DEPARTMENT OF THE INTERIOR
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# Geomechanical Aspects of Subsidence in Eastern Maine

By

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## CONTENTS



## ILLUSTRATIONS

TABLES

# GEOMECHANICAL ASPECTS OF SUBSIDENCE IN EASTERN MAINE

By Fitzhugh T. Lee

## ABSTRACT

Information from several sources indicates that the eastern Maine coast is subsiding. Recent releveling surveys indicate a current rate of subsidence as much as 9 mm per year relative to Bangor. The anomalously rapid rise in sea level accompanying the subsidence has led to shoreline erosion, landsliding, and submergence of archaeological sites and historical manmade structures. In situ stress measurements, well-bore breakouts, and earthquake focal mechanisms show that the maximum principal stress is horizontal, strikes N. $80^{\circ}$ E., and is correctly oriented to produce thrusting on north-south faults, right-lateral motion with minor thrusting on northeast and east-northeast faults and major thrusting with left-lateral motion on northwest-striking faults.

Maximum seismicity in Maine occurs in the subsiding zone which also includes the maximum (positive) gravity anomaly in the State. Epicenters are diffusely aligned with the Oak Bay fault which strikes N. $20^{\circ}$ W. Deflection of isobase lines drawn on ice-marginal deltas forms a trough whose axis strikes approximately parallel to the Oak Bay fault. An acceptable contemporary crustal deformation mode should incorporate zones of contrasting rock density and intensity of fracturing, localized seismicity, east-west tectonic compression, and weak compression or extension in the north-south direction.

## INTRODUCTION

Crustal subsidence in coastal New England has been recognized from first-order leveling surveys for more than 50 yrs (U.S. Department of Commerce, 1973; Tyler and Ladd, 1980). Geomorphic and cultural evidence suggest that subsidence has occurred over a much longer period, perhaps for 3,000 yrs B.P. (Thompson, 1973; Borns, 1980; Thompson and Kelley, 1983). After subtracting the calculated eustatic sea level rise, Thompson used radiocarbon dates from basal salt-marsh peat at Addison, Maine, to show a sea level rise of about 4 m in the last 3,000 yrs with some indication that the rate of rise has been decreasing.

Other methods used to detect crustal movement include submergence of colonial dikes on salt marshes and of harbor facilities, submergence of 3,000- to 5,000-yr-old Indian shell mounds, and changes of altitudes of glacial-marine deltas and beach deposits resulting in displacement of the postglacial-uplift isobases (Anderson and others, 1984). These authors report at least 12 m of crustal subsidence during historical times in the Machias-Eastport area. The amount of subsidence has been established best for the last 200 yrs during which time the sea has transgressed over manmade structures in coastal Maine. Most rapid present-day subsidence is located in eastern Washington County where a maximum relative rate of 0.91 m per century has been measured (Tyler and Ladd, 1980). Between 1942 and 1966, subsidence in the area has been as much as 17.5 cm (Tyler and Ladd, 1980).

Less prominent subsidence has been identified in southern York County, Maine (Tyler and Ladd, 1980). Phenomena that may be associated with the subsidence in eastern Maine include localized seismicity, heavily faulted dense bedrock, and tectonic stresses.

Several economic effects of subsidence have been identified; foremost, are continuing coastal erosion and landsliding. In some coastal communities, some harbor installations are now under water at high tide. In Eastport, where the subsidence rate is 9 mm per yr, part of the harbor sank as a result of the March 17, 1870, earthquake, and landslides occurred in nearby New Brunswick (Smith and Bridges, 1983).

The purpose of this report is to summarize structural and tectonic information in eastern Maine and to compare this data with earthquake information, in situ stresses, and gravity interpretations.

## ACKNOWLEDGMENTS

The writer is thankful for the help of several individuals in expediting the field and office investigations. Allan Ludman and Olcott Gates spent time in the field explaining the geology of the Fredericton and Eastport $2^{o}$ quadrangles and suggesting drill sites. David Stevens of the H. E. Fletcher Company made available drill sites in the Hall's Ridge quarry at Jonesboro, Maine, and aided us in our operations. John E. Ebel, Henri S. Swolfs, and R. Ernest Anderson reviewed the first draft of the manuscript and suggested several improvements. The Maine Geological Survey supplied field vehicles and logistical support, and the Nuclear Regulatory Commission provided partial funding for the project. Sharon F. Diehl made microscopic fabric and modal analyses of the granite at the three field sites. Danny R. Miller and C. Bruce Boydstun obtained in situ strain-relief measurements. Danny R. Miller assisted with office calculations, drafting, and accomplished numerous logistical chores.

## REGIONAL GEOLOGY AND TECTONIC HISTORY

Southeastern Maine is underlain by lower and middle Paleozoic sedimentary and volcanic rocks intruded by Devonian plutonic rocks--some of which have batholithic dimensions (fig. 1). There is little granite in the rapidly subsiding area between Machias and Passamaquoddy Bay, a fact which will be discussed in a later section. North and west from the coast in this area the percent of granite bedrock increases significantly (Gates, 1982; Ludman, 1982).

The regional structure trends northeast, although prominent faults and major joints trend northwest. The major stratified rock units have a well-developed northeasterly strike and are separated by faults into five lithotectonic blocks or belts (Ludman, 1981). Three blocks, the Fredericton

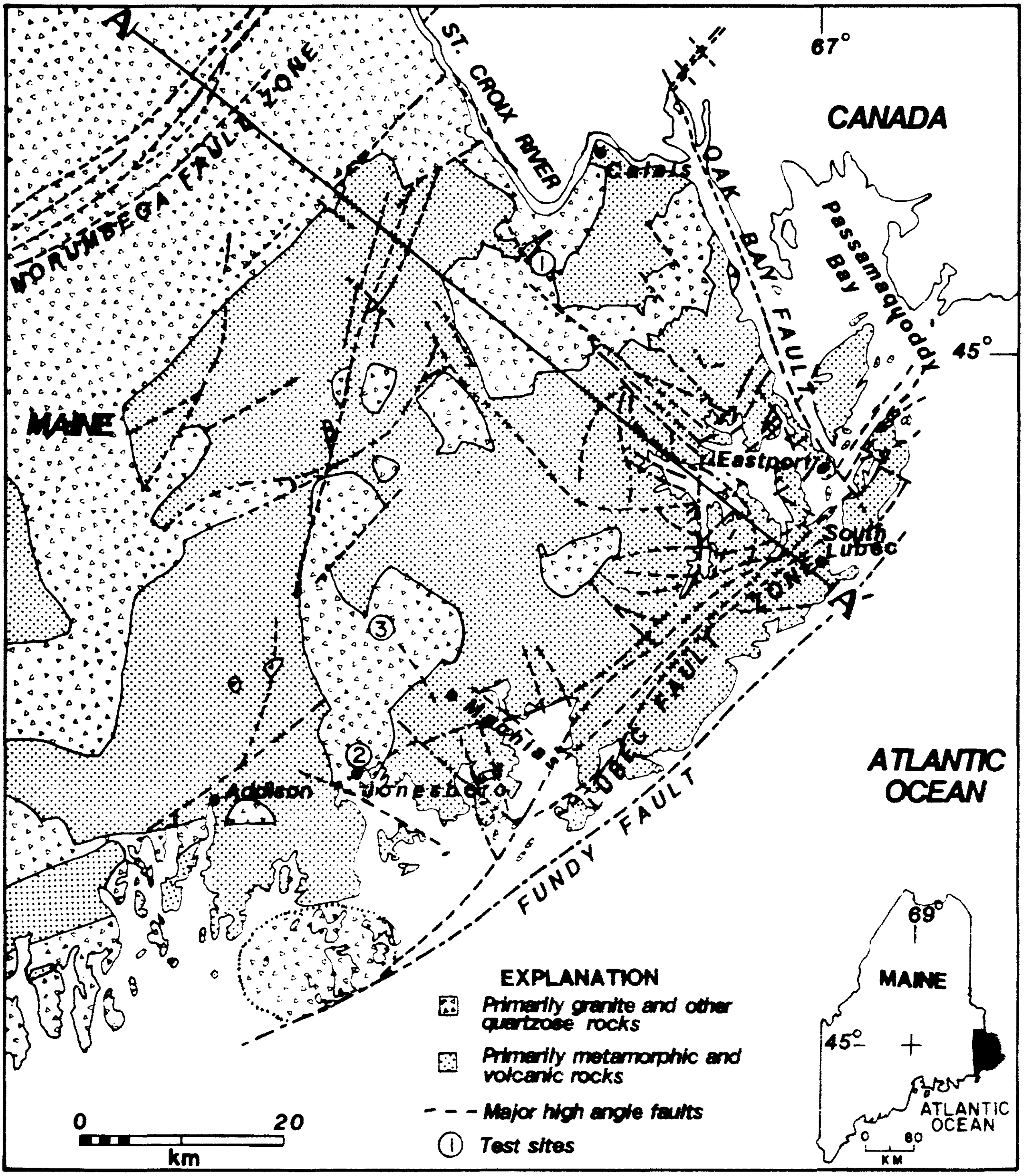


Figure 1. Generalized lithologic map showing major faults in eastern Maine. Modified from Gates (1982) Ludman (1982).

trough, the Calais Cambro-Ordovician belt, and the coastal volcanic belt, are within the zone of subsidence. Rock units in each block display a complex record of folding, faulting, and plutonism. According to Ludman (1981), only Carboniferous(?) red beds that were deposited after most of this deformation have been relatively unaffected, although they have been tilted and dip from $60^{\circ}$ to $80^{\circ}$. Low-grade Acadian (Early Devonian) regional metamorphism, isoclinal folding, and faulting have affected all stratified rocks in the study area with the exception of the Carboniferous(?) red beds.

