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Neotectonic Activity in Coastal Maine

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ABSTRACT

Recent observations on sea-level change along the Maine coast have led to speculation that the rise in relative sea level is anomalously rapid in some areas, and cannot be solely the product of eustatic sea-level rise. A multidisciplinary study was initiated to determine whether the coastal submergence might be partly the result of neotectonic crustal subsidence. Project activities included bedrock mapping in eastern coastal Maine, where there is a concentration of recent earthquakes and faulting has occurred over much of Phanerozoic time, and in other areas of southern Maine with seismic activity and major fault zones. Evidence of Holocene crustal movement was sought through various research methods involving geodesy, geophysics, and measurement of relative sea-level change. Investigators used several means to determine the amount of vertical crustal movement indicated by sea-level fluctuations, each method being suited to a particular interval of postglacial time. These techniques included analyses of uplifted glaciomarine deltas, salt-marsh accretion, differential erosion of coastal archaeological sites, drowning of salt-marsh dykes and other historic coastal structures, and tide-gauge records.

The crustal warping study has shown that neotectonic activity in Maine is defined by recurrent seismicity and secular changes in relative sea level. Earthquakes have been recorded historically in the state since the 1700's. They occur most commonly in certain areas of Maine, such as the Passamaquoddy Bay region on the Maine-New Brunswick border. Earthquakes also occur in a less concentrated band subparallel to the coast. Although slumping of late Pleistocene and modern marine sediments was observed on the sea floor near mapped bedrock faults, neither the slumps nor the earthquakes have been conclusively linked to specific faults. No postglacial tectonic movement along bedrock faults has yet been recorded in Maine. The causes of Maine earthquakes are unclear, but probable mechanisms include plate tectonic and glacioisostatic stresses.

Sea level has fluctuated profoundly in the western Gulf of Maine during late Quaternary time, but the rate of sea-level change in this region has not been uniform. Maine has experienced the greatest amount of late-glacial marine submergence and subsequent isostatic emergence of any state or province bordering the Gulf of Maine. Sea level is now rising along the Maine coast at rates exceeding the average eustatic rise. Several lines of evidence suggest that eastern Maine is undergoing more rapid submergence than coastal localities to the southwest, probably because

of differential crustal subsidence in the vicinity of Passamaquoddy Bay. The collapse and migration of a crustal bulge which formed along the margin of the Laurentide Ice Sheet may be contributing to the downwarping and seismic activity. However, this theory alone is not adequate to explain the apparent localization of more rapid subsidence in eastern coastal Maine, which is occurring at rates of up to at least 5 mm/yr. The distinctive bedrock lithology, structure, and long-term tectonic mobility of this area are believed to cause its present instability.

INTRODUCTION AND METHODOLOGY

About 20 years ago, archaeological research by David Sanger (University of Maine) showed that prehistoric clamshell middens on the shore of Passamaquoddy Bay (Figure 1) are being rapidly eroded by the sea. He noticed that intertidal mud flats from which the clams could have been harvested are either absent due to erosion, or have been submerged and are no longer exposed at low tide (Sanger, 1971). Sanger hypothesized that sea level has risen significantly since these middens were made by the prehistoric inhabitants approximately 2,400 to 350 years ago. He also noted a lesser degree of wave erosion of middens along the coast southwest of Passamaquoddy Bay. He concluded that this difference could not be explained simply by uneven erosion along the coast, and proposed that there had been less sea-level rise to the southwest. Sanger's observations are the first modern suggestion of a differential relative sea-level rise on the Maine coast during late Holocene time. This phenomenon can be interpreted as the result of differential crustal subsidence. Further evidence of tectonic instability is provided by the frequent occurrence of low-intensity earthquakes in the Passamaquoddy Bay area (Ebel, this volume; Smith and others, this volume; Johnston and Foley, 1987). Moreover, the bay is located in an area of persistent subsidence and bedrock faulting through geologic time (Gates, this volume).

As a test of the crustal subsidence hypothesis, Thompson (1973) developed a local relative sea-level rise curve based on the thickness and rate of salt marsh accretion in Addison, Maine, located midway along the eastern half of the Maine coast. Although his sampling technique allowed some unquantifiable errors, the resulting radiocarbon-dated curve showed a progressive sea-level rise in the Addison area of approximately 5 m during the last 2,500 years. The rate of relative sea-level rise averaged 2 mm/yr during this time interval, but was exponentially slower towards the present. Thompson's work also suggested that the relative sea-level rise from 5,000 to 2,000 years ago was greater than could be accounted for by eustatic rise alone. Hence he concluded that crustal subsidence was responsible, thus supporting Sanger's original premise.

In the mid 1970's the Maine Geological Survey received numerous requests for technical assistance concerning coastal erosion and shoreline change. Although this attention at first resulted from an emerging environmental awareness related to coastal development, geologic processes soon became linked with issues involving politically and economically sensitive subjects like the siting of power plants, dredging of harbors, and construction of seawalls. Consultation with Harold W. Borns, Jr. of the Institute for Quaternary Studies at the University of Maine inspired the Maine Geological Survey to focus attention on the phenomenon of sea-level rise, and its relation to neotectonic activity, as the principal mechanism influencing shoreline change on the coast of Maine.

