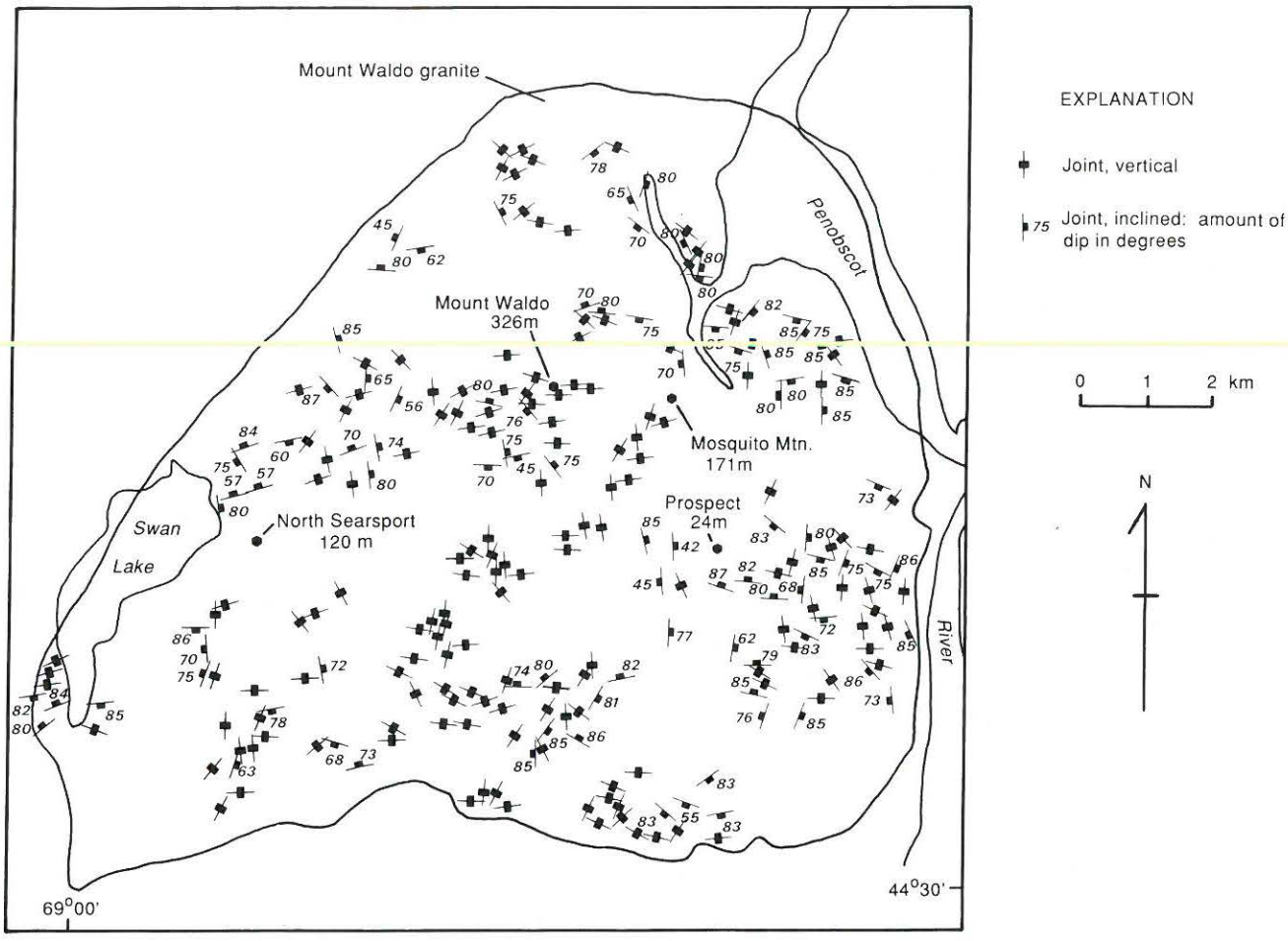

Figure 6. Primary cooling joints (longitudinal and cross) mapped in outcrops, quarries, and roadcuts.

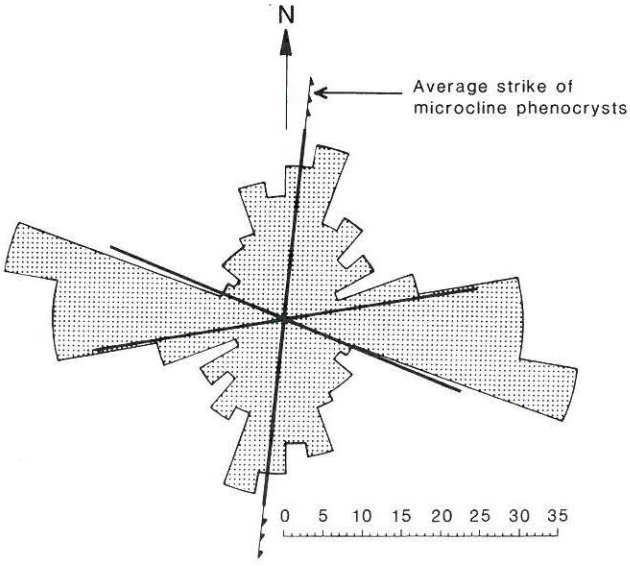

Figure 7. Rose diagram of the strikes of 300 primary cooling joints in the Mount Waldo granite. One scale division equals one joint. Heavy lines represent average strikes of predominant microfracture orientations.

Parallel and intersecting fluid inclusion planes are a common feature in vertical and horizontal planes of view within quartz aggregates and feldspar crystals (Fig. 11a). Tuttle (1949) believed that the fluid inclusions formed along old, partially healed microfractures which were produced in the rock during previous stress regimes.

The least common type of microfractures that were observed are mineral-filled, parallel sets of microfractures confined within the large microcline phenocrysts. The minerals filling the microfractures include quartz, plagioclase, biotite, and epidote. These do not appear to be simple dilational microfractures because the lamellae of plagioclase grains enclosed by the microcline are offset (Fig. 11b). Kinked biotite and deformed quartz grains next to these microcline grains suggest that shearing took place. Epidote-lined microfractures found within shear zones in the granite support this conclusion. The vertical mineral-filled and open microfractures that trend in the cross-joint (east-west) direction appear to be the same age.