The Fredericton trough consists of northeast-trending, upright, tight to isoclinal folded graywackes, slates, sandstones, siltstones, and phyllites of Silurian to Early Devonian age (Ludman, 1983). There has been dip-slip reactivation of the earliest northeast-trending steeply dipping faults in this block, and this movement appears to have been the last significant deformation here.

The Calais Cambro-Ordovician belt is a thick rock section containing a wide variety of rock types: highly carbonaceous shales, quartzite, slate, metasandstone, and massive and pillowed basalts. In addition to the deformations that are recorded in rocks of the Fredericton trough, these rocks also record an episode of recumbent folding that occurred between the isoclinal folding and early stages of northeast-trending faulting (Ludman, 1981).

The coastal volcanic belt consists of a sequence of Early Silurian through Early Devonian predominantly mafic volcanic rocks interbedded with sedimentary rocks consisting of argillite, shale, tuff breccias, bedded tuffs, and basaltic and rhyolitic flows (Gates, 1983). An early syndepositional period of extension was followed by extensive volcanism, and in turn, by a period of folding. The section is at least 8,000 m thick in the easternmost part of the belt but thins rapidly to the west (Gates, 1983). Although metamorphism has partially altered many of the original minerals to those of the greenschist facies, the original sedimentary and volcanic structures and textures remain.

## Plutonism

Intrusive igneous activity associated with the Acadian orogeny followed folding and faulting in the lithotectonic blocks and has been variously dated, from late Early Devonian to early Late Devonian (Gates, 1983). Initially, locally subconcordant gabbro-diorite complexes and associated granophyric hornblende-biotite granite masses were intruded into Silurian-Lower Devonian volcanic rocks which were followed by discordant intrusion of steepsided oval-shaped plutons of biotite granite. Many of the gabbroic plutons are complex multiple intrusions of gabbro, diorite, and quartz diorite with local igneous layering, multiple dikes and sills. They have wide border zones of brecciated gabbro and wall rocks veined by diorite, quartz diorite, and granite (Gates, 1983). Mafic intrusions preceded felsic intrusions in all instances; to the south, large volumes of mafic rocks intrude folded strata in the three southernmost lithotectonic belts but these dense intrusive rocks give way to younger more felsic types toward the north and west.

Contact metamorphic aureoles surround the plutonic rocks and are superimposed on the low-grade regionally metamorphosed terrane. Accordingly, gneissic rocks in the Calais area are the result of contact metamorphism and do not represent high-grade regional metamorphism (Ludman, 1981).

## Faulting

Faults in the subsiding area under consideration can be grouped into two categories according to their strike: northeast- and northwest-trending faults (fig. 2); (Gates, 1983; Ludman, 1983). Within each category there are several ages and types of offset. Figure 3 shows a decrease in the number of faults from east to west and from the coast inland, which in part, reflects the preponderance of relatively weak heterogeneous sedimentary and volcanic rocks in the coastal volcanic belt in contrast to the many younger massive granitic plutons inland and to the west.

Gates (1983) recognized five episodes of faulting in the study area: Silurian, Early to Middle Devonian (Acadian), Late Devonian, Carboniferous, and Triassic-Jurassic.

### Northwest-trending faults

Northwest-trending faults are less abundant than northeast-trending faults in the study area (fig. 2), but this group may contain faults having the youngest movement in the region, and it may be associated with trends of current seismic activity (Lepage and Johnston, 1985; Ludman, 1983).

The Oak Bay fault and other faults parallel to it (fig. 1) are the major northwest-trending faults in the study area. The fault has been traced along the Maine-New Brunswick border for more than 50 km from Campobello Island to upper Oak Bay along the western edge of Passamaquoddy Bay. The fault offsets the probable extension of the Lubec fault zone, and therefore, Gates (1983) considers it to be Carboniferous or younger in age. At the surface, the fault plane is nearly vertical, and Gates has calculated a vertical displacement of at least 1 km with the northeast side downdropped. According to Ludman (1983), there has been left-lateral motion on some northwest-trending faults, and course changes in the St. Croix River are caused by northwest- and northeast-trending faults.

### Northeast-trending faults

Northeast-trending faults include many of the regional strike-slip faults that cut all rocks in the region. Offset of pluton contacts suggests right-lateral movement (Wones and Thompson, 1979). The Norumbega fault (fig. 1) belongs to this group and is a vertical zone 6-8 km wide, consisting of several faults and shear zones with abundant slickensided surfaces which show right-lateral motion as do associated minor folds whose axes are uniformly vertical. Mylonitization within the plutons is not as extensive as in the country rock, an indication that much fault displacement preceded granite emplacement. According to Ludman (1983), there is considerable

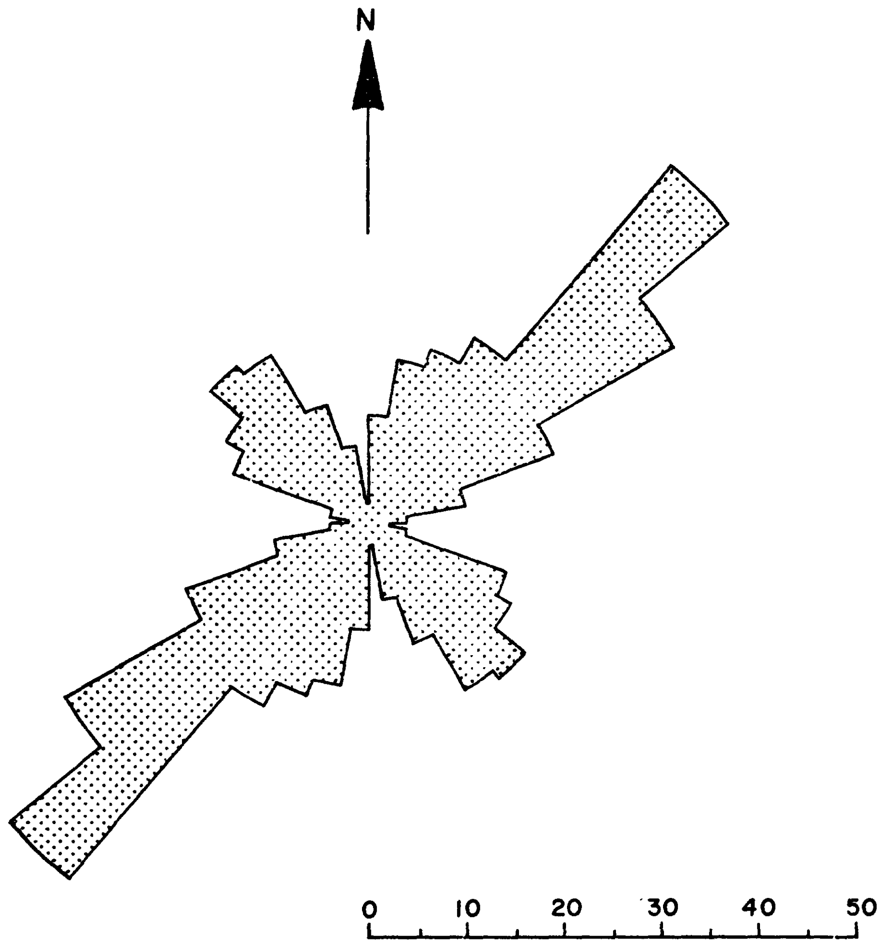


Figure 2. Strikes of 287 steeply dipping faults measured within 1350 $km^2$ area centered on A-A' in figure 1.