In 1977, in collaboration with the Institute for Quaternary Studies, the Maine Geological Survey submitted a research proposal to the United States Nuclear Regulatory Commission entitled: "An Investigation of Late Glacial-Holocene Crustal Warping Along the Maine Coast." The Nuclear Regulatory Commission was, at that time, considering several coastal sites in Maine for a nuclear power plant, and the multidisciplinary proposal to investigate seismicity, sea-level change, and crustal movement was funded. The study began in 1978 and continued through 1986; the results are summarized in this volume.

The research approach has been to measure relative sea-level change on a variety of time scales, utilizing several methods, and then subtract eustatic sea-level rise, which is approximately 1 mm/yr (Gornitz and Lebedeff, 1987). This leaves any residual difference attributable to land-level change. In order to test the hypothesis that the eastern part of Maine's coastal zone may be subsiding more rapidly than the western part, the study compared first-order elevation data measured by the U.S. Coast and Geodetic Survey (now the National Ocean Survey) in 1942 with survey data obtained in 1966. This comparison strongly suggested that crustal subsidence occurred in the time interval between surveys, and that it was progressively greater toward the east, reaching a maximum of 9 mm/year (approximately 1 m per century) in the Passamaquoddy Bay area (Tyler and Ladd, 1980; Tyler, this volume).

Given these initial findings, an interdisciplinary team was formed to obtain overlapping, but independently derived, data sets to measure crustal warping over the span of time from deglaciation (about 14,000 years ago) to the present. The plan was to measure crustal deformation on a variety of time scales, and to validate and refine independent data sets in terms of magnitude, vertical direction, and geographic distribution of crustal deformation. This approach would document postglacial crustal mobility more accurately and over a longer period of time than would have been possible using only one type of information.

This investigation of neotectonics in coastal Maine has included research in the fields of bedrock geology and geophysics, seismology, glacial and marine geology, paleobotany, archaeology, history, oceanography, and geodesy.