Microfractures influence the ease of splitting in the granite. The greatest ease of splitting (rift) is subhorizontal, parallel and subparallel to the sheeting fractures. The second easiest direc-

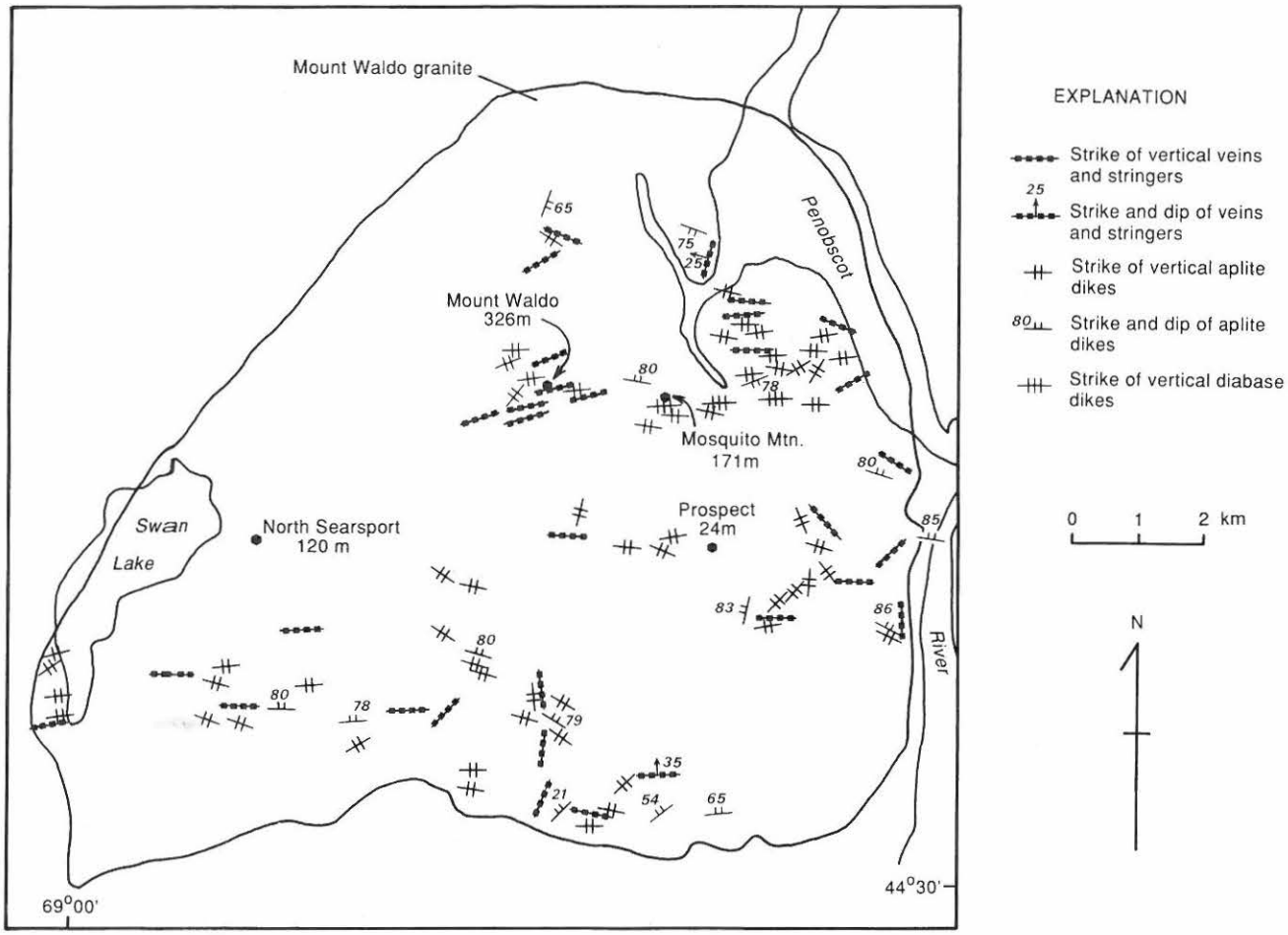

Figure 8. Dikes, aplite veins, and mineralized stringers in the Mount Waldo granite.

tion of splitting (grain) is parallel to the cross joints. The most difficult direction of splitting (hardway) is parallel to the longitudinal joints (Fig. 9).

MECHANICAL PROPERTIES AND ROCK FABRIC

Microfracture geometry and microcline phenocryst alignment are the chief factors responsible for directionality in the tensile and compressive strength, Young's modulus, and sonic velocities in this rock (Lee et al., 1984). The influence of microfracture orientation on the compressibility, strength, and porosity of granitic rocks has been investigated by several workers (Walsh, 1965; Brace, 1965; McWilliams, 1966; Norman, 1967; Douglass and Voight, 1969). The observed microfractures are short (< 13 mm) and discontinuous, and their abundance varies spatially. Values of Young's modulus as measured by both static compression and ultrasonic tests for the stiffest horizontal directions, are consistently concordant with the microcline alignment (N10°W-N25°E), and range from 10 to 84% greater than the east-west values (Table 1). A partial explanation for this apparent control is that microcline, the most abundant mineral in the granite, has a high Young's modulus parallel to the long C-axis. According to Brace (1965), microcline is the most anisotropic of common, low-symmetry minerals, and he reported values of linear compressibility for various axial directions that vary by as much as 382%. At test site 4 (Fig. 3) in the southern part of the pluton, the microcline alignment departs from the norm and is aligned at N60°W, and the maximum direction of greatest horizontal stiffness is approximately N45°W.