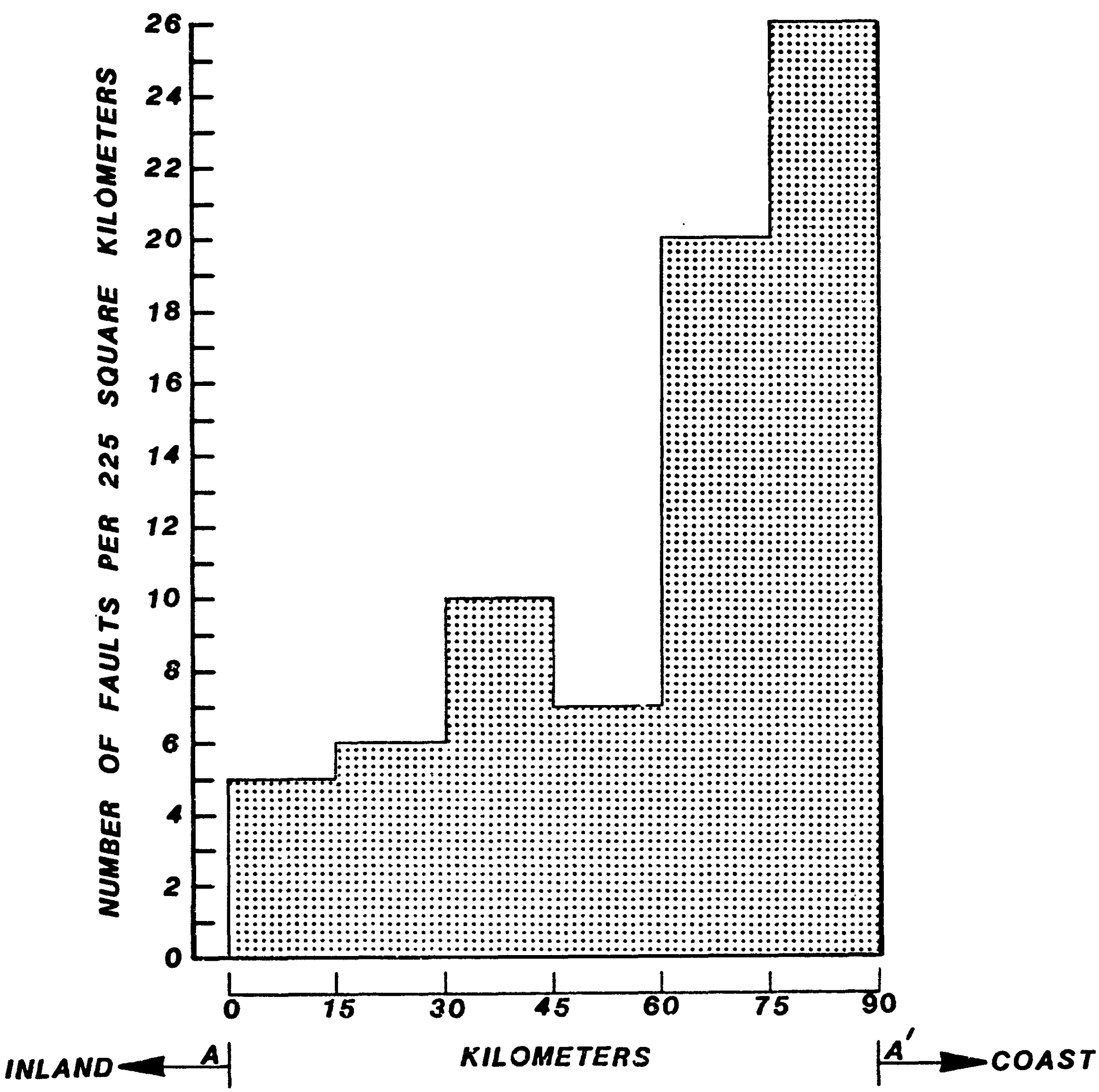


Figure 3. Faults counted within 1350 $km^2$ area centered on A-A' in figure 1. Traverse trends N. 53° W., perpendicular to subsidence contours of Tyler and Ladd (1980).

evidence to show that the youngest movement on the Norumbega faults was of a dip-slip nature, particularly the downdropping of Carboniferous beds along the fault traces. Thrust faulting is common in the Calais area.

The Lubec fault zone of Gates (1983) is very nearly parallel to the Norumbega fault zone 65 km to the northwest, and the Lubec fault zone consists of a downdropped block of the Eastport Formation. The rock units involved are highly sheared with closely spaced vertical- to southeast-dipping fracture cleavage, tight isoclinal folds with nearly horizontal plunges, and slickensiding and mineral streaking down the dip of the cleavage. Apparently these faults are of Carboniferous age and the normal movement was not preceded by strike-slip movement; however, the subparallel Machias Bay fault of Acadian age is marked by highly sheared rocks and small stratigraphic separation suggesting predominately Acadian strike-slip displacement.

The Fundy fault (fig. 1) strikes N. 47° E., to N. 67° E., paralleling the western shoreline of the Bay of Fundy, and cuts, or very nearly cuts, the coast of easternmost Maine (Gates, 1982). Rocks on the east side of this fault have been downdropped, and the fault marks the border of a swarm of normal faults in the Gulf of Maine and the Bay of Fundy, making the Triassic-Jurassic graben system, as shown on the seismic-reflection profiles of the floor of the Bay of Fundy (Ballard and Uchupi, 1975).

## Joints and Microfractures

Joints were recorded from exposures of granite at the field test sites (fig. 1), and microfractures were determined in thin sections prepared from drill hole cores. Joints were designated as major or minor primarily on the bases of continuity and ease of splitting, as recognized in quarries. The attitudes of major joints are similar at all sites: N. 85° E., 80° SE; N. 80° W., 75° SW; and N. 50° W., 82° NE. The joints are widely spaced (1 to 5 m) and typically show little wideness of alteration or movement, although Dale (1907) noted movement along a N. 56° E., fracture. Faults are not numerous in the Devonian granites in eastern Maine.

Sheeting fractures are encountered in all exposures of the granite. They generally conform to the surface topography and become thicker with depth, ranging from less than 2 cm to more than 2 m at a depth of 17 m.

The metamorphic and volcanic rocks display numerous, closely spaced joints and small faults usually without apparent pattern. The most common joint sets parallel the regional foliation (N. 50°-60° E.) and their spacing ranges from 0.2 cm to 0.75 m.

Microfractures occur abundantly in granite from the test sites, and have been analyzed to determine their significance to the interpretation of regional deformation. An analysis of microfractures can provide clues regarding rock anistropy, deformability, and the possible correlation of micro- and macrostructures (Brace, 1965; Dula, 1981). In some instances, the relative ages of microfractures can be determined. In this study, microfractures include: (1) healed fluid-inclusion planes in quartz grains, (2) open unlined microfractures occurring as short intragranular cracks to major transgranular features in all minerals, and (3) microfractures that are usually found in feldspar grains and lined with alteration products such as sericite, calcite, or iron oxide. Cleavage planes are often disregarded in a microfracture study, but if there appeared to be a mechanical loss of cohesion along a cleavage surface, especially in the case of a transgranular microfracture paralleling a cleavage plane, its orientation was included in the compilation. Both vertical and horizontal thin sections were prepared, and microfracture frequency and orientation were obtained from two traverses down the length of the thin section. Fabric features were determined using a five-axis universal stage, and then plotted on the lower hemisphere of an equal area net as poles to their respective planes. Data from vertically oriented thin sections were rotated into the horizontal plane and plotted in the composite diagram (fig. 4).

The dominant orientations of microfractures are: N. 76° E., 70° NW; N. 46° E., vertical; and N. 86° E., 24° NW; in addition to ubiquitous flat-lying sheeting fractures. The N. 46° E., and N. 86° E., strikes are parallel to planes of easy splitting at sites 2 and 3, respectively. There is a marked dominance of steeply dipping N. 45° E., to east-west striking microfractures (fig. 4). This strike range of fractures is present on several scales (fault zones, joints, microfractures), and in all rock types it is the most prevalent discontinuity observed at the surface in eastern Maine.

## GRAVITY INFORMATION

Several gravity studies of subsurface rocks in eastern Maine have been made at various scales (Kane and Bromery, 1968; Kane and others, 1972; Biggi and Hodge, 1982; Hodge and others, 1982).