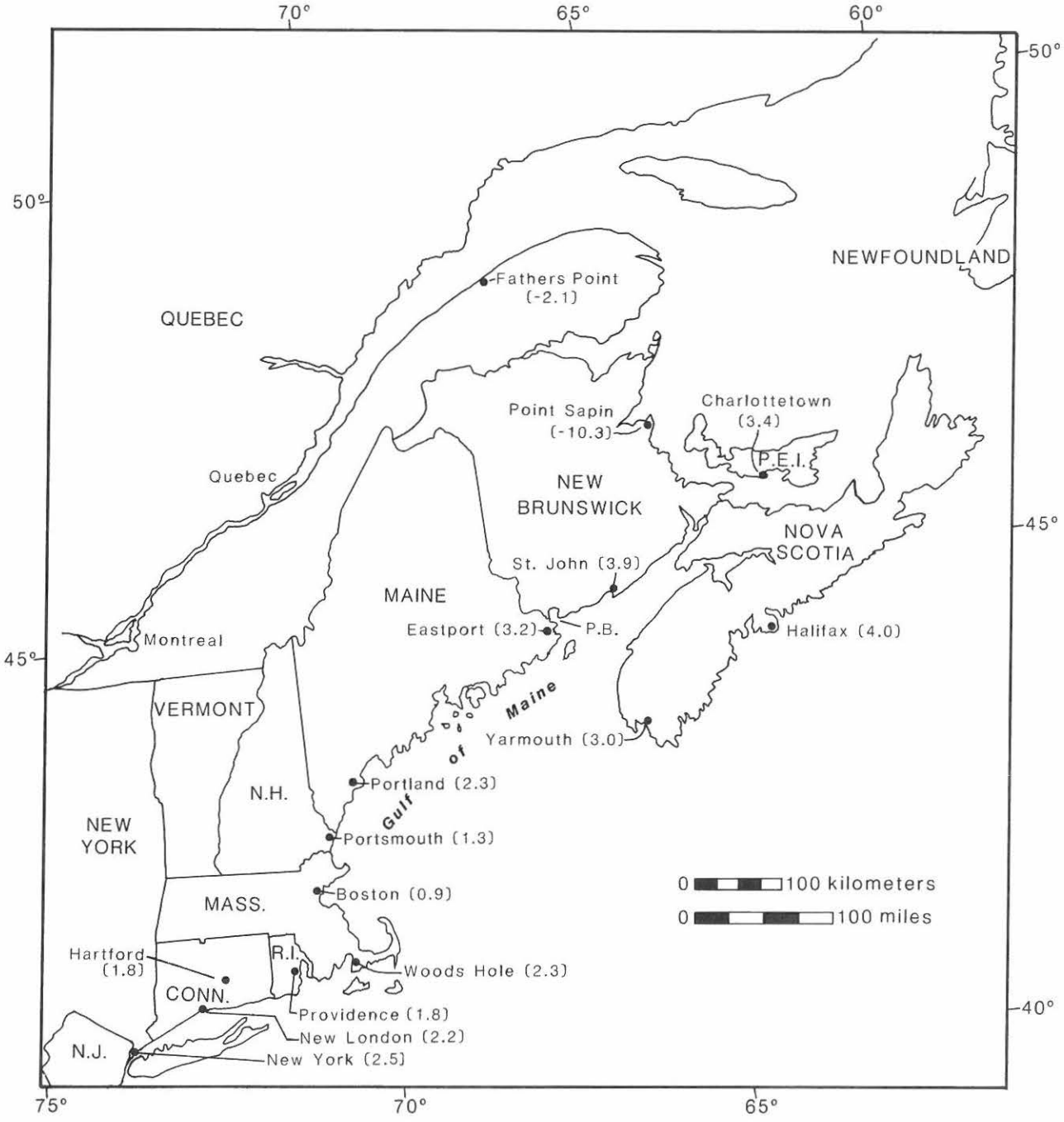

Figure 1. Location of Maine with reference to the other New England states and neighboring Canadian provinces. The numbers in parentheses refer to the local rates of sea-level rise in mm/yr as evaluated by tide gauges. The United States data are from Hicks and others (1983), and represent the time interval 1940-1980. The Canadian data are from Vanicek (1976) and represent a variety of time intervals. "P.B." indicates Passamaquoddy Bay.

Along with the interdisciplinary research plan, a management plan was formulated for the interaction of participants to allow a free flow of information and ideas. It included regular group meetings and field conferences to compare current results in order to modify and set future research directions. In addition, the group set guidelines for sharing and publishing data under individual or collective authorship.

The work generally has progressed as visualized. It has demonstrated that the rate of relative sea-level rise along the Maine coast has varied in time and place during the last 2,000 years, and that this phenomenon is most likely the result of differential crustal subsidence. However, the resolution of rates of sea-level change during particular segments of postglacial time has varied in accuracy as a function of field conditions and limitations inherent in the research methods.

Finally, the research is most complete for the eastern half of the Maine coastal zone. More work is needed in the western part to bring that area to the same level of understanding. The data presented in this volume suggest that the crust, although probably subsiding, is more stable in the latter region. Methodologies are now in place for expanding this research into the western coastal zone and enlarging the data base available for determining the cause of crustal activity along the passive continental margin of the Atlantic states.

The research team included:

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- David Sanger, *Archaeologist*
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- David C. Smith, *Historian*
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GEOLOGICAL SETTING AND LATE QUATERNARY SEA-LEVEL HISTORY

The state of Maine is located along the western Gulf of Maine (Figure 1), in the northeast-southwest trending Appalachian Orogen. The northern and western portions of the state are mostly part of the Central Highlands physiographic province of New England, with elevations commonly exceeding 200 m and reaching a maximum of nearly 1600 m (Denny, 1982). The central and coastal regions of the state possess low, rounded hills less than 200 m in elevation with several isolated peaks over 400 m. Denny (1982) suggested that the major topographic elements of the region are preglacial in origin, and that the highland and possibly the lowland areas have been emergent throughout much of the Cenozoic. No Cenozoic sedimentary rocks are known to exist in Maine.

The Gulf of Maine is a 93,000 square-kilometer basin, which is 70 percent enclosed on the landward sides by the New England states and Canadian maritime provinces (Figure 1), and largely protected on the seaward side by the shallow Georges and Brown's Banks. The greatest depth in the Gulf of Maine is approximately 400 m, and its configuration results from glacial and possibly fluvial action during the Cenozoic. Sedimentary rocks of Cenozoic age are known from the bottom of the Gulf of Maine, and underlie Georges and Brown's Banks.

Maine is characterized by northeast-southwest trending lower to middle Paleozoic metamorphic rocks. These rocks range from high to low metamorphic grade from south to north (Osberg and others, 1985). Several lithotectonic belts cross central, coastal, and offshore Maine (for recent reviews, see Williams and Hatcher, 1982, and Hutchinson and others, 1988). Each belt appears to record the sequential arrival, collision, and accretion of a volcanic or continental terrane welded to the North American Grenville basement. These large-scale Paleozoic

crustal processes were accompanied by extensive and complex structural overprinting, faulting, fracturing, and suture development; and the entire region has been intruded by Paleozoic and Mesozoic igneous bodies (see, for example, regional descriptions by Gates and Hussey in this volume). Subsequent continental extension during the Mesozoic resulted in crustal thinning, reactivation of bedrock faults, and the development of graben basins in the Bay of Fundy and outer Gulf of Maine.

