Neotectonic history of eastern Maine evaluated from historic sea-level data and $^{14}$C dates on salt-marsh peats

W. Roland Gehrels
Daniel F. Belknap
Department of Geological Sciences, 119 Boardman Hall, University of Maine, Orono, Maine 04469

ABSTRACT

We constructed a local relative-sea-level curve for eastern Maine from $^{14}$C dates on salt-marsh peats to evaluate potential Holocene neotectonic activity. This sea-level chronology indicates that, contrary to suggestions made previously, low elevations of late-glacial shoreline features in eastern Maine are not related to neotectonic activity during the past 5 ka. A comparison between seismicity and tide-gauge records leads to the conclusion that there is no relation between seismic activity and contemporary subsidence of eastern coastal Maine. We propose that eastern Maine has not been affected by anomalous subsidence during at least the past 5 ka.

INTRODUCTION

Salt marshes are excellent recorders of vertical crustal movements during the middle and late Holocene due to their tendency to maintain themselves near an equilibrium with sea level while sea level is changing. Salt-marsh deposits have been studied to infer seismic activity and earthquake recurrence intervals along the Pacific coast of the northwestern United States (Atwater, 1987; Atwater et al., 1991; Atwater and Moore, 1992; Bartsch-Winkler and Schmoll, 1992; Nelson, 1992, 1993). Along passive continental margins, such as the east coast of the United States, smaller earthquakes, magnitude 5 or less, leave little, if any, stratigraphic record. However, these earthquakes can be associated with longer term anomalous crustal subsidence, which in coastal areas can be detected by radiocarbon dating of basal peat deposits in tidal marshes. Sea-level curves from adjacent coastal regions based on radiocarbon-dated salt-marsh peats would show contrasting slopes if differential crustal movements had occurred (Newman et al., 1987).

Crustal motion during historic times may be inferred from anomalous tide-gauge trends. By comparing tide-gauge records with leveling data, Brown (1978) detected tectonic motion in the Connecticut Valley graben, Chesapeake Bay, Cape Fear arch, and Cape Canaveral prominence. Gornitz and Seeber (1980) found evidence for subsidence in South Carolina and southern Chesapeake Bay.

Eastern Maine has been investigated for inferred neotectonic activity for almost a decade. The case for crustal warping was made by Anderson et al. (1984), who noted anomalies in leveling surveys, tide-gauge records, and elevations of late-glacial shoreline features, paired with historical seismicity (Chibulis, 1981). Reilinger (1987) took exception to these conclusions by demonstrating a systematic error in the crucial 1942 releveling survey. The latest tide-gauge records cast further doubts, showing a submergence rate for Eastport of 2.5 mm/yr from 1980 to 1990 (Lyles et al., 1988; National Oceanic and Atmospheric Administration, 1992, written commun.), only slightly faster than that for St. John, New Brunswick (2.3 mm/yr; Marine Environmental Data Service, 1992, written commun.), and Portland (2.1 mm/yr; Lyles et al., 1988; National Oceanic and Atmospheric Administration, 1992, written commun.).

Eastern Maine shows a prominent anomaly in the contoured pattern of elevations of topset-forest contacts of late-glacial-age glaciomarine deltas (Thompson et al., 1989; Fig. 1). At the peak of late Wisconsin marine onlap into interior Maine, about 12.5 ±0.5 ka (Stuiver and Borns, 1975; Smith, 1985), these deltas were deposited at sea level along the ice front as floating ice grounded (Belknap et al., 1987). As Maine was deglaciated, isostatic adjustments caused uplift of the deltas. In the north, ice was thicker and, therefore, depression of the crust was greater, so that rebound was greater than in the south, resulting in a southward-tilting plane of delta elevations. Superimposed on this general tilt is an area in eastern Maine, near Eastport (Fig. 1), where delta elevations appear to be anomalously low by at least 12 m (Thompson et al., 1989). In spite of limited radiocarbon dating control, Anderson et al. (1984) assumed that these deltas were approximately contemporaneous and emplaced along an originally horizontal plane of sea level. Several authors (Anderson et al., 1984, 1989; Reilinger, 1987) have used the locally anomalous elevations