In their model of the regional gravity field in Maine, Kane and Bromery (1968) noted that the gravity values increase toward the coast in a steplike fashion from -6 mgals in the northwest to +40 mgals in easternmost Maine. Hodge and others (1982) found that the depth of the density contrasts causing the steep northeast-trending gravity gradients is shallow with the basement becoming increasingly shallower toward the coast.

Because gravity anomalies are directly related to the density of the rock below the location of measurement, maps showing Bouguer gravity anomalies are helpful in the evaluation of the thickness of plutons and the distribution of rocks of different densities. Figure 5 is a simplified Bouguer anomaly map of eastern Maine that shows a belt of relatively high-density rocks (positive anomalies) trending northeasterly along the coast, and the eastern part of this belt approximately coincides with the area of most rapid subsidence (fig. 6). According to Kane and Bromery (1968), the average density for rocks in the coastal belt is 3.0 g/cm$^3$, whereas it is 2.65 g/cm$^3$ for the belt to the northwest which contains a larger volume of granitic rocks than the coastal belt.

High gravity values in the northeastern part of the coastal belt correspond to areas underlain by mafic rock, and the sharp gravity gradients at the boundaries of the mafic masses in this area show that these rocks are

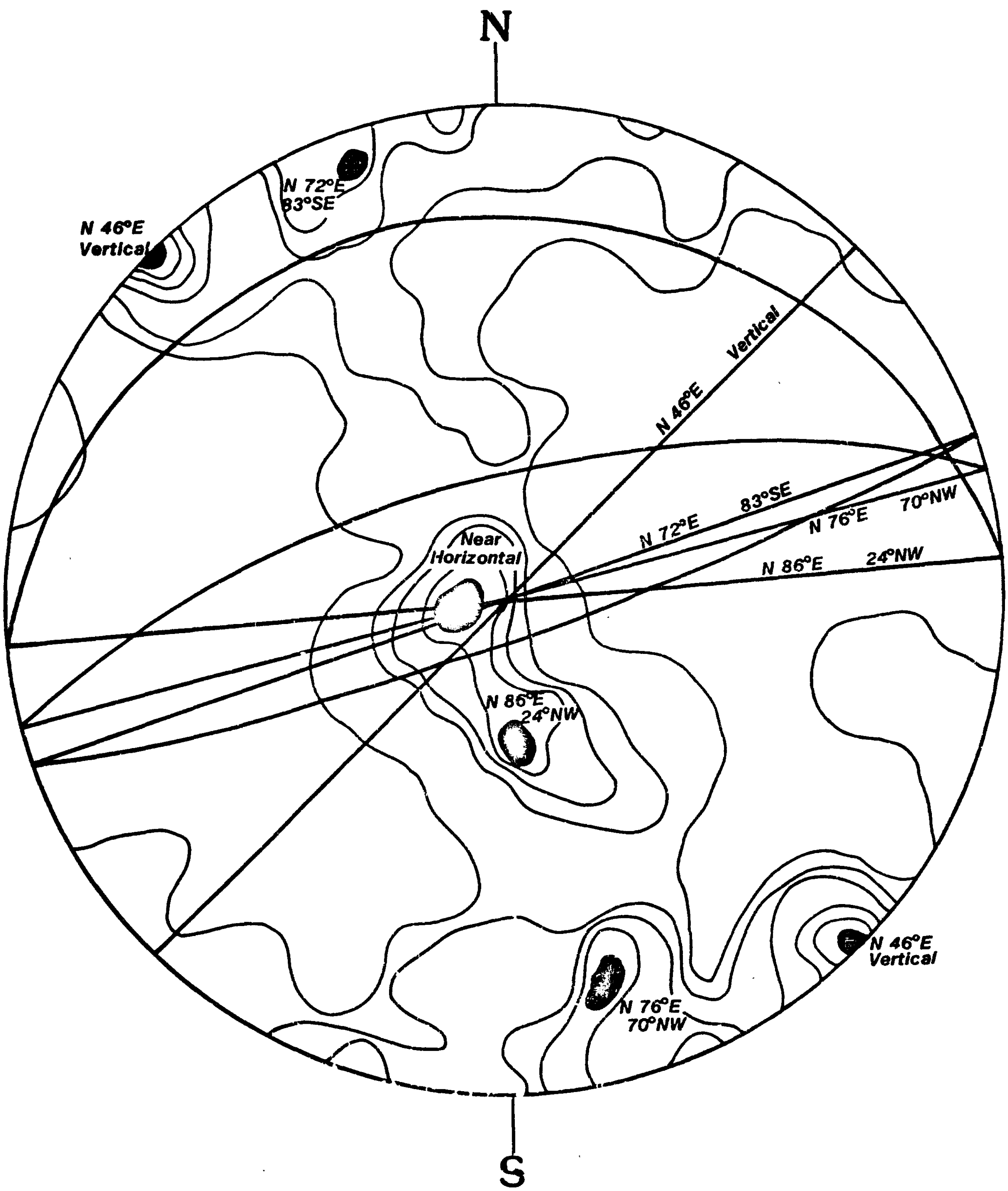


Figure 4. Lower hemisphere equal area diagram of poles to 438 microfractures measured in thin sections taken from granite core samples from sites 1, 2, and 3. Contoured on 0.4, 1.6, 4.0, 5.2, and 6.4 percent per 1 percent area.

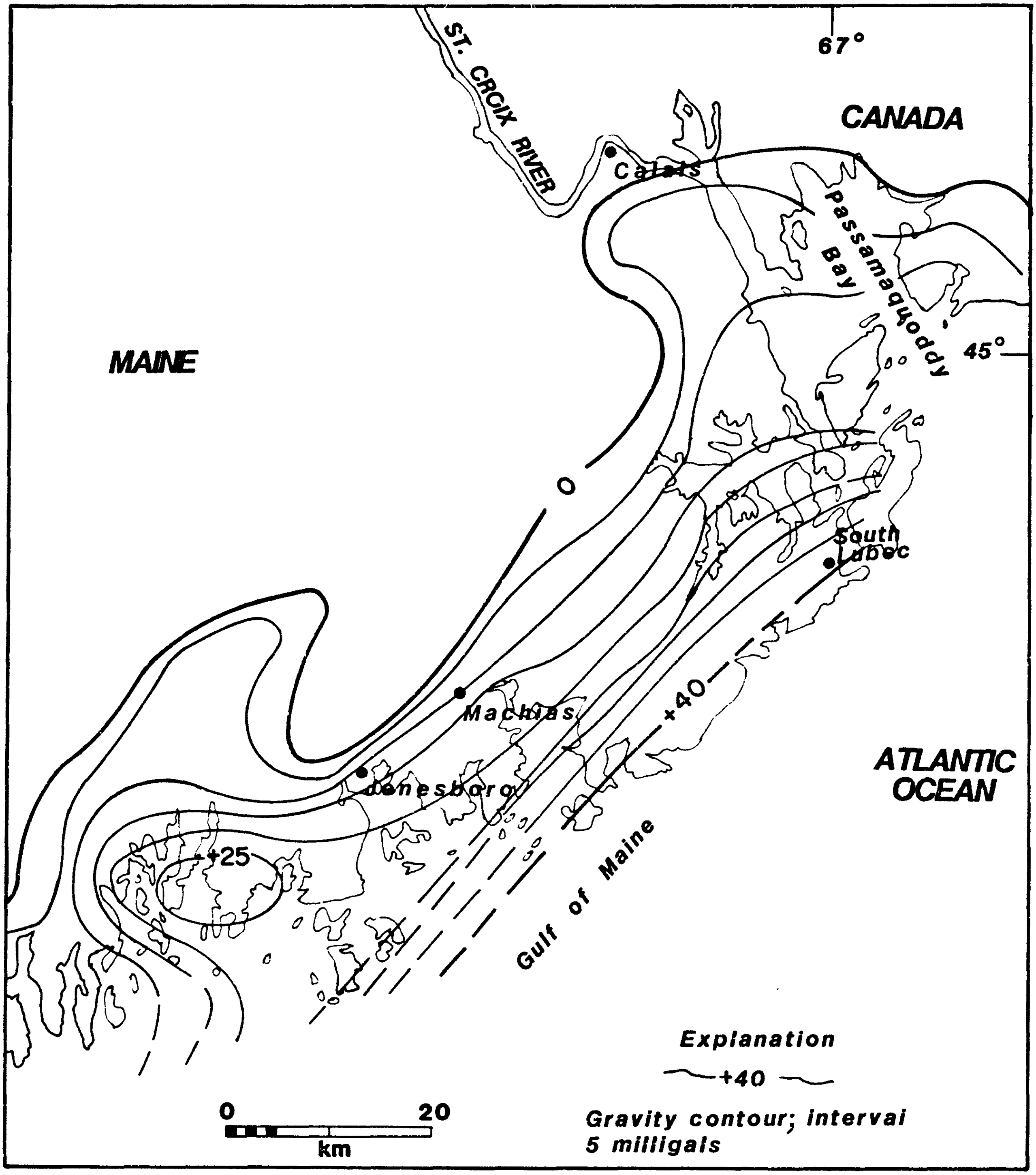


Figure 5. Bouguer gravity anomaly map of eastern Maine. Positive contours near the coast reflect large coherent mafic masses relative to the predominantly felsic bedrock inland. Data is from Kane, et al., (1972).