Following the development of bedrock terranes, the Quaternary geologic history of Maine has included at least two glaciations recorded by till deposits (Borns and Calkin, 1977; Thompson and Borns, 1985b). The most recent glacial episode in Maine probably began about 25,000 years ago. The late Wisconsinan Laurentide Ice Sheet advanced across New England, achieving its terminal position on the continental shelf between about 21,000 and 18,000 BP (Stone and Borns, 1986). The glacier margin then retreated across the Gulf of Maine and into central Maine, accompanied by a marine transgression. It is unclear whether an extensive ice shelf existed in the Gulf during this time. Radiocarbon dates on seaweed and marine shells in stratified moraines indicate the presence of a marine-based ice sheet along the coast of Maine and New Brunswick between 14,000 and 13,000 BP (Stuiver and Borns, 1975; Thompson and Borns, 1985b; Stea and Wightman, 1987). Fine-grained glaciomarine sediments, known as the Presumpscot Formation (Bloom, 1963), occur extensively in the lowlands of Maine as far as 150 km inland from the present coast (Thompson and Borns, 1985a). The inland marine limit (Figure 2) is marked by glaciomarine deltas, but is poorly constrained in time. The widespread glaciomarine sediments, the range of radiocarbon dates on fossils within these sediments (Smith, 1985), and the pattern of end moraines suggest that the retreating ice margin reached the inland marine limit sooner in some areas than in others.

Terraced meltwater channels crossing the tops of ice-contact glaciomarine deltas imply that isostatic rebound was already occurring when glacial ice was still present in Maine (Thompson and others, this volume). Although well-preserved regressive, emerged shorelines are uncommon, radiocarbon dates from fossil shells and tree remains within the upper Presumpscot Formation suggest that falling sea level reached the position of the present coastline in western Maine between 11,500 BP and 11,000 BP (Figure 3; Belknap and others, 1987; Smith, 1985; Thompson and Borns, 1985b), while eastern Maine was emergent as early as 12,500 to 12,000 BP (Stuiver and Borns, 1975). Since Bloom's (1963) early work, there has been no doubt that sea level once dropped lower than the present shoreline. Considerable disagreement exists, however, concerning the age and depth of the postglacial lowstand shoreline (Figure 3).

Bloom's (1963) inference of a postglacial sea level 10 m lower than present was based on the depth of weathered glaciomarine sediments (paleosol) beneath modern salt marshes. Using seismic reflection profiling, Schnitker (1974) suggested that the lowstand shoreline is at a present depth of -65 m. Belknap and others (1986) recognized a lowstand paleodelta off the mouth of the Kennebec River, and estimated its age as 9,500 ± 1,000 BP. This paleodelta has been investigated by Belknap and others (in press) and Shipp and others (in press). Oldale and others (1983) interpreted drowned beach deposits from seismic profiles across a submerged paleodelta off the Massachusetts coast at about the -50 m depth, which conflicts with estimates of a -30 m shoreline (Birch, 1984) in nearby New Hampshire. Scott and others (1987) described peat deposits off the Bay of Fundy which presently mark the lowstand shoreline in that area from about 7,000 BP. While these observations of shallower lowstand shorelines northeast and southwest of the Maine coast are plausible reconstructions from near the edge of areas that were glacially downwarped, neither the above nor Peltier's (1986) model (Figure 3) accounts for all observed sea-level fluctuations in the western Gulf of Maine. This discrepancy may result from the complex deglacial history of the region and the global nature of Peltier's model.

There are no radiocarbon dates from sea-level indicators in Maine between about 11,000 BP and 6,000 BP (Belknap and others, 1987). Beginning around 5,000 BP there are many radiocarbon dates from the base of salt marshes in the Gulf of Maine (Figure 4; Oldale, 1985; Belknap and others, 1987; Scott and others, 1987). Dates from the base of a salt marsh deposit which is resting on an uncompactable substrate are understood to represent the approximate position of high tide at a time in the past (Oldale, 1985). Not all sea-level dates from the New England region are from marsh peats, however. The sea-level data from Masachusetts and New Hampshire, summarized by Oldale (1985), form a relatively steep sea-level rise line with a slope representing more than 5 mm/yr of sea-level rise between 4,500 and 2,000 BP (Figure 4). This line contains many dates from freshwater peats, tree stumps, and wood fragments at the base of a salt marsh. The dated materials predate the time of marine inundation by an uncertain amount. Similarly, the relatively steep line from the Bay of Fundy (Figure 4) is based on radiocarbon dates from wood fragments collected from high-marsh peat (Scott and Greenberg, 1983). Newly collected dates from Maine, however, are all from basal salt marsh peat deposits (Belknap and others, 1987 and this volume). These data show a relatively gentle slope of about 1.8 mm/yr between 4,500 BP and 2,000 BP (Figure 4). If wood-fragment dates on samples from the basal peat horizons were added to the latter plot, the slope would be steeper, and the scatter in the data would be greater.