Downhole seismic measurements showed low dynamic Young's moduli (2.5-16.2 GPa) for the granite, which intially appeared anomalously low when compared to static (horizontal) values that range from 15.0 to 33.6 GPa. These values, however, were confirmed by laboratory ultrasonic testing of cored granite. Samples taken from fresh, massive blocks yield Young's modulus values for the east-west grain direction that are about 2.5 times greater than those for the vertical direction. By applying a vertical uniaxial compression perpendicular to the rift

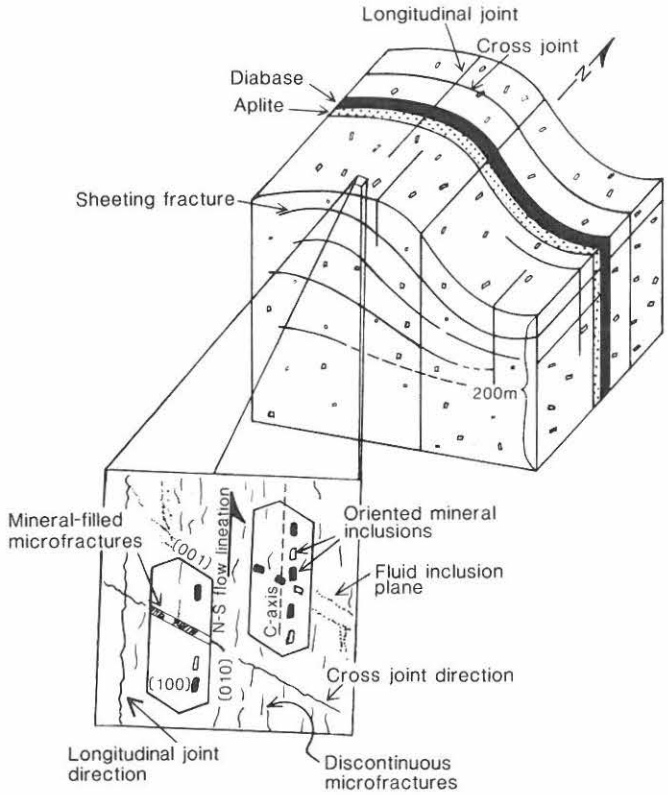

Figure 9. Generalized diagram of central zone of Mount Waldo granite. Structural features are exaggerated. Rift direction (easiest splitting) is subhorizontal, grain direction is parallel to the cross joints, and C-axes of microcline and the hardway follows the longitudinal joints. All three directions are parallel to microscopic fluid inclusion planes or open microfractures. Enlargement shows two microcline phenocrysts and various microstructures.

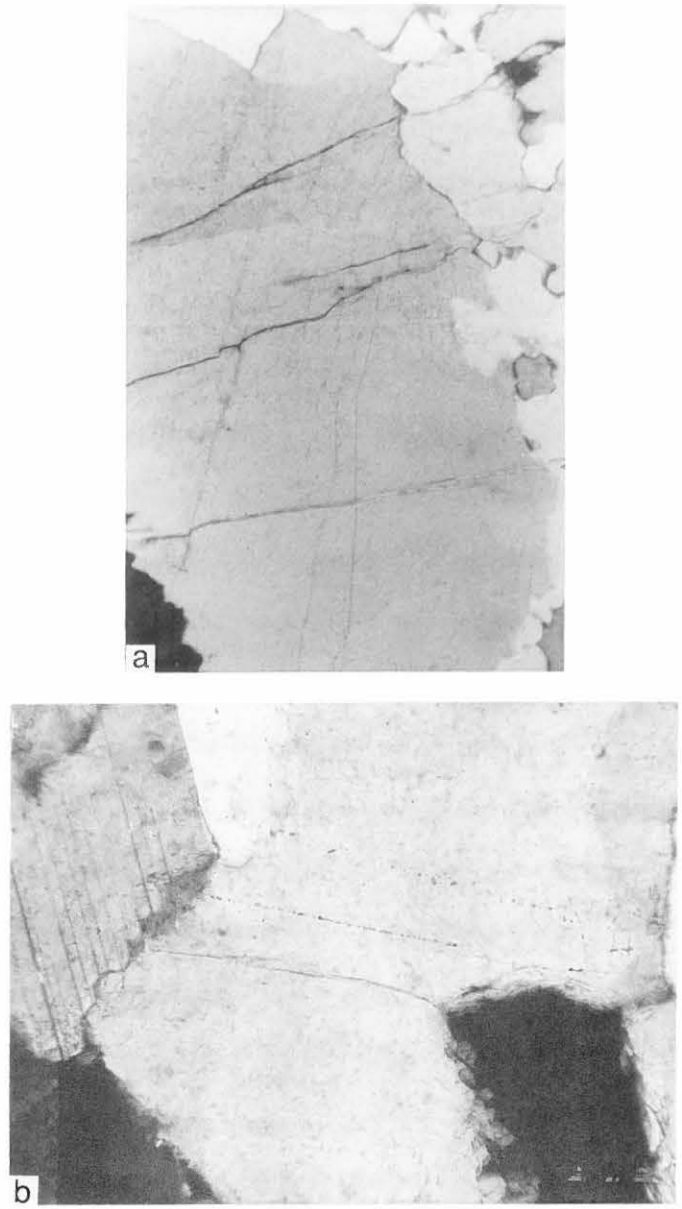

Figure 10. (a) Photomicrograph of transgranular, open microfractures through quartz and plagioclase grains (site 2 on Fig. 3). These open microfractures are horizontal and parallel the young sheeting fractures. Field of view is 5 cm. (b) Photomicrograph of open horizontal microfractures that are parallel to fluid inclusion planes. Field of view is 2 cm.

direction, this difference can be reduced to 10-20 percent under average pressures of 20 MPa, which corresponds to a depth of approximately 800 m. Upon removal of load, samples recover only a fraction of their high pretest anisotropy. The seismic field results reflected the presence of closely spaced horizontal to subhorizontal open microfractures (Figs. 10a and 10b). At depth, fractures are probably closed and differences in modulus anisotropy should be reduced.

IN-SITU STRESSES

Measurements of horizontal stresses in the Mount Waldo granite and the adjacent metamorphic rock were obtained from shallow drill holes by using the U.S. Bureau of Mines (USBM) overcoring method (Hooker and Bickel, 1974). These field operations were carried out in 1978 and 1982 (Fig. 12).