Figure 1. Study sites Sanborn Cove and Jasper Beach marsh are located in Machias Bay, eastern Maine, within region of anomalous elevations of topset-forest contacts of late-glacial glaciomarine deltas (Anderson et al., 1984). Elevations contours modified from Thompson et al. (1989) are in 10 m intervals. Open circles are tide gauges. Solid circles denote locations from which salt-marsh peats have previously been dated (Belknap et al., 1989).
as an argument for postglacial neotectonic activity in eastern Maine.

An alternative hypothesis to explain the anomalously low elevations of the deltas was proposed by Thompson et al. (1989) and involves time-transgressive deposition during the lingering of late Wisconsin thinning ice in eastern Maine. Rates of rebound were extremely rapid (~10 m/100 yr; Belknap et al., 1987), so that if ice remained in eastern Maine only slightly longer than in adjacent areas, younger deltas would have been deposited at significantly lower sea levels.

To test the hypothesis that differential crustal movements have occurred in eastern Maine during the Holocene, we obtained an independent data set by collecting radiocarbon dates on peats from salt marshes along Machias Bay at Machiasport (Fig. 1). These dates were used to establish a precise trend of local relative sea level for the past 5 ka. Finally, to investigate crustal behavior during historic time, we examined the tide-gauge record of Eastport and its relation to records of adjacent coastal locations.

**METHODS**

Extensive reconnaissance coring located two salt marshes within the area of anomalous delta elevations that were suitable for the creation of a local relative-sea-level curve. These marshes, Sanborn Cove marsh and Jasper Beach marsh (Fig. 1), contain thick sections of salt-marsh peats (Fig. 2). The peats directly overlie the incompressible Pleistocene substrate. Seven cores (four in Sanborn Cove marsh, three in Jasper Beach marsh) were collected with a 7.6-cm-diameter Vibracorer. The cores were opened in the laboratory, logged, and photographed, and the basal peat was sampled for radiocarbon dating. Displacement by autocompaction could not be ruled out in two cores (MA-VC-91-1, MA-VC-86-3) that failed to penetrate the substrate, and in one core (SN-VC-2) where the lowest peat was avoided during sampling for conventional dating because it appeared to be affected by humic acid contamination (see Belknap et al., 1989). Six bulk samples were conventionally dated by Beta Analytic, Inc., and one by the University of Pittsburgh Radiocarbon Laboratory. We also obtained four accelerator mass spectrometry (AMS) 14C dates from the University of Arizona National Science Foundation accelerator facility on individual, horizontally embedded, basal plant fragments.

Elevations of 14C samples from the Sanborn Cove marsh were measured with an infrared theodolite relative to a nearby U.S. Coast and Geodetic Survey benchmark. Elevations in Jasper Beach marsh were measured relative to tide levels predicted by National Oceanic and Atmospheric Administration (NOAA) tide tables. Tide levels were related to the National Geodetic Vertical Datum (NGVD) of 1929 using relations provided by the National Ocean Service (NOS). Mean high water (MHW) occurs at 2.03 m above NGVD at Machiasport; the tidal range at Machiasport is 3.84 m (National Oceanic and Atmospheric Administration–National Ocean Service, 1991). Tide-gauge data for Eastport, Bar Harbor, and Portland, Maine, were obtained from published accounts (Lyles et al., 1988) and directly from NOAA in Rockville, Maryland. The records for St. John, New Brunswick, were provided by the Marine Environmental Data Service in Ottawa.