Many workers have inferred that the rate of sea-level rise slowed down at around 2,000 BP. For locations within the Gulf of Maine to the northeast and southwest of Maine, that time is taken as 2,500 BP (Oldale, 1985; Scott and Greenberg, 1983), while in Maine, some time between 2,000 and 1,500 BP seems to better locate the change in slope of the sea-level rise line (Figure 4). Oldale (1985) suggests that sea level has risen at a rate of 1 mm/yr for the past 2,500 years for regions from New Hampshire to New Jersey. Modern rates of sea-level rise as evaluated by tide gauges indicate rates of inundation 3 to 4 times

that estimate around parts of the Gulf of Maine between 1940 and 1980 (Figure 1).

EVIDENCE FOR NEOTECTONICS IN MAINE

There are four broad disciplines -- seismology, bedrock geology, sea-level studies, and geodesy -- within which evidence has been generated pertaining to neotectonics in Maine. One indicator of neotectonic activity is seismic energy release in the form of historical and modern earthquakes (Figure 2). Large and damaging earthquakes have occurred in Maine within historical time (Smith and others, this volume), and numerous smaller earthquakes have been instrumentally detected in the state and region in recent years (Johnston and Foley, 1987; Shakel and Toksoz, 1977; Ebel, 1984, this volume). The locations of Maine earthquakes do not appear to be randomly distributed. Rather, they are concentrated in a broad zone subparallel to the present coast and largely confined to the lowland region of late-glacial marine submergence (Figure 2). Within this zone, many of the recent earthquakes have clustered in the eastern extremity of the state (Passamaquoddy Bay area) and in central Maine, and there is a lesser concentration in the southwestern coastal region (Johnston and Foley, 1987).

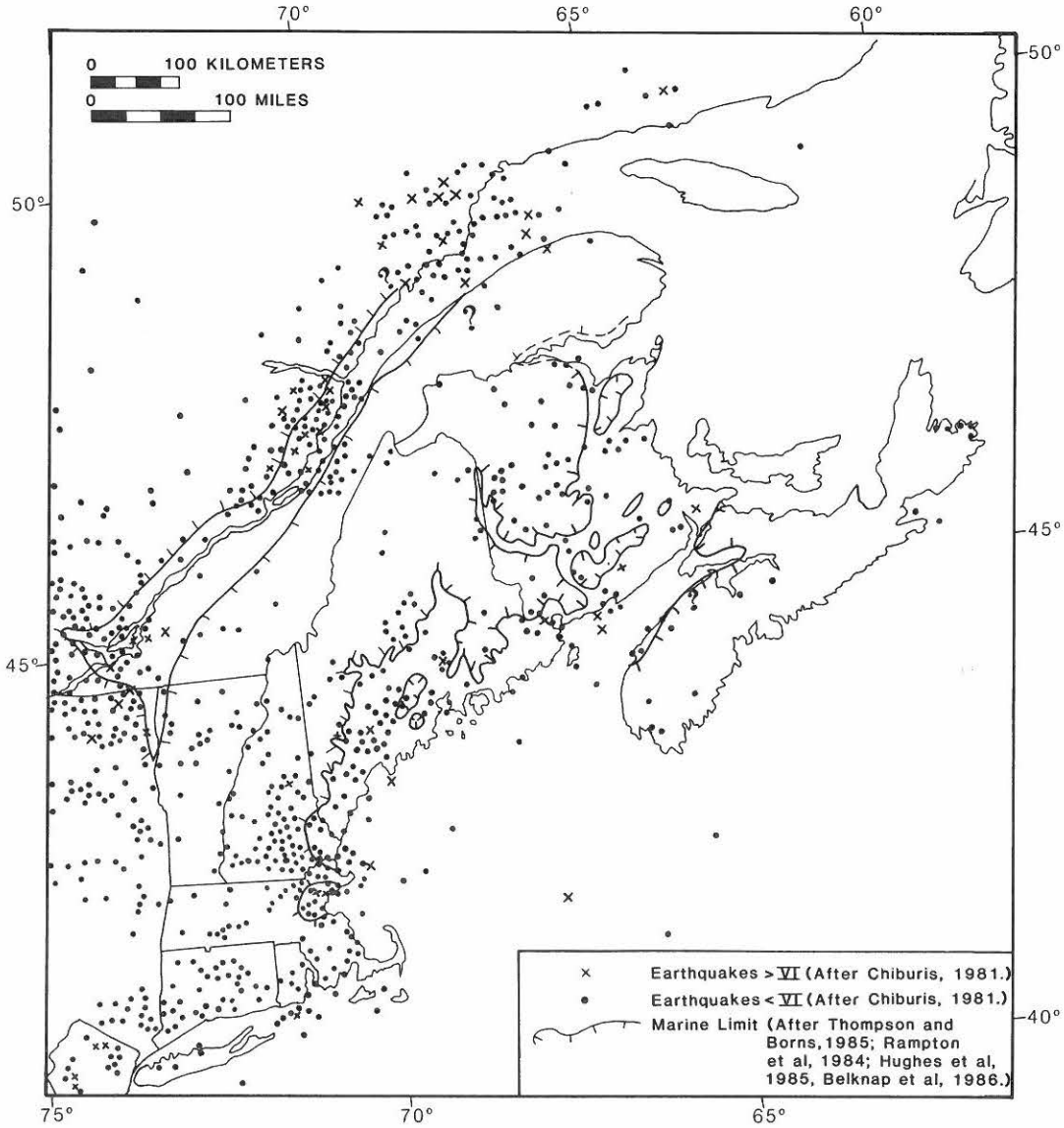

Figure 2. Map showing earthquake distribution in northeastern United States and adjacent Canada and the inland limit of late-glacial marine submergence. The distribution of earthquakes in New England and the Canadian Maritimes between 1534 and 1977 is modified from Chiburis (1981).