Measurement Procedures

The USBM overcoring method for measuring stress consists of: (1) drilling a 38-mm diameter hole in the rock with an EX-size diamond drill bit; (2) placing an oriented borehole deformation gauge in the hole; and (3) drilling a concentric 152-mm diameter slot around the inner borehole and gauge, while monitoring the resultant change in diameter of the inner borehole. The borehole deformation gauge detects the changes in diameter simultaneously along three diameters oriented at 60° to each other in the plane perpendicular to the axis of the hole. These diametral changes occur when the annular volume of rock between the gauge and the outer slot is freed from the stresses

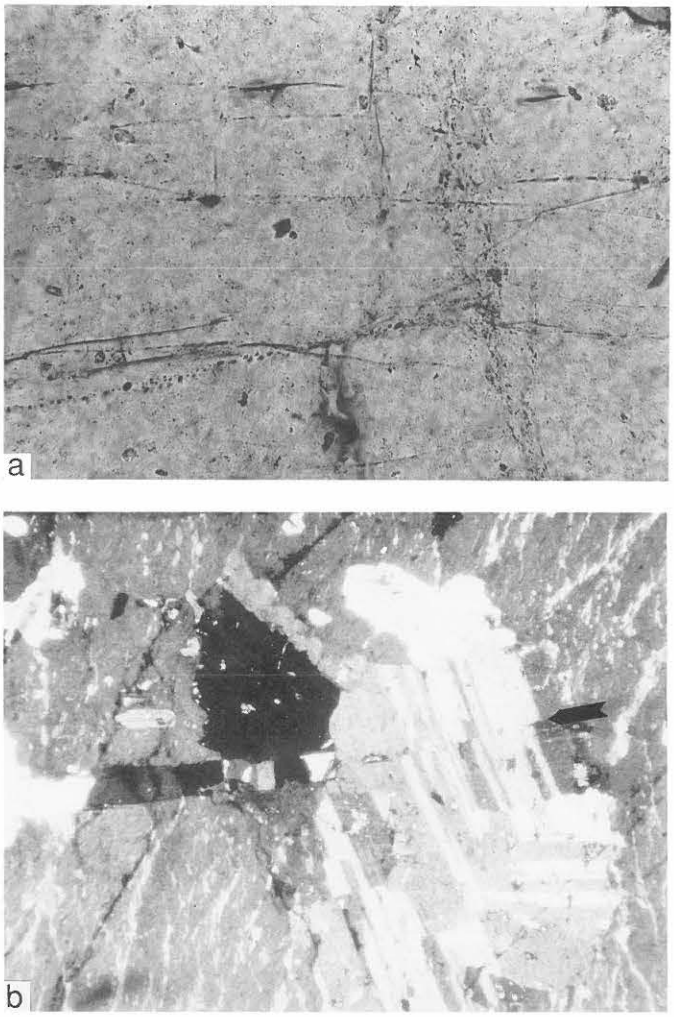

Figure 11. (a) Vertical photomicrograph of intersecting vertical and horizontal fluid inclusion planes in a quartz grain (site 2 on Fig. 3). Field of view is 2 mm. (b) Horizontal photomicrograph of parallel sets of mineral-filled microfractures within a microcline grain. Note the offset of lamellae in the included plagioclase grain (arrow). Field of view is 7 mm.

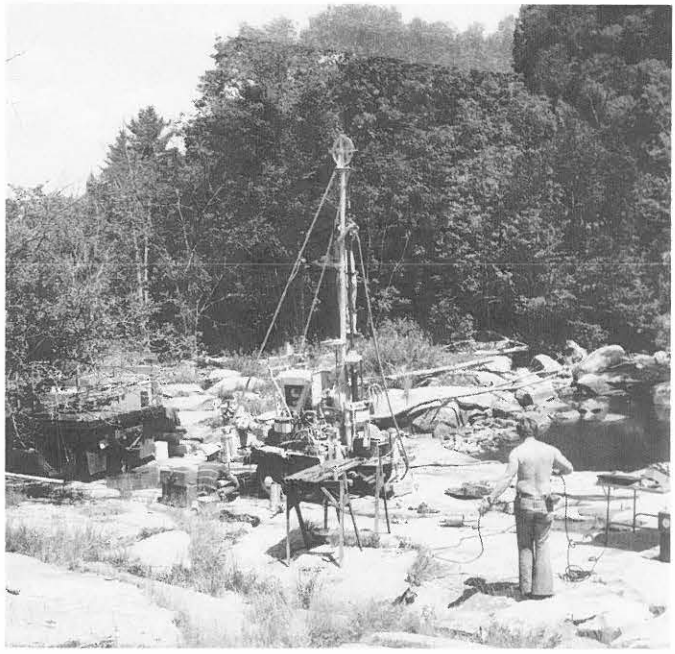

Figure 12. Overcore stress-relief measurements being made at site 2 (Fig. 3). Traces of widely spaced vertical, orthogonal cooling joints are accented by vegetation.

that existed on it prior to the overcoring. A knowledge of the rock's elastic constants allows one to convert the diametral changes into stresses that existed prior to drilling the inner hole. The Young's modulus of the rock is measured after overcoring by using a biaxial pressure chamber to pressurize the outside diameter of the sample, while the change in its inner diameter is measured with the borehole deformation gauge (Fitzpatrick, 1962). Modulus measurements were generally made within 1-3 hours after overcoring.

Factors That Influence Stress Measurements

Stress measurements and their interpretation may be influenced by several factors including rock anisotropy, faulting, temperature, and topography (Hooker and Johnson, 1969; Tullis, 1981; Lee et al., 1976; Savage and Swolfs, 1986). For these reasons, stress-relief measurements should be analyzed in light of in-situ conditions. Sites for this study were selected in order to minimize local topographic effects, where possible, and were concentrated in the eastern part of the pluton where an oil-storage facility most likely would be located.

Topographic Effects. Topographic modifications of gravitational and tectonic stresses can be caused by valleys or ridges (Savage and Swolfs, 1986; Jaeger and Cook, 1969). The results of the study by Savage and Swolfs (1986) show that topography reduces horizontal tectonic compression near the crests of ridges and concentrates tectonic stress in valleys. In the case of gravity-induced stresses, compression is developed at and near ridge crests and horizontal tension develops under the valley. These latter effects were not detected in our measurements. Quantitatively correcting stress measurements for the effects of minor irregularities and subdued topography is difficult and probably unwarranted.

However, several of our measurement sites (1, 2, 5, and 7) were on ridges or hillslopes whose presence may have altered the regional stress field. For example, north-trending ridges and an east-oriented principal horizontal stress would cause shallow stresses (i.e., above the intervening valley bottoms) to be reduced in the east-west direction. Measurements on or near the ridge tops would erroneously indicate that the regional stress was greater in the north-south direction. Inspection of the topography and stresses at site 1 (Fig. 13, Table 1) shows that the east

TABLE 1. IN SITU HORIZONTAL STRESSES, YOUNG'S MODULI, AND RELATED INFORMATION FROM THE MOUNT WALDO GRANITE AREA, MAINE.