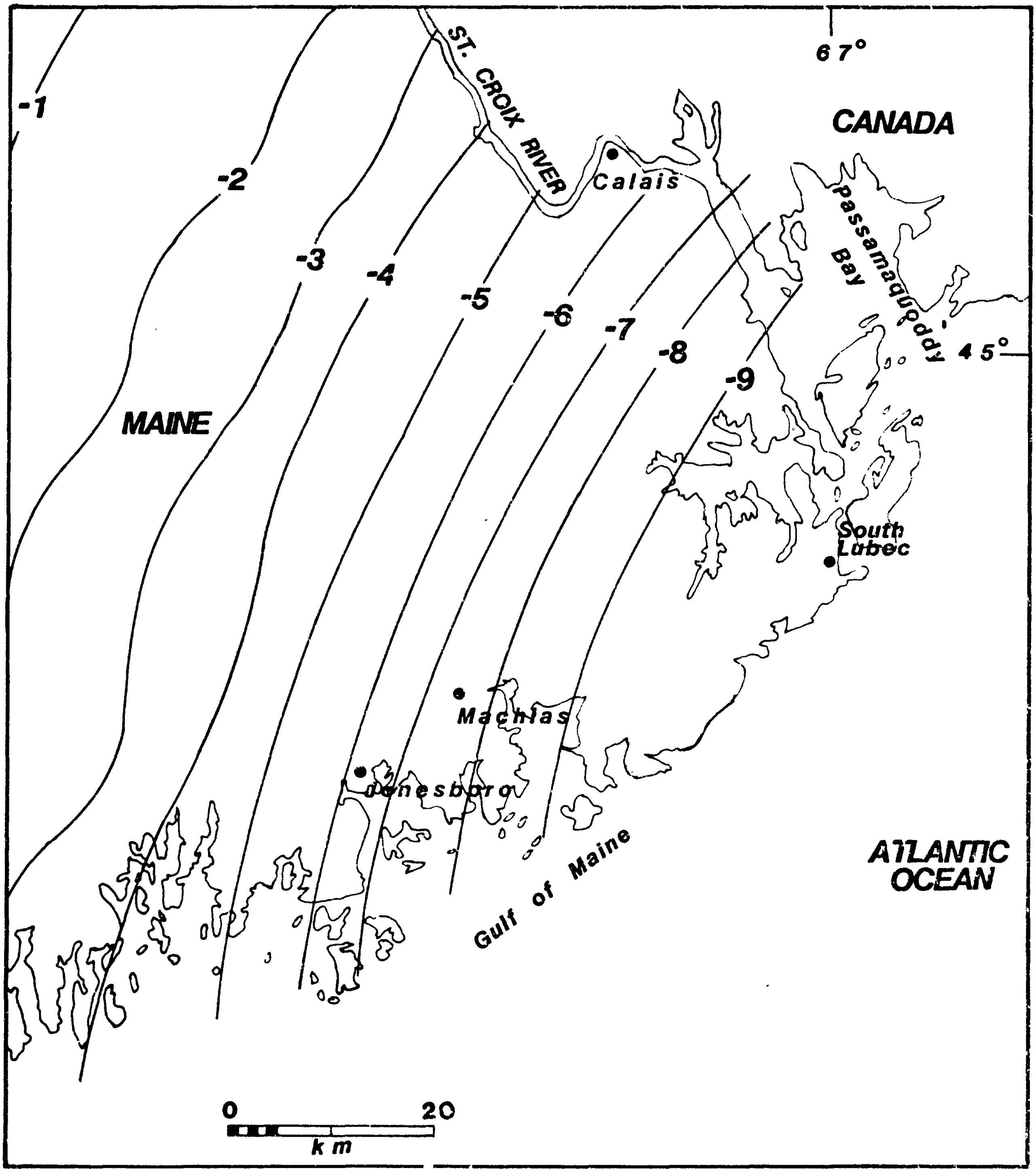


Figure 6. Map showing rates of relative vertical crustal movement in mm/yr (from Tyler and Ladd, 1980). Negative contours denote subsidence.

the principal sources of the gravity highs (Kane and Bromery, 1968). These authors interpret gradient-amplitude relations to mean that contrasts in density (across the boundaries separating blocks of contrasting density) must take place at shallow crustal levels.

Gravity modeling by Hodge and others (1982) indicates that the circular- to elongate-shaped exposures of the Jonesboro, Marshfield, and Meddybemps granitic plutons (Sites 2, 3, and 1, fig. 1) join at depth to produce an elongate northeasterly trending batholith. This large granitic mass has an average thickness of approximately 3.5 km (Hodge and others, 1982, table 3).

## EARTHQUAKE ACTIVITY AND FOCAL MECHANISMS

Thirty-nine small earthquakes that occurred from 1976 through 1984 were reported by Lepage and Johnston (1985) in the Calais-Machias area. Twenty-three are concentrated in the western Passamaquoddy Bay (fig. 7) and range in magnitude from less than 1.0 to 3.9. Epicenters are more densely clustered in this area than elsewhere on the Maine coast. However, insufficient information is available for these small tremors to calculate reliable focal mechanism parameters.

Focal mechanisms reported for several adequately recorded earthquakes in central Maine, northeastern New York, and southeastern Canada are given in table 1. Several of the tabulated earthquakes have multiple references. References with the most complete data have been used, which usually includes an interpretation of in situ stresses and type of faulting. The Blue Mountain Lake information is a composite solution of several events ("swarms"). The inferred stress directions indicate an east-west subhorizontal orientation of the maximum principal compression axes for the region. Focal depths range from 2 to 15 km and fault motions are characteristically thrust and reverse (dip of fault plane is greater than $45^{o}$), although some have a significant strike-slip component. The principal exceptions to the inferred east-west maximum principal stresses are events 7 and 10 at Otisfeld, Maine, and Lake Fairlee, Vermont, where these stresses trend N. $30^{o}$ W., and N. $35^{o}$ E., respectively.

The largest earthquakes closest to the subsiding zone (events no. 2, 4, 6, 8, table 1) suggest horizontal pressure axes oriented east-west, and would be consistent with thrusting on north-south striking fault surfaces. For event 4, Yang and Aggarwal (1981) determined that the thrust surface strikes N. $11^{o}$ E. and dips $48^{o}$ NW. Ebel and McCaffrey (1984) analyzed the 1983 Dixfield, Maine earthquake (event 6, table 1) and determined that the main shock showed thrust motion on north-south striking fault surfaces that dip $45^{o}$ W. From a teleseismic analysis of event 2, Choy and others (1983) found that the direction of movement was updip on a west-dipping, north-northeast striking fault plane. According to these authors, the steep dip ($65^{o}$) of the inferred fault surface suggests that the earthquake occurred on a preexisting fault that at one time was a normal fault.