**LONG-TERM SUBSIDENCE**

New radiocarbon dates on basal peats from two Machias Bay salt marshes are listed in Table 1. Jasper Beach marsh is part of a barrier-lagoon system. The stratigraphy shows a transgressive sequence with evidence of barrier retreat over back-barrier sediments (Duffy et al., 1989; Fig. 2, A-A'). Sanborn Cove marsh fringes the tidal flats of Machias Bay. Creek meandering has destroyed much of the peat stratigraphy, except in one locality where a thick, high-salt-marsh peat section was preserved (Fig. 2, B-B'). When plotted in an age vs. depth diagram (Fig. 3), the conventional dates show some scatter and are younger than comparable AMS 14C dates. We believe that AMS analyses of individual detrital plant fragments most accurately date the former marsh surface because, in contrast to large bulk samples, they are not contaminated by root intrusion and humic acid percolation (see Belknap et al., 1989; Gehrels and Belknap, 1992). In addition, the plant fragments are too fragile to have been significantly reworked. The peats in which these plant fragments are embedded consist primarily of the remains of Juncus gerardii and Solidago sempervirens, plants that grow between mean higher high water (MHHW) and highest high water (HHW) on the marsh today. The salt-marsh foraminifer Trochammina macrescens is present in abundance in the peats (97%-99% of total fossil fauna), another indication of an origin close to HHW (Scott and Medioli, 1978). On the modern marsh surface, the Trochammina macrescens zone is between 53 and 68 cm above MHW. A regression line through the AMS 14C dates should approximately represent the rise of HHW. The curve repre-

![Figure 2. Stratigraphic cross sections from Jasper Beach (A-A') and Sanborn Cove (B-B'). Jasper Beach cross section is partially adapted (1986 cores) from Duffy et al. (1989). MHW is mean high water.](image-url)
senting the MHW rise should lie ~60 cm below the HHW curve (neglecting tidal range changes). When the dates are calibrated into calendar years (Stuiver and Reimer, 1986; Table 1), the rate of MHW rise between 5 ka and 2.5 ka is ~1.0 mm/yr.

HISTORICAL CRUSTAL INSTABILITY

Crustal motion in the Eastport area can be evaluated by comparing the Eastport tide-gauge record with records of nearby stations, whereby Eastport is chosen as a reference point (e.g., Brown, 1978). Figure 4 shows the yearly mean sea level in Eastport relative to Portland, Bar Harbor, and St. John for the period 1930–1986. For the following discussion it is assumed that oceanographic and atmospheric effects are identical among the four tide gauges. For Eastport, Bar Harbor, and Portland, this assumption is supported by the lack of difference in seasonal sea levels (Lyles et al., 1988). The tide-gauge record of St. John is influenced by the discharge of the St. John River (El-Sabh and Murty, 1986). The motion trend of Eastport relative to St. John is similar, however, to those relative to Bar Harbor and Portland, suggesting the insigificance of seasonal effects in the signals depicted in Figure 4.

Earthquake epicenters in eastern Maine are clustered within a 20 km radius around Eastport (Chubris, 1981; Nottis, 1983). Several authors have suggested a relation between anomalous subsidence in eastern Maine as indicated by tide-gauge records and seismicity in the Eastport area (e.g., Anderson et al., 1984, 1989; Reilinger, 1987; Gornitz and Seeber, 1990). Contemporary sea-level rise at Eastport, however, was underestimated because of the time interval selected to compute the submergence rate. Figure 4 shows that determination of submergence rates is highly dependent on the time period used, because the relative vertical motion of Eastport has been very irregular. Brown (1978), for example, chose the interval 1930–1966, because in 1966 a relevelling survey took place that enabled him to compare directly the tide-gauge data with surveying information. Unfortunately, 1966 is also the time of a reversal in the crustal motion trend at Eastport (Fig. 4), which gave Brown (1978) a deceptively high rate of sea-level rise. Furthermore, a comparison between significant earthquake events (magnitude ≥2) and the crustal motion trends (Fig. 4) indicates that an inverse relation between seismicity and subsidence may exist, although we cannot support this notion with statistical data. For the purpose of this paper, it is sufficient to demonstrate the lack of a correlation between seismicity in Eastport and periods of subsidence (Fig. 4).