Field Site[1]	Depth (m)	Principal horizontal stress Maximum (MPa)	(σ_1) (strike)	Minimum (MPa)	(σ_2) (strike)	σ_1/σ_2	Average Young's modulus (E) (GPa)	High E / Low E	High E direction	Low E direction	Strike of topographic contours	Strike of microcline C-axes	Strike of steeply dipping joints[2]	Strike of steeply dipping microfrac.
1	0.46	5.88[3]	N14°E	2.45	N76°W	2.40	23.30	1.13	N12°W	N63°E	----	----	----	N5°E
	2.33	5.36	N36°W	2.67	N54°W	2.01	25.16	1.19	N63°W	N27°W	----	----	N30°E	N18°E
	5.38	12.02	N35°E	5.61	N55°W	2.14	29.92	1.10	N3°E	N87°W	N-S	N-S	N80°E	----
2	0.81	2.86	N3°E	0.74	N87°W	3.86	15.03	1.22	N23°W	N52°E	----	----	----	N20°E
	2.41	5.15	N1°W	1.25	N89°E	4.12	18.48	1.47	N8°W	N82°E	----	N-S	----	N45°E
	5.49	1.02	N19°E	0.02	N71°W	3.19	20.54	1.84	N52°E	N53°W	----	----	N40°E	N85°E
	7.85	7.65	N28°E	1.41	N62°W	5.43	19.65	1.35	N60°E	N26°W	N18°E	----	N20°W	N59°W
3	0.53	1.36	N69°E	0.03	N21°W	45.33	26.34	1.37	N12°E	N63°W	----	----	----	----
	4.42	1.11	N45°E	-0.16	N45°W	6.94	26.47	----	----	----	----	----	----	----
	6.76	5.86	N54°E	3.36	N36°W	1.74	26.47	----	----	----	N79°W	----	N50°E	----
													N80°W	----
4	0.36	4.23	N77°W	0.60	N13°E	7.06	23.99	1.22	N45°W	N75°E	----	N60°W	----	N72°E
	3.56	8.38	N56°E	2.46	N34°W	3.41	30.13	1.15	N15°W	E-W	----	N80°E	N40°E	----
	5.38	14.95	N79°W	4.74	N11°E	3.15	33.64	1.26	N30°W	N45°E	N15°E	N70°E	N62°W	----
5	2.24	5.17	N14°E	3.87	N76°W	1.34	24.27	1.20	N7°W	N82°W	----	N2°W	----	N-S
	3.56	6.32	N42°W	4.25	N48°E	1.49	25.99	1.34	N38°E	N67°W	----	N13°E	----	N84°E
	4.80	4.64	N10°E	1.94	N80°W	2.32	25.65	1.41	N8°E	N83°E	----	N7°W	----	----
	5.82	2.81	N12°E	0.88	N78°W	3.19	25.37	1.25	N37°W	N83°E	----	----	----	----
	6.64	1.85	N22°E	-0.68	N68°W	2.73	24.82	1.18	N22°W	N83°E	----	N7°W	N15°E	----
	6.96	2.55	N17°E	-0.26	N73°W	9.81	23.51	1.37	N7°W	N83°E	N13°W	N7°W	N80°W	----
6	3.81	4.20	N62°W	1.48	N28°E	2.84	22.54	1.23	N8°W	N83°W	----	N11°W	----	N65°W
	5.38	5.78	N28°W	2.23	N62°E	2.59	27.16	1.32	N7°E	N83°W	----	----	----	N82°W
	6.55	5.50	N36°E	3.14	N54°W	1.75	30.68	1.31	N7°E	N83°W	----	N8°W	----	----
	7.19	6.63	N51°W	2.97	N39°E	2.23	27.99	1.32	N8°W	N67°E	----	N13°W	----	----
	7.59	4.55	N41°E	3.81	N49°W	1.19	26.96	1.35	N8°W	N83°W	----	----	----	----
	8.00	5.22	N82°W	3.70	N8°E	1.41	28.96	1.29	N8°W	N67°E	----	N2°E	N5°E	----
	8.41	5.69	N57°W	3.22	N33°E	1.77	29.85	1.51	N23°W	N82°E	N7°E	----	N60°W	----
7	3.76	4.28	N23°E	2.01	N67°W	2.13	26.61	1.29	N12°W	N78°E	----	N10°E	----	N-S
	5.77	7.22	N16°W	4.74	N74°E	1.52	26.27	1.28	N27°W	N63°E	----	N25°E	----	N55°W
	8.38	3.41	N8°W	2.10	N82°E	1.62	25.99	1.47	N3°E	N78°E	----	----	N80°W	----
	8.91	2.94	N6°W	1.72	N84°E	1.71	26.96	1.58	N18°E	N87°E	N18°W	N25°E	N10°E	----

[1]Field sites shown on Figure 3.
[2]The most prominent joints at each site are given first.
[3]Compressive stress is positive.

flank of Mount Waldo trends north to northeast. The maximum principal horizontal stresses are consistently northeast, which suggests that a topographic effect may be present.

Stresses at several other sites appear to be influenced by local topography, particularly in the northern part of the pluton where there is steeper terrain. At sites 2, 5, and 7 the maximum horizontal stress is typically within a few degrees of the strike of local topography (Table 1, Fig. 13). At depths well below the water table where oil-storage caverns would be excavated, we expect horizontal stresses to be compressive and the maximum compression to be oriented in an east-northeasterly to easterly direction.

Rock Coupling. In areas where the bedrock is fractured and weathered, the rocks near the surface may be poorly coupled to the deeper rock mass. Such a condition would affect the magnitudes and possibly the directions of shallow horizontal stresses, and make unreliable their extrapolation to the depths at which an oil-storage facility would be located. These effects would be minimal, however, in the massive, unweathered rocks where our stress measurements were made. At most sites, joints are widely spaced and closed. Sheeting fractures, which decrease with depth, attain a spacing of more than 1 m below a depth of 3-4 m and their effect on stress directions is minimal below these depths (Table 1).

Anisotropic Rock Properties. Rock-mass anisotropy that is caused by fractures and mineral alignment commonly produces directional stiffness variations that may be sufficiently great to affect stress determinations (Becker and Hooker, 1967).