These focal mechanisms are consistent with thrust motion on approximately north-south striking moderate to gently dipping surfaces with a horizontal east-northeast to east-west maximum principal stress. A strike-slip component

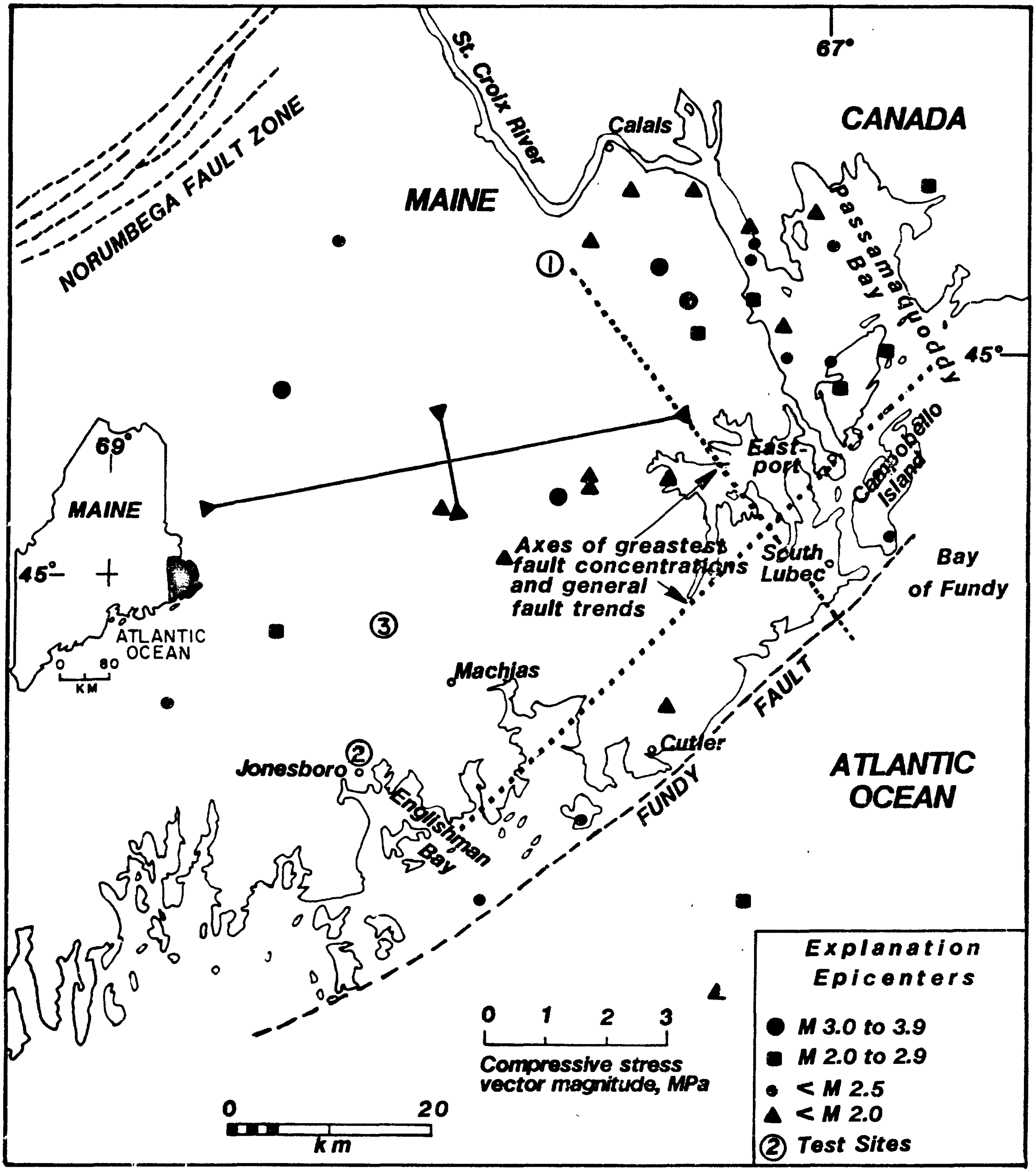


Figure 7. Earthquakes reported in eastern Maine from January 1, 1976 through December 31, 1984. Earthquakes with magnitudes greater than 2.9 occurred after August 11, 1983. Solid lines represent average maximum and minimum principal horizontal stress vectors. Earthquake data from Lepage and Johnston (1985).

TABLE 1.--Epicenter and source data for earthquakes in northern New England and southeastern Canada

[Leaders (---) indicate data missing; R=reverse; T=thrust; SS=strike slip; H=Horizontal]

| Event No. | Geographic region | Date | Latitude (°N) | Longitude (°W) | Depth (km) | Magnitude | Maximum principal stress axis: Azimuth | Maximum principal stress axis: Plunge | Minimum principal stress axis: Azimuth | Minimum principal stress axis: Plunge | Distance from Machias, ME (km) | Type of fault movement | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | La Malbaie, Quebec | 6/30/74 | 47.7 | 69.8 | 15 | *2.0 | N. 86° W. | 5° N. | N. 4° E. | 83° S. | 390 | R | Leblanc and Buchbinder (1977). |
| 2 | Miramichi, New Brunswick. | 1/9/82 | 47.0 | 66.6 | 6-10 | 5.7 | E.-W. | H | N.-S. | 70° S. | 250 | R/SS | Adams and Wetmiller (1983); Hasegawa (1983); Choy and (1983). |
| 3 | Maniwaki, Quebec... | 7/12/75 | 46.3 | 76.1 | 17-19 | 4.3 | N. 50° E. | 19° N. | N. 40° W. | ------ | 695 | R/SS | Horner and others (1975). |
| 4 | Maine-Quebec....... | 6/15/73 | 45.28 | 70.97 | 7 | 4.8 | N. 77° E. | H | N. 13° W. | 90° | 286 | T | Yang and Aggarwal (1981). |
| 5 | Altona, NY......... | 6/9/75 | 44.90 | 73.67 | 10 | 4.2 | N. 73° E. | 8° N. | N. 17° W. | 84° S. | 518 | R | Aggarwal and others (1977). |
| 6 | Dixfield, ME....... | 5/29/83 | 44.51 | 70.41 | 1.8-2.4 | 4.4 | E.-W. | H | N.-S. | 90° | 235 | T | Ebel and McCaffrey (1984). |
| 7 | Otisfield, ME...... | 1/4/78 | 44.04 | 70.51 | 3 | 3.2 | N. 30° W. | 30° N. | N. 70° W. | 70° S. | 256 | R | Graham and Chiburis (1980). |
| 8 | Bath, ME........... | 4/18/79 | 43.95 | 69.76 | 3 | 4.0 | E.-W. | H | N.-S. | 90° | 199 | T | Pulli and Toksöz (1981). |
| 9 | Blue Mountain Lake, NY. | 5-7/71 | 43.88 | 74.33 | 2-3 | 3.1-3.6 | N. 71° E. | 18° N. | N. 19° W. | 73° S. | 515 | T | Sbar and Sykes (1977). |
| 10 | Lake Fairlee, VT.... | 5/5/77 | 43.86 | 72.26 | 6 | 2.1 | N. 35° E. | 30° N. | N. 55° W. | 35° S. | 398 | R/SS | Graham and Chiburis (1980). |
| 11 | Boonville, NY....... | 6/6/80 | 43.60 | 75.10 | 2 | 3.5 | N. 75° E. | 10° N. | N. 42° E. | 80° S. | 650 | T | Pulli and Toksöz (1981). |
| 12 | Gaza, NH........... | 1/19/82 | 43.52 | 71.61 | 3 | 4.6 | N. 65° E. | H | N. 25° W. | 90° | 357 | SS | Pulli, J. J. (written commun., 1984). |
| 13 | Hopkinton, NH...... | 12/25/77 | 43.19 | 71.65 | <5 | 3.2 | N. 76° W. | 15° N. | N.-S. | 35° S. | 381 | T/SS | Graham and Chiburis (1980). |
| 14 | Candia, NH........ | 4/23/79 | 43.04 | 71.24 | 2 | 3.1 | E.-W. | H | N.-S. | 90° | 350 | T/SS | Pulli and Toksöz (1981). |
| | Average.............................................................. | | | | | | N. 83° E. | 10° N. | N. 14° W. | 74° S. | | | |

*Largest of 35 events over a 7-week period.

is also present on some fault surfaces. The 1982 Gaza, New Hampshire, earthquake (event no. 12, table 1) is exceptional in producing strike-slip motion on a N. 20° E.-80° SE oriented fault surface.

Considering the diversity of fault attitudes, ages of faulting, and variety of rock types in northeastern New England and adjacent Canada, the consistency of pressure axes of focal mechanism solutions is good.

## IN SITU STRESSES

In situ measurements of rock stress were made in the subsiding zone at the three sites shown in figure 1. Because of the intensity of fracturing and scarcity of granitic rocks in the most rapidly subsiding zone, a suitable site could not be located there. If all three test sites are located in the same northeasterly elongated, partially buried granite pluton, then regional significance may be attributed to a discussion of in situ stresses and contemporary rock deformation. The composition of the rocks at the test sites is shown in figure 8. The slightly more mafic composition of the granite at site 1 is caused by local mixing of gabbroic country rock (Amos, 1963). On the basis of similarity of the petrographic characteristics, this author determined that the granites belong to the same plutonic complex and were probably emplaced during a relatively short time interval. This finding agrees with the age determinations of four granites in southeastern Maine which range from 403 to 407 m.y. (Faul, 1960).

The objectives of the stress-measurement program were as follows:

1. Determine directions and magnitudes of principal horizontal stresses.
2. Measure vertical rock stresses and compare results with vertical gravitational stresses ($\rho g H$).
3. Compare shallow measurements of horizontal rock stresses with stress directions inferred from earthquake focal mechanisms.
4. Suggest potential subsidence mechanisms.