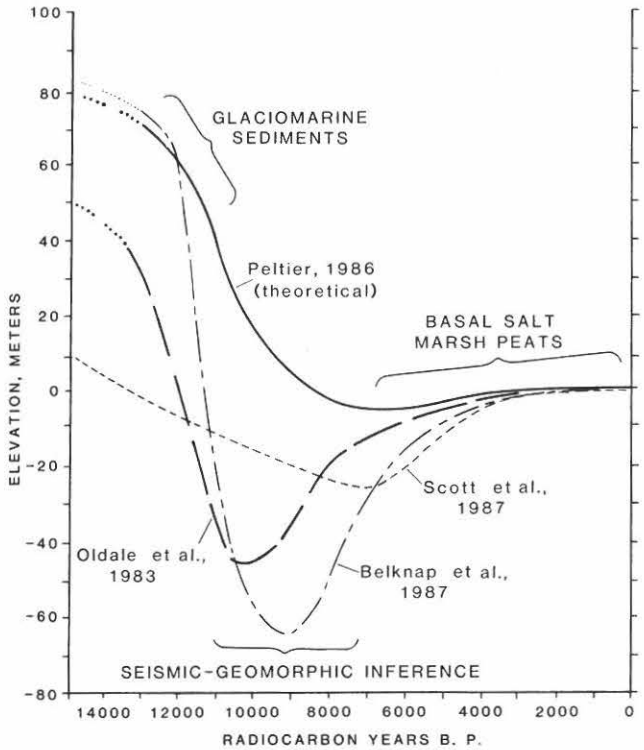

Figure 3. Late Quaternary sea-level change curves for the western Gulf of Maine. The data from Maine are modified from Belknap and others (1987); those from the Bay of Fundy are modified from Scott and others (1987); and those from New Hampshire and Massachusetts are modified from Oldale and others (1983). The curve from Peltier (1986) is derived from theoretical considerations.

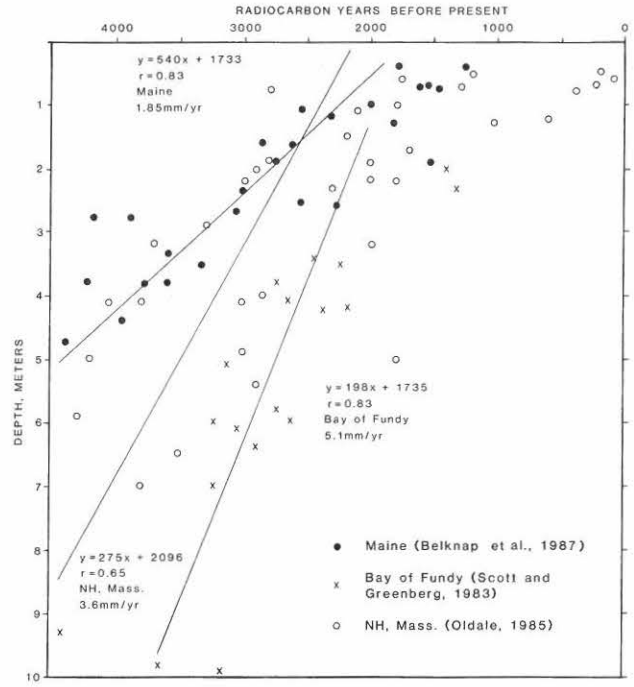

Figure 4. Sea-level rise as determined from dating basal salt marsh deposits. The data from Maine are modified from Belknap and others (1987); those from the Bay of Fundy are modified from Scott and others (1987); and those from New Hampshire and Massachusetts are from Oldale (1985). The regression lines were fit to the data between 4,500 BP and 2,000 BP, because that is the time interval in which each of the locations had the most complete record.

In the Passamaquoddy Bay area, a major fault zone runs parallel to the present coast, separating an offshore Mesozoic rift basin from a lower Paleozoic volcanic terrane in coastal Maine. The Oak Bay fault trends normal to the axis of this rift basin and follows the international border between Maine and New Brunswick (see map by Gates, this volume). An investigation of rocks along the Oak Bay fault found no indication of Cenozoic activity, and a Mesozoic diabase dike that crosses this fault shows no apparent offset (Gates, this volume). A statewide reconnaissance search for postglacial fault movements similarly revealed no evidence of recent activity at the ground surface (Koons, this volume). However, geophysical work by Lee (this volume) indicates the presence of a horizontal compressive stress striking N 80° E in the bedrock of eastern Maine. Papers in this volume by Ebel, Gates, and Lee propose a causal relationship between tectonic stresses within the North American plate and the occurrence of Maine earthquakes. Ebel (1983, this volume) also notes that a 1979 earthquake and aftershocks near Bath, Maine, may have occurred along known faults.