In order to convert the borehole displacements that were measured during the overcoring process to stresses, it is necessary to know the elastic properties of the rock. Tullis (1981) has discussed the procedures involved and has presented the approximate solutions for stresses in anisotropic or nonelastic rocks. In general, the granite samples that we tested are approximately linearly elastic, but not isotropic. For example, the Young's moduli at each site are directionally dependent and

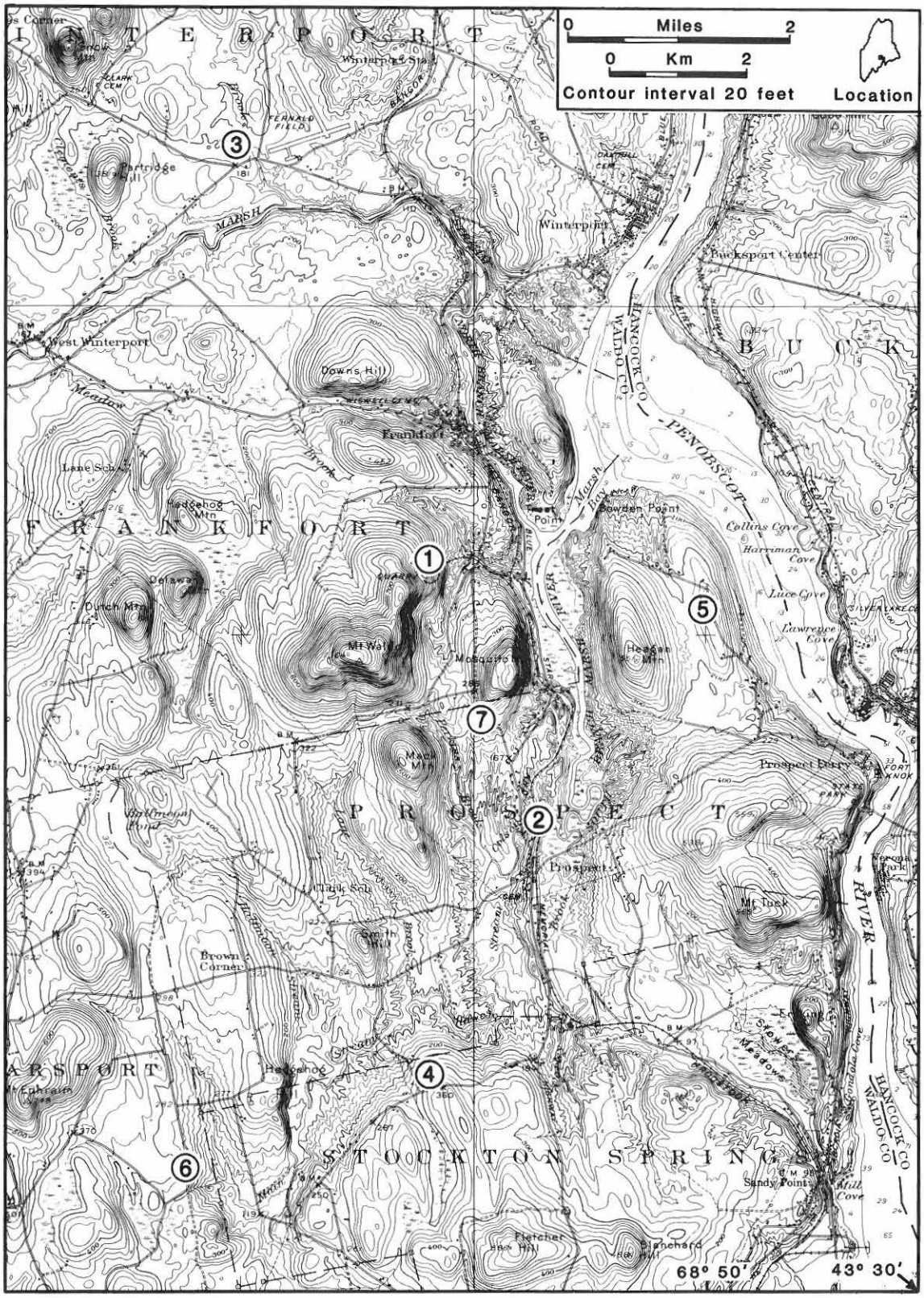

Figure 13. Location map of sites of overcore stress measurements in the Mount Waldo granite and adjacent gneiss showing the relation of sites to topography. Base from 1:62,500-scale, U. S. Geological Survey Bucksport 15-minute quadrangle map.