### Results of Stress Measurements

Several factors affect shallow rock stresses, the most important of which are temperature, topography, rock fabric, and geometric stress concentrations from quarry walls and corners. These factors were carefully considered in site selection, and drill holes were located in areas of subdued topography on bedrock surfaces distant from rock walls, faults, and fracture zones. The most severe diurnal and annual temperature changes occur in the upper 3 to 4 m in the rock mass (Hooker and Duvall, 1971). Therefore, the deepest measurements at the three sites (average of 5.03 m) are regarded as the most reliable. No rock mass is devoid of fractures; hence, the influence of faults, joints, and microfractures on strain relief should be examined. Except at site 1, joints are so widely spaced that they were not encountered in the boreholes and should have a negligible effect on the measurements. The joints were commonly tightly closed with no alteration. The influence of microfractures on horizontal strain-relief measurements could cause directional differences in Young's modulus (stiffness). The ratio of maximum

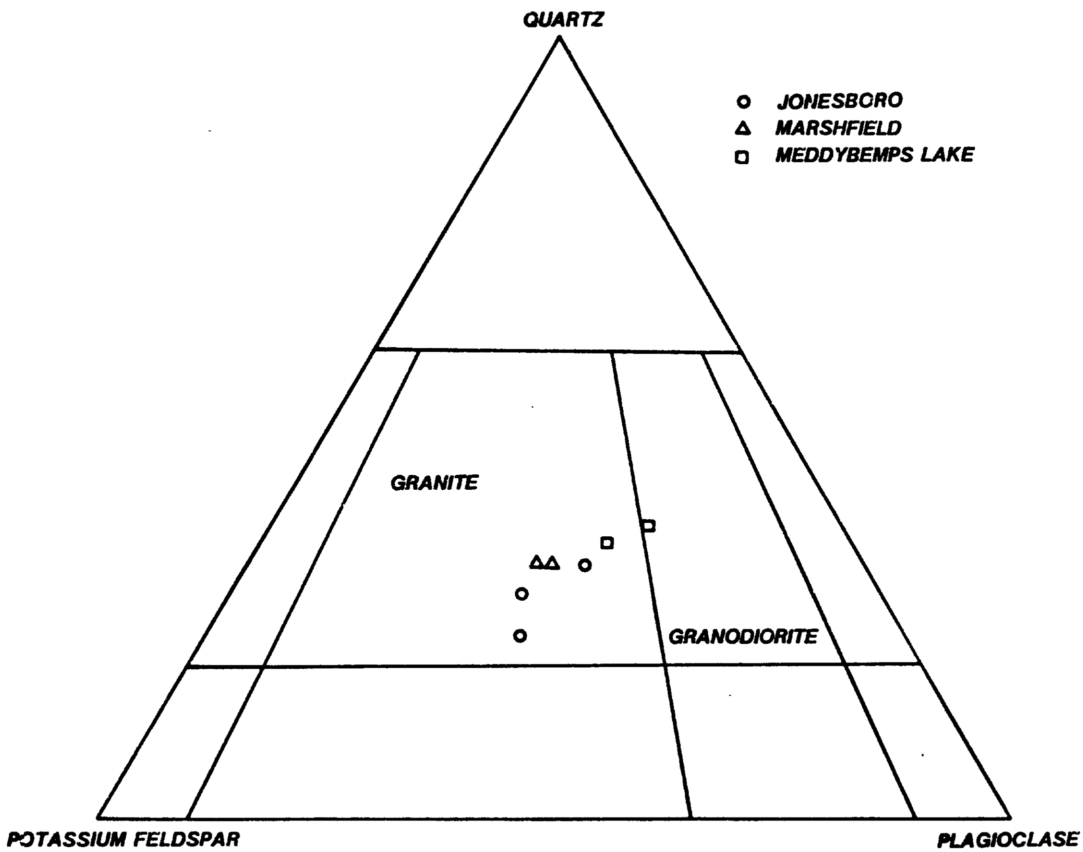


Figure 8. Modal analyses of granite from three field sites. Samples from Meddybemps Lake (site 1) contain some admixing of more basic country rock.

to minimum stiffness in the horizontal plane for the deepest measurement at each site is: site 1, 1.16; site 2, 1.15; and site 3, 1.11. Except at site 2, the direction of maximum stiffness coincides with the major microfracture directions (fig. 4; table 2). At site 2, the only identified structural fabric element, which is close to the maximum stiffness direction, is a 2 m-thick aplite dike which strikes N. 5° E., and dips 75° NW. The stiffness anisotropy (average ratio of 1.14 for the deepest) is overwhelmed by the ratio of maximum to minimum horizontal stresses (average ratio of 7.4). Therefore, the strongly deviated horizontal stresses, as reported, are little affected by stiffness variations but mainly controlled by the far-field regional stresses.

Horizontal stresses were determined at all three sites by the stress-relief overcoring method using the U.S. Bureau of Mines borehole gage in vertical holes (Hooker and Bickel, 1974). In addition, vertical stresses were measured in a horizontal borehole at site 2. Three horizontal displacement measurements were made in vertical holes at each site at depths ranging from 0.95 to 6.4 m. As expected, Young's modulus values are lowest at site 1 and highest at site 2, where the rock is most massive (table 2).

Maximum principal horizontal stress directions range from N. 56° E., to N. 85° W., and average N. 79° E. The minimum principal horizontal stress directions range from N. 5° E., to N. 34° W., and average N. 11° W. Stress magnitudes were greatest at site 2 in the Jonesboro Granite where a maximum value of 14.01 MPa was obtained at a depth of 6.4 m. Lowest maximum principal stress magnitudes were found at site 1, where three measurements averaged only 1.39 MPa. At this site, tensile stresses were measured at shallow depths (table 2). The horizontal stress deviator, or difference in the horizontal principal stresses, is shown in table 2. Significant stress deviation may be an indication of potential instability along fracture surfaces due to the presence of shear stresses.

The vertical stress was measured in a wall of the quarry at site 2 in a subhorizontal hole (+3°) at a distance of 4 m from the collar. The vertical rock column above the measurement position is approximately 6 m, which corresponds to a vertical stress of 0.14 MPa. This is in good agreement with the measured value of 0.11 MPa. This measurement suggests that near the earth's surface, the minor principal stress (least compression) is vertical, and the maximum and intermediate principal stresses are horizontal.

The approximate east-west maximum horizontal compression that was calculated from our stress-relief overcoring measurements is in good agreement with the orientation of tectonic forces estimated by other methods. An east-west horizontal principal compression is also shown from an analysis of well bore breakouts (sidewall spalling in near-vertical holes) in six deep wells in the Georges Bank (Zoback and others, in press; R. L. Dart, written commun., 1985). Further evidence of east-west compression was obtained by Tyler and Leick (1985) from a geodetic survey in the Calais area. These authors obtained first order accuracy using macrometer-satellite distance measurements. Comparing these 1983 values with 1890 triangulation survey data according to Tyler and Leick (1985), the results indicate a strong