Single-channel, high-resolution seismic reflection profiles across the Oak Bay fault and other mapped bedrock faults in Maine's estuaries and offshore areas were inconclusive about the possibility of recent movement (Kelley and others, this volume). Over the Oak Bay fault, seafloor scarps were recognized in Quaternary sediments, but the shallow penetration of the equipment did not allow examination of the underlying bedrock surface. Along the Oak Bay fault and other fault lines in Maine, seismic reflection and side-scan sonar observations indicated numerous postglacial slumps. These slumps are confined to Holocene and late Pleistocene glaciomarine muddy sediments. The ubiquitous presence of natural gas in the mud obscures the relationship of the slumps to nearby faults, but the association is probably coincidental. Glacial erosion very likely overdeepened the fractured rock near the faults and formed relatively steep modern submarine slopes, which are experiencing slumps as a result of wave action assisted by natural gas generation in organic-rich, muddy sediments (Kelley and others, this volume).

The papers in this volume describing the bedrock geology of eastern and southwestern Maine, by Gates and Hussey respectively, provide a framework in which to evaluate the neotectonics of these widely separated parts of the coastal zone. Although there are major differences in the geologic history of the bedrock in these areas, both regions are cut by many faults and experience frequent low-intensity earthquakes. However, the Passama-

quoddy Bay area in eastern Maine shows more concentrated seismic activity and is believed to be experiencing more rapid crustal downwarping than other sections of the coast. Several papers included here discuss the evidence for this downwarping, and Gates found that eastern Maine has been an area of crustal instability and subsidence since Silurian time.

Much of the evidence for neotectonic activity in Maine is provided by research on the varying rates of local relative sea-level rise. The longest time interval over which data exists on the land-sea boundary begins near the end of the Pleistocene. Radiocarbon dates on fossils from glaciomarine sediments indicate that the late-glacial marine submergence of Maine's coastal lowland began shortly after 14,000 BP (during deglaciation) and persisted until isostatic uplift brought the coastal zone above sea level between about 12,500 and 11,000 BP (Stuiver and Borns, 1975; Smith, 1985; Thompson and Borns, 1985b). Precise surveying of the elevations of glaciomarine deltas permits the construction of a contour map of the upper marine limit, showing the general tilt of the crust resulting from postglacial isostatic adjustment (Thompson and others, this volume). The marine-limit contours show a pronounced deflection at the Maine/New Brunswick border near Eastport, which suggests postglacial warping of the crust. Alternatively, glacial ice may have existed later in that area and formed deltas at lower elevations. We do not yet have any radiocarbon dates from the deltas to help resolve the problem; nor do we have nearly enough information on the subsequent lowstand shoreline (now drowned by rising sea level) to employ deformation of this shoreline as a measure of crustal warping.

Radiocarbon dates from the base of salt marshes in the Gulf of Maine yield sea-level rise lines with significantly different slopes between Boston, Maine, and the Bay of Fundy (Figure 4). As discussed above, these differences may result from the differing materials used for dating. Alternatively, a migrating peripheral crustal bulge (resulting from the last glaciation) and regional variations in thickness of glacial ice may be affecting rates of residual isostatic response.

Studies of coastal Maine archaeological sites have generated evidence of differential crustal subsidence over the last few thousand years (Sanger and Kellogg, this volume). There are marked differences in ages of preserved sites between certain sections of the coast. This contrast is most pronounced between Penobscot Bay in the midcoastal region and the Passamaquoddy Bay area. Early (Archaic) sites are relatively common around Penobscot Bay, but appear to be absent in easternmost coastal Maine. This observation suggests a greater degree of late Holocene crustal stability in the central coastal zone. Analysis of the ages of archaeological sites along eroding shorelines also indicates that the rate of crustal subsidence has been uneven through time and may be unusually rapid at present (Sanger and Kellogg, this volume).

The relationship of sea level to man-made coastal structures built during the eighteenth and nineteenth centuries provides a crucial link between the archaeological data and evidence of more recent sea-level change. Although there are many places where colonial wharves, salt-marsh dikes, and other structures are partly or entirely submerged at high tide, it is difficult to use these structures for precise determination of sea-level rise and crustal warping. Their ages must be accurately known, as well as their original position with respect to sea level. Further problems have been introduced in some cases by human disturbance and compaction of underlying salt-marsh peat. Nevertheless, coring on the flanks of colonial salt-marsh dykes in eastern Maine has shown evidence of sea-level rise averaging about 3 mm/yr since construction of the dykes by settlers in the early 1800's (Smith and others, this volume).