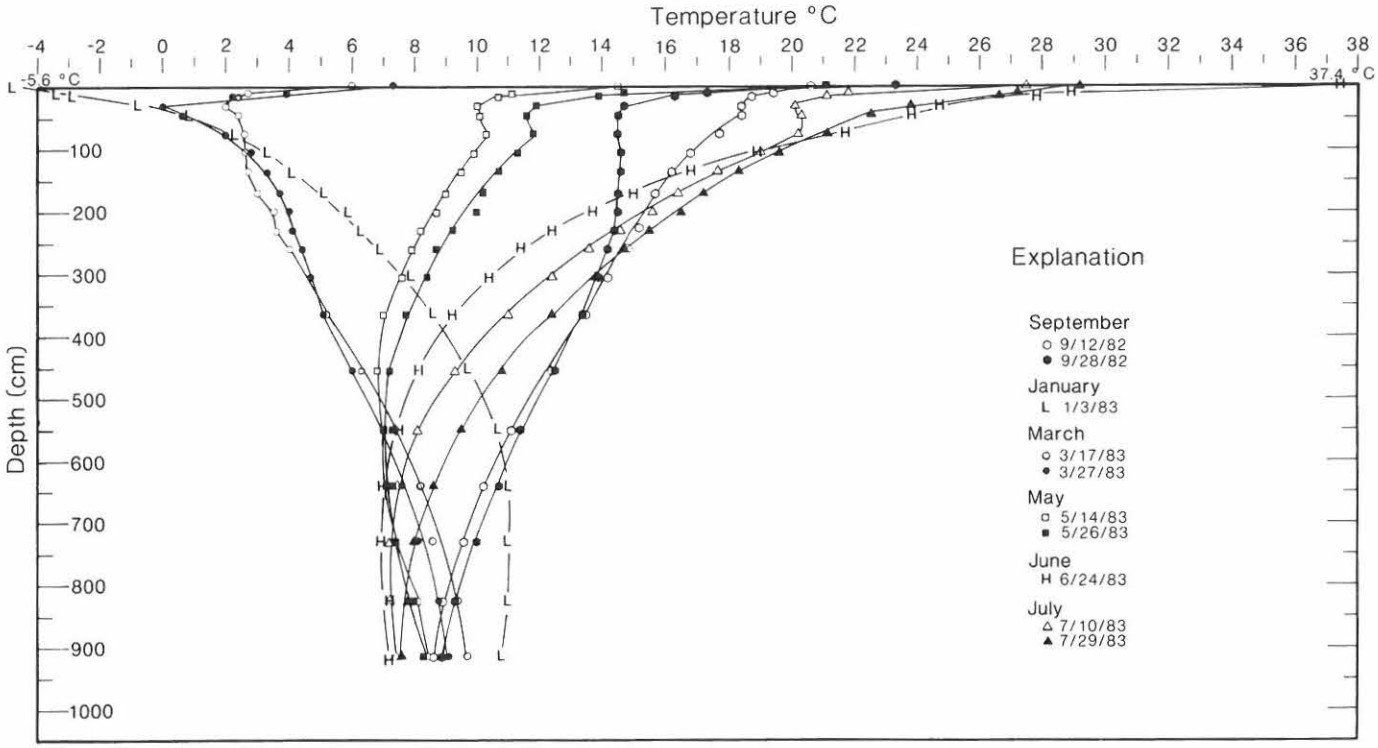

Figure 14. Graph of measured variation of rock temperature with depth and time at site 5 (Fig. 13) showing attenuation in amplitude of the annual surface-temperature cycle. In 1982-83 near-surface temperature extremes occurred in early January (L) and late June (H). However, in other years lows occurred in January and February and highs occurred in July and August.

commonly vary by 20-70% in the horizontal plane (Table 1). We used the approximate anisotropic treatment of Tullis (1981), which consists of modifying the observed expansion upon overcoring by a factor that accounts for the relative stiffness in each direction as compared to the average. This modification increases those actual expansions measured in directions of large modulus and decreases those actual expansions that were "too large" because of a small modulus. The calculated stress directions are little changed by this operation (Tullis, 1981).

Rock Temperature. Several investigators have determined that rock-temperature changes may significantly affect near-surface stresses. Hooker and Duvall (1971) made measurements to depths of 5 and 25 feet in granite quarries near Mount Airy, North Carolina, and Marble Falls, Texas, respectively. These researchers found that diurnal variations are significant to a depth of 1-2 ft (0.3-0.6 m) and annual temperature variations are significant to a depth of at least 25 ft (7.6 m). Hooker and Duvall (1971) measured heat flow in the Texas granite and found the diffusivity constant to be 0.013 cm/s. This agrees well with the results of a study by Swolfs and Savage (1984) who determined a diffusivity constant of 0.012 cm/s for a volcanic cap rock. Both of these investigations showed that observed temperature variations compared favorably with theoretical predictions. Hooker and Duvall (1971) found that the yearly temperature change at a depth of 1 ft (0.3 m) is 47.2°F (8.4°C) which produces a stress change of 1166 lbs/in^2 (8.04 MPa), and that at a depth of 25 ft (7.6 m) the annual stress change is less than 60 lbs/in^2 (0.41 MPa).

The annual temperature cycle from the surface to a depth of 9.2 m was measured at sites 4 and 5 (Fig. 13). A typical plot of rock temperature variation with depth and time at site 5 is shown in Figure 14. Below a depth of 5.5 m, the annual temperature variation is less than 3°C, which would produce stress changes of approximately 0.5 MPa using the stress/temperature relationship of Hooker and Duvall (1971). Most of the stresses reported here (Table 1) were determined in July and August of 1978 and 1982, although the measurements at sites 6 and 7 were made in October 1982. At depths greater than about 6.5 m, the highest temperatures are in early winter and the lowest are in early summer, so that there is minimal temperature-induced stress at these levels. However, the magnitudes of horizontal stresses measured at all sites in granite at approximate depths of 0.5-5 m likely have a large component of temperature-induced stress, as much as 3 MPa at 1 m. According to Hooker and Duvall (1971), changes in rock temperature do not significantly affect stress directions. The extreme fluctuations of diurnal and annual temperature in the upper 0.3 m of the granite may account in part for the spalls and pop-ups observed on large, exposed surfaces.

ROCK-MASS PERMEABILITY

The ability of fluids to flow through the rock mass is of obvious importance in its evaluation for oil-storage or water-supply use. Sheeting fractures and primary cooling joints form an intersecting network near the surface of the pluton that enhances ground-water movement and permeability. However, the decreased frequency of sheeting fractures with depth creates a favorable situation for oil storage in underground chambers. Constant-pressure injection tests were performed in order to make a preliminary estimate of ground-water conductivity within the granite. The testing was done at site 2 (Fig. 13) where vertical jointing is probably representative of the granitic mass, although sheeting fractures are more closely spaced at greater depths than at other sites. Of special interest at this location is a nearby perennial stream which may account for the alteration found on joints and sheeting surfaces as well as on associated microfractures at the 30 m depth mentioned previously. The ground-water level was approximately 2 m below the surface at the time of testing (mid-September). A series of 13 tests were made at depths of 24-27.3 m in a 7.57 cm-diameter hole. Straddle packer pressure averaged 2.76 MPa, and water pressure in the 0.91-m test zone averaged 1.52 MPa.

Hydraulic conductivity, K, in meters per second, was calculated according to the formula given by Zeigler (1976):

$$K = Q/(2\pi L \Delta H_w) \ln(r_e/r_w) \qquad (1)$$

where Q = flow, in meters per second,
L = length of pressurized zone, in meters,
H_w = water head, in meters,
r_w = radius of well bore, in meters, and
r_e = radius of influence, in meters.

For an average depth of 26.8 m and assuming a radius of influence of 10 m (Zeigler, 1976), equation (1) yields a hydraulic conductivity (K) of 4.71×10^{-7} m/s, a moderately low value for in-situ granite (Brace, 1980). Brace reported that in-situ permeability in several crystalline rocks varied widely, through 11 orders of magnitude. Four to six orders of magnitude variation is typical at a particular site (Brace, 1980). This variability is due largely to rock-mass discontinuities, particularly joints and faults. These features are particularly significant in brittle, nonplastic rocks such as granite, which have a low rock-matrix permeability. It is probable that the radius of influence decreases with depth because steeply dipping primary joints maintain a uniform spacing and sheeting fractures become less abundant and discontinuous. The closure of horizontal fractures with load (depth) was discussed previously.