TABLE 2. In situ stresses measured in the subsidence zone

| Site No. $\left(\frac{\sigma_1 + \sigma_2}{2}\right)$ | Depth (m) | Maximum principal horizontal stress ($\sigma_1$) (MPa) | Maximum principal horizontal stress ($\sigma_1$) (Strike) | Minimum principal horizontal stress ($\sigma_2$) (MPa) | Minimum principal horizontal stress ($\sigma_2$) (Strike) | Mean horizontal stress (MPa) | Stress deviator ($\sigma_1$-$\sigma_2$) | Average Young's modulus (GPa) | Direction of maximum Young's modulus | Rock type |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.9 | 0.08 | N. 78° E. | -3.82 | N. 12° W. | -1.87 | 3.92 | 27.9 | N. 80° E. | Granite. |
| | 4.3 | -0.12 | N. 84° E. | -2.11 | N. 6° W. | -1.12 | 1.99 | 33.6 | N. 70° W. | Gneissic granite. |
| | 5.2 | 4.20 | N. 66° E. | 0.29 | N. 24° W. | 2.25 | 3.91 | 30.8 | N. 80° E. | Gabbro. |
| Average--- | 4.5 | 1.39 | N. 76° E. | -1.88 | N. 14° W. | -0.25 | 3.27 | 30.8 | E.-W. | |
| 2 | 3.45 | 12.03 | N. 85° E. | 3.25 | N. 5° W. | 7.64 | 8.78 | 51.2 | N. 10° W. | Granite. |
| | 4.19 | 10.95 | N. 87° E. | 2.53 | N. 2° W. | 6.74 | 8.42 | 50.7 | N. 10° W. | Do. |
| | 6.45 | 14.01 | N. 85° W. | 2.45 | N. 5° E. | 8.23 | 11.56 | 50.1 | N. 10° W. | Do. |
| Average--- | 4.7 | 12.33 | N. 89° E. | 2.74 | N. 1° W. | 7.54 | 9.59 | 50.7 | N. 10° W. | |
| 3 | 0.95 | 11.67 | N. 56° E. | 5.15 | N. 34° W. | 8.41 | 6.52 | 29.9 | N. 70° E. | Do. |
| | 2.97 | 8.96 | N. 82° E. | 3.43 | N. 8° W. | 6.20 | 5.53 | 34.3 | N. 70° E. | Do. |
| | 3.43 | 10.26 | N. 78° E. | 5.25 | N. 12° W. | 7.76 | 5.01 | 34.7 | N. 80° W. | Do. |
| Average--- | 2.45 | 10.30 | N. 72° E. | 4.61 | N. 18° W. | 7.46 | 5.69 | 32.97 | N. 80° E. | |
| Average for sites 1-3. | 3.87 | 8.01 | N. 79° E. | 1.82 | N. 11° W. | 4.92 | 6.19 | 38.13 | | |

Note: Site locations are shown on figure 1.
Negative values denote tensile stresses.

possibility of significant crustal motion although their data are not sufficient to provide unequivocal evidence of crustal deformation.

The stress-resolution procedure of Swolfs (1984) is helpful in estimating the sense of potential fault movement. This procedure utilizes a triangular diagram on which the three principal stresses are represented by a single point that designates the preferred mode and orientation of faulting (fig. 9). Pore-water pressures in the massive, practically impermeable granites are considered to be low so that the total stresses ($S_1$, $S_2$, and $S_3$) are approximately equal to the effective stresses ($\sigma_1$, $\sigma_2$, and $\sigma_3$) . The measured stresses plot in the thrust faulting section of the diagram (Sy>Sx>Sz). If the vertical stress (Sz) increases with depth relative to the minimum horizontal stress (Sx), as has been observed at several locations in the depth range <1 km to 5 km, a component of strike-slip motion will be present on appropriately oriented faults (Swolfs, 1984). This is shown by the dashed line on figure 9. A component of strike-slip motion was reported for several of the events listed in table 1.

## DISCUSSION AND CONCLUSIONS

The nature and origin of tectonic forces along continental margins has been inferred from geophysical and geomorphic data. For example, Yang and Aggarwal (1981) found that the parallelism between the maximum principal horizontal stress, determined from focal plane mechanisms, and the age gradient of oceanic lithosphere spreading, was parallel to the gradient of offshore magnetic anomalies determined by Pitman and others (1974). Intraplate movements near the Atlantic margin of the northeastern United States may be generated by an east-west horizontal compression reflecting the gravitational drive acting at the continental margin, owing to horizontal density variations in the oceanic lithosphere as it cools and moves away from spreading centers (Yang and Aggarwal, 1981). The stress generated by this gravitational force was modeled by these authors to be in the direction of absolute plate motion, of less than a few hundred bars magnitude (<20 MPa) and could be readily modified by local effects. Heller and others (1982) stated that the regional tectonic regime along the United States Atlantic margin has been consistent since rifting (mid-Mesozoic), but they could not identify the driving force of episodic Cenozoic subsidence.

Crustal loading from dense, thick volcanic rocks, fracturing, and the orientation of tectonic stress directions relative to Acadian or Taconic faults are factors that could facilitate subsidence in eastern Maine. The decrease of subsidence to the northwest inland from the coast approximates the decreases in rock density and severity of fracturing in the same direction (figs. 5, 6). At shallow depths, the contemporary maximum horizontal stress (N. 79$^{\circ}$ E.) is correctly oriented to produce "pure" thrust on north-south faults, right-lateral motion with minor thrusting on northeast and east-northeast faults, and left-lateral motion with major thrusting on northwest-striking faults. Seismicity is a maximum in Maine in the area of maximum subsidence, and epicenters also show a diffuse pattern along the Oak Bay fault (fig. 1). The abrupt change in elevations of glaciomarine

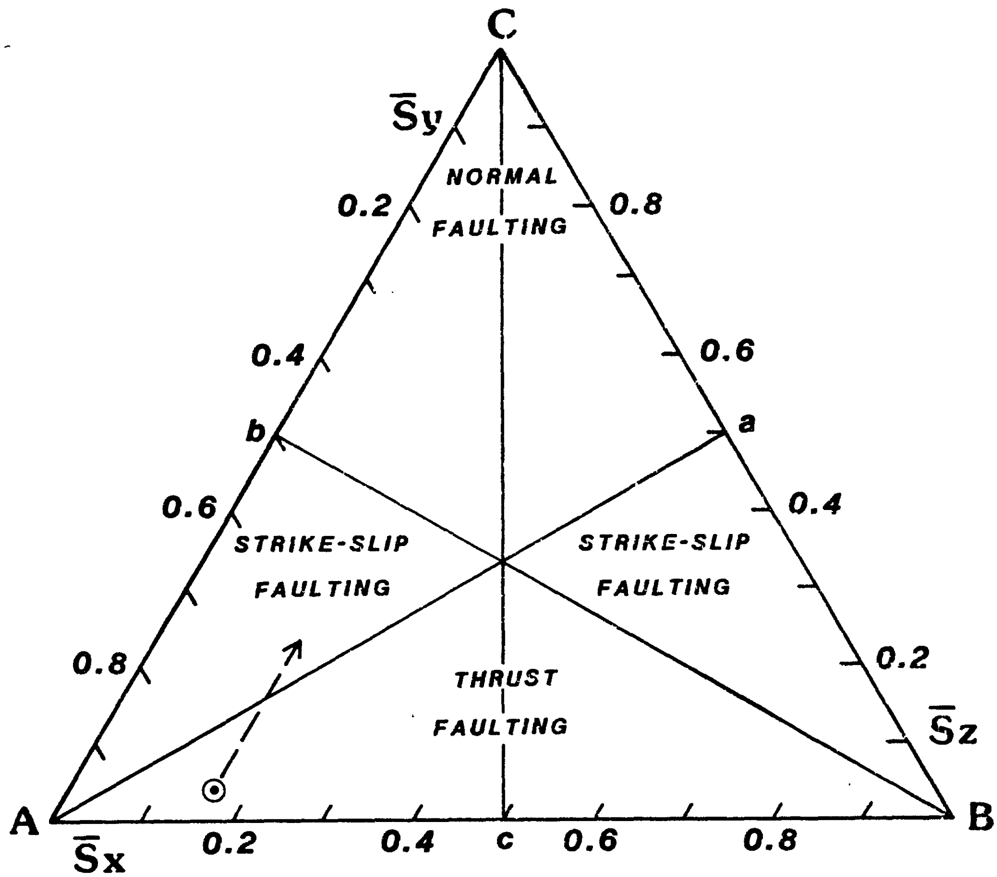


Figure 9. Triangular stress diagram showing structural definition of six panels in terms of the preferred mode and orientation of faulting (after Swolfs, 1984). The average stresses from table 2 are plotted in percent along the appropriate total stress sides (Sy>Sx>Sz). A thrust-faulting regime is indicated. Dashed line is explained in text.

ice-marginal deltas and wave-cut terraces in eastern Maine has produced a deflection of isobases which also suggests that subsidence may be controlled by north and northwesterly striking faults (Anderson and others, 1984). Alternatively, this deformation could be accounted for by sharp flexing. In the vicinity of the Oak Bay fault, the isobases delineate a trough whose axis is approximately parallel to the fault. Contemporary subsidence contours in New Brunswick and Nova Scotia trend north to northwest (Lambert and Vanicek, 1979), which suggests that northerly striking structures may be involved.

Neotectonic regional crustal behavior in eastern Maine and adjacent Canada is not sufficiently well understood to quantify the role of individual structural elements or blocks in the current subsidence. An acceptable qualitative model for crustal subsidence in eastern Maine should incorporate zones of contrasting rock density, intensity of fracturing, and localized seismicity in addition to tectonic compression directed east-west, and weak compression or extension in the north-south direction. It is clear that future leveling should reconcile present differences in contour magnitude and trend across the national boundary. Additionally, future research should include establishing a portable microseismic array in the area of most rapid subsidence in order to evaluate more accurately local fault activity at shallow depths.

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