DISCUSSION AND CONCLUSIONS

The new sea-level data from Machias Bay are shown in Figure 3 with previous data collected from other salt marshes along the Maine coast. On the basis of the older data, Belknap et al. (1989) concluded that no differential crustal movements along the Maine coast between 6 and 1.5 ka could be inferred. However, the study by Belknap et al. (1989) did not include data from easternmost Maine, nor did it include AMS 14C dates. It is evident from Figure 3 that the radiocarbon dates collected from the Machias Bay marshes lie within the range of the data from other parts of the Maine coastline. The rate of relative sea-level rise in eastern Maine between 5 and 2.5 ka does not exceed that from other coastal localities in Maine; on the contrary, sea-level rise in eastern Maine appears to have been slightly slower. We do not have basal dates that are younger than 2.5 ka. Differential warping during the past 2.5 ka, however, cannot have exceeded 1 m (Fig. 3). The conventional dates from Machias Bay are in close agreement with the trend of sea-level rise proposed by Belknap et al. (1989) (Fig. 3). Because conventional 14C dating on large bulk samples has shown a tendency to underestimate the true age of salt-marsh peats (Gehrels and Belknap, 1992), additional AMS 14C dates from other salt marshes in Maine may not only reduce the scatter in the older data but also result in an estimate of a slower rate of late Holocene sea-level rise for other parts of the Maine coast.

Neither historical nor late Holocene sea-level data support the hypothesis that anomalous elevations of glacimarine deltas in eastern Maine are related to neotectonic activity. The anomaly in the pattern of late-glacial shoreline features in eastern Maine was produced prior to 5 ka, either as a result of time-transgressive delta formation during an early phase of the late-glacial regression when rates of isostatic rebound were rapid, or as a result of more intense neotectonic activity during deglaciation.

The late Holocene submergence rate in eastern Maine is slow when compared with rates in adjacent Atlantic Canada. In the Bay of Fundy, sea level has been rising at 2.7 mm/yr (corrected for changes in paleotidal range; Scott and Greenberg, 1983; Smith et al., 1984; Belknap et al., 1989). This difference

| Table 1. Radiocarbon Dates on Salt Marsh Peats from Machias Bay |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Laboratory      | Core             | MHW depth (cm)  | 14C age (ka)   | Calibrated age (ka) | 14C age (ka) | 14C age (ka) | 14C age (ka) | 14C age (ka) | 14C age (ka) |
| number          |                 |                 |                |                               |               |               |               |               |               |

Note: MA and SN cores are from Jasper Beach and Sandhorn Cove marshes, respectively. MHW = Mean High Water; BH = basal high marsh peat; HHW = in-core high marsh peat; B. diff. S. = basal deposit of Spartina alterniflora; B. plant fr. = undifferentiated basal planar fragments.

Figure 3. Machias Bay 14C dates plotted in age vs. depth diagram and compared with data collected during previous studies (open circles; Belknap et al., 1989) from Wells, Popham, Gouldsboro, and Addison (for locations, see Fig. 1). Squares are accelerator mass spectrometry basal dates; solid circles are conventional basal dates; triangles are conventional in-core dates. Highest high water (HHW) curve represents best-fit regression line through Machias Bay AMS 14C dates. Mean high water (MHW) curve is established from foraminiferal analyses (see text). Dashed line is Maine sea-level curve proposed by Belknap et al. (1989) for dates older than 2.5 ka.
The identification of neotectonic warping using salt-marsh peat data is relatively straightforward along the Pacific coast of the northeastern United States because of the large giant earthquakes and large offsets. In mid-plate coastal plain settings with sudden warping, such as South Carolina, Chesapeake Bay, and the Cape Fear arch, and in mid-plate settings with overprints of glacioisotasy, such as Maine, separation of neotectonic effects from overall variance is more problematic. We believe that AMS 14C dates from carefully selected plant fragments (to avoid contamination inherent in bulk dates), careful leveling, and use of foraminifera to indicate paleotidal levels are crucial for making this determination.

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