ROCKBURSTS AND IN-SITU STRESSES

Knowledge of the magnitude and orientation of in-situ rock stresses is required for optimal design and has a direct bearing on the ease of excavation and the stability of an underground excavation. Although highly deviatoric horizontal stresses can be tolerated in an underground excavation, they need to be recognized in advance and allowed for in design. Otherwise, unstable, hazardous conditions, including destructive rockbursts, may occur.

Rockburst Occurrences in Maine

Rockburst is the sudden failure of brittle, usually massive, highly stressed rock and is accompanied by the very rapid release of strain energy. Such violent rock breakage can occur in quarries or in deep mines, in both sedimentary and crystalline rocks, and in glaciated and nonglaciated terranes.

More than 150 granite quarries have been operated at one time or another during the past 100 years along the Maine coast and on nearby islands (Rand, 1958). Although only a few of these quarries are deeper than 30 m, numerous destructive rockbursts have been reported. On Vinalhaven Island, 56 km south of Mount Waldo, Feld (1966, p. 139) described a granite quarry in which solid sheets of granite at a depth of 45 m buckled upwards. After bending 1 m, the rock "blew up" and was so severely fractured that little usable stone could be recovered. The work soon became too hazardous, and the excavation was abandoned. Joints in this quarry are very tight. Although the workings were mostly below sea level, the quarry remained dry until it was filled (for safety reasons) by pumping. Such impermeability would be a desirable rockmass attribute for fluid storage, of course.

Dale (1907) reported rockbursting in several quarries in granitic rocks in Maine. One severe burst, which occurred in the late 1890's in the main quarry on the northeast spur of Mount Waldo, produced north-northwest-trending fractures. This fracturing occurred in the summer when near surface thermal stresses were highest, and was accompanied by loud explosive noises. In the upper part of the east wall of the quarry, part of this broken zone is still visible as a vertical central zone of shearing and crushing as much as 2 m wide, 10 m long, and 3 m deep, that strikes N28°W (Fig. 15). Vertical curvilinear fractures extend approximately 20 m in toward the quarry from both ends of the crushed zone. The intensely deformed zone terminates abruptly downward at a sheet surface. The removal of a 3 m deep channel at this location appears to have triggered the rockburst.

Lee et al. (1979) analyzed this burst and compared it with the results of the laboratory rockburst experiments of Holzhausen (1977). They found that channels cut normal to vertical walls, which were parallel to the maximum horizontal stress, caused failure by concentrating applied stresses at the tips of small fractures (flaws). The fractures propagated unstably in areas of maximum shear stress, roughly normal to the channels and parallel to the maximum load. In the laboratory model, development of through-going fractures was preceded by localized crushing of the rock, which produced features similar to those observed at the Mount Waldo quarry. Under these stress conditions it is desirable to orient the long axis of an underground excavation approximately parallel to the maximum horizontal stress.

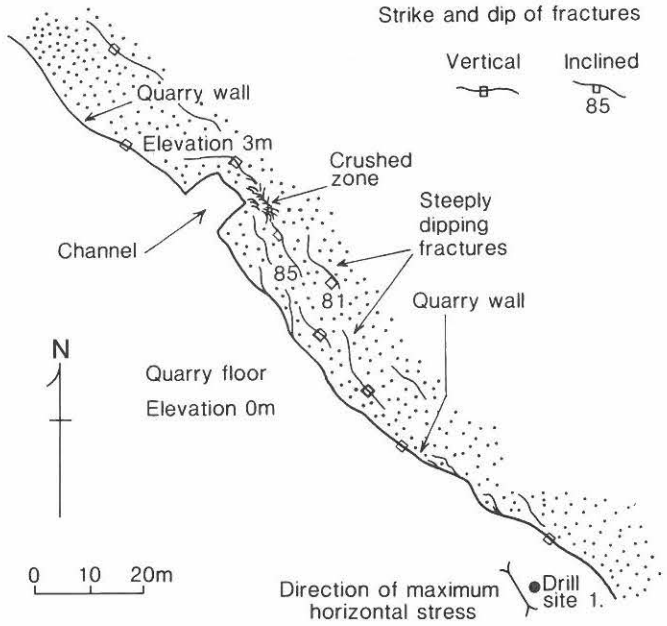

Figure 15. Simplified plan view of old channel cut and old rockburst features in Mount Waldo quarry. Formation of crushed zone was followed by unstable propagation of steeply dipping curvilinear fractures. Vertical fractures not adjacent to crushed zone were formed in response to excavation parallel to quarry wall.

DISCUSSION

The Mount Waldo granite, a generally massive rock, has rock-fabric properties that could influence the efficiency and cost of underground excavation. Exposures of the granite in quarries show that the rift is horizontal, the grain is east-west and vertical, and the hardway is north-south and vertical. These characteristics have permitted the quarrying of very regular blocks that are well-suited to the construction of buildings and bridges. Where the alignment of potassium-feldspar phenocrysts can be clearly recognized, the direction of most efficient underground excavation can be established, but if this relation is disregarded (as was observed locally in one quarry), difficult excavation and uneven breakage may result. Fabric and stress relationships suggest that long axes of underground openings should be oriented east-west. Geometrically more uniform openings ("rooms") should have walls oriented north-south and east-west. Fluid migration in the Mount Waldo granite is slow, as indicated by the injection tests and by perched water levels in some mountainside quarries that were observed to lose little water annually, other than through evaporation losses.

A vertical section of 325 m, which was exposed in the pluton, was valuable for obtaining fabric information in a third dimension. However, our samples were taken from depths of 28 m or less, and obviously, were under less load than the rock would be at depths of possible underground storage sites. The open microfractures that are present in our samples (particularly those fractures that may have been caused by erosional unloading) would not exist or would be closed at depth as was shown by field and laboratory tests. Care must be used in extrapolating mechanical and hydrologic properties whose variability is controlled mainly by open microfractures. Petrographic examination is necessary to establish the age relationships, condition, and significance of microfractures.

Temperature-produced stresses in the rock may be significant to a depth of 6-7 m, and the large near-surface temperature changes may account in part for the numerous pop-ups and spalls that are observed on large, exposed surfaces.

Stress directions in the upper, closely sheeted parts of the granite, especially in valleys and ridges, are not aligned with the regional east-west trends that have been identified in other studies (Lee, 1985). Instead, shallow principal horizontal stresses in the northeastern part of the pluton, where relief is strong, are approximately parallel to the northerly topographic trend. Below valley level more uniform regional stress conditions are expected.

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