The briefest and most recent set of data on changing sea level in the western Gulf of Maine has been obtained from tide gauges. Tide-gauge records along the New England coast show increasing rates of relative sea-level rise from Boston to Eastport (Figure 1; Brown, 1978), and these rates do not correspond exactly to trends determined from releveling the first-order level network of the United States.

Tide gauges sum the vertical changes in sea level together with changes in the elevation of the land. Thus, there are many factors which may lead to apparent sea-level rise, including eustatic sea-level change, meteorological effects like barometric changes and storm frequency, and oceanographic factors such as tidal and current influences, as well as fluctuations in river discharge (Chelton and Enfield, 1986). The brief interval of time represented by tide-gauge records, in conjunction with the possibly longer period of the other factors influencing tides, does not inspire confidence in quantitative comparisons of these records even within small regions like the Gulf of Maine (El-Sabh and Murty, 1986). While stations from Boston to Eastport show a regular increase in the apparent rate of sea-level rise between 1940 and 1980 (Figure 1), we must interpret this information with caution. If the increase in submergence toward Eastport is a tectonic signal, it would still be useful to subtract the extraneous influences from this record to establish the magnitude of crustal downwarping.

Tyler and Ladd (1980) provided geodetic evidence that crustal warping is occurring in Maine by comparing the 1942 and 1966 levelings of the United States first-order level network. They concluded that the Eastport area subsided at a rate of 9 mm/yr with respect to Bangor (in central Maine) in the time between surveys, and that if Bangor were assigned an uplift rate of 2 mm/yr, the subsidence in eastern Maine was in agreement with rates of downwarping in adjacent Canada (Vanicek, 1976). Reilinger (1987) questioned Tyler and Ladd's use of the 1942 survey line, claiming that it has an unusually large root-mean-square error. He concluded that eastern Maine is experiencing contemporary subsidence of only 1-2 mm/yr, a value in better accord with tide-gauge records. Nevertheless, in considering possible errors in the original survey data, Tyler (this volume) concludes that the releveling indicates a maximum subsidence rate of at least 5 mm/yr. To address this problem, and to provide a baseline for measurement of crustal motion, the Global

Positioning System (GPS) of satellite receivers was recently used to survey a new network of monuments in eastern Maine which will be monitored into the future (Lambert, 1988). Tyler (this volume) discusses other geodetic work that has been carried out to detect both vertical and horizontal neotectonic crustal movements.

CONCLUSIONS

Any model of neotectonic activity that seeks to explain the pattern of seismicity and crustal warping in Maine must account for similar changes in the greater Gulf of Maine area. Late Quaternary changes in sea level in the region have resulted from deglaciation, specifically from changes in eustatic sea level together with the isostatic response of the earth's crust and mantle to melting of the Laurentide Ice Sheet and collapse of a peripheral bulge (Peltier and Andrews, 1976). Vertical crustal movement due to the collapse and migration of this proposed bulge may be an ongoing process, and perhaps is responsible, at least in part, for Maine earthquakes.

Nonglacial explanations for earthquake activity in northern New England have invoked continued seismicity along fault zones associated with Mesozoic continental fragmentation, like the New England seamount chain (Sbar and Sykes, 1973) and the Bay of Fundy rift basin (Rast and others, 1979). The association of earthquakes with different tectonic terranes has been noted as a useful guide for anticipating future earthquakes on a regional scale (Wheeler and Bollinger, 1984; Seeber and Armbruster, 1988), just as the spatial relationship between seismicity and lowland areas is potentially useful on a smaller scale (Barosh, 1981).

The distribution of Maine earthquakes in time and space is becoming well known through historical and instrumental records, but -- as indicated above -- the precise causes of these earthquakes are poorly understood. Papers in this volume by Ebel, Gates, and Lee discuss the horizontal crustal stress recorded in Maine, and infer that this stress is a plate-tectonic phenomenon that may induce earthquakes along new or preexisting fractures. Gates' work on the stratigraphy and structure of the Passamaquoddy Bay area provides a plausible explanation for the concentration of seismic activity and anomalous downwarping in this area, based on a history of faulting and subsidence through much of Phanerozoic time. However, the relative importance of plate tectonics versus glacioisostasy (or other causes) in triggering earthquakes and crustal movement in the Gulf of Maine region continues to be a controversial subject.

The data presented in this volume indicate that the rate of relative sea-level rise varies along the Maine coast, and has been uneven through postglacial time. The techniques discussed here differ in their ability to accurately measure changes in land and sea level, and to determine the chronology of these changes. Collectively, however, the results lead us to conclude that relative sea level in Maine is rising more rapidly than can be explained by the eustatic sea-level rise of approximately 1 mm/yr (Gornitz and Lebedeff, 1987). Subtracting this global rise from the total rise shown by tide-gauges (Figure 1) suggests as much as 2.2 mm/yr of crustal subsidence in coastal Maine. Leveling data analyzed by Tyler (this volume) support the downwarping theory, indicating subsidence rates of up to at least 5 mm/yr, but much additional geodetic work and analysis of tide-gauge records is needed to quantify the amount and distribution of crustal motion across Maine.

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