Sea-Level and Crustal Movements along the New England-Acadian Shore, 4,500-3,000 B.P

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SEA-LEVEL AND CRUSTAL MOVEMENTS ALONG THE NEW ENGLAND–ACADIAN SHORE, 4,500–3,000 B.P.[1]

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ABSTRACT

Remains of three drowned forests have been investigated at Odiorne Point, New Hampshire, and Fort Lawrence and Grand Pré, west-central Nova Scotia. Carbon-14 ages and altitudes below mean tide levels were determined for four in-place stumps of white pine at each locality. Assuming that each dated stump was killed by rising salt water, and that its C^{14} age represented its true age at death, it was possible to construct curves showing the sequence of submergence and emergence at each site.

A continuous transgression of the sea, approximating 0.31 foot per century, is indicated for the period 4,500–3,200 B.P. This rate corresponds well with Shepard's (1960) estimate of eustatic sea-level rise along the stable Texas coast for this time interval.

Interpretation of the submergence-emergence curves in terms of crustal movements yields the following history: 4,500–3,800 B.P.: crustal stability at all three sites; 3,800–3,400 B.P.: crustal downwarping of west-central Nova Scotia at the approximate rate of 2.6 feet per century; slightly greater downwarping at Grand Pré possible, indicating a hinge for the warping lying to the north of Fort Lawrence; slight crustal depression of the New Hampshire coast may have taken place; 3,400–3,250 B.P.: upwarping of west-central Nova Scotia at the approximate rate of 4 feet per century; crustal stability of New Hampshire shore; 3,250–3,000 B.P.: renewed downwarping in west-central Nova Scotia at the approximate rate of 0.88 foot per century; crustal stability of New Hampshire shore.

INTRODUCTION

Authors' previous work.—Our previous study of the drowned-forest sites shown in figure 1 dealt with the rates of submergence of the sites (Lyon and Harrison, 1960). Submergence rates were inferred from dated tree stumps found at the highest and lowest altitudes at each site, our assumption being that the trees had been killed by rising salt water. We indicated (1960) that samples of stumps from intermediate altitudes at each site were being dated for the purpose of checking our preliminary submergence rates and the geological speculations that we had made from them.

In this paper we present the new C^{14} determinations, additional information on the forest sites, and our interpretation of the events that we believe are indicated by the data now available.

Other recent work.—A study by Frankel and Crowl (1961) on the drowned forests along the eastern coast of Prince Edward Island summarizes the radiocarbon dating of the drowned forests of the area prior to our 1960 study and presents evidence of the submergence of eastern Prince Edward Island by 5–8 feet during the last 900 years. Pringle *et al.* (1957) present a C^{14} date of 5,300 ± 150 years B.P. for a stump from the drowned forest at Fort Lawrence (cf. our fig. 5), and Cameron (1956) reports a date of 4,200 ± 200 years B.P. for the drowned forest at Avonport, near Grand Pré (cf. fig. 5). Bloom (1960) reports a date of 2,970 ± 140 years B.P. for a stump submerged 13.5 feet at high tide in Blue Hill Bay, Maine. All of these dates are in general agreement with ours and substantiate the geomorphic evidence of coastal submergence in the last few thousand years.

Barghoorn (1959) has reported a series of C^{14} dates from a section of sediments at Boston Back Bay, Massachusetts, and from a section of peat at Barnstable Marsh, central Cape Cod, Massachusetts. These C^{14} dates and the approximate altitudes of the organic materials from which they came permit rough calculations of the *rates* of sub-

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mergence of the Boston and Cape Cod areas over portions or all of the time interval covered by our study. The rate of submergence at Boston for the period 4,500–3,850 B.P. approximates 0.55 foot per century, and at Cape Cod, for the period 5,480–1,880 B.P., it approximates 0.28 foot per century. The average of these two rate values is 0.41 foot per century, which corresponds well with our value of 0.31 foot per century for the rate of submergence of the drowned-forest site at nearby Odiorne Point, New Hampshire (Lyon and Harrison, 1960; this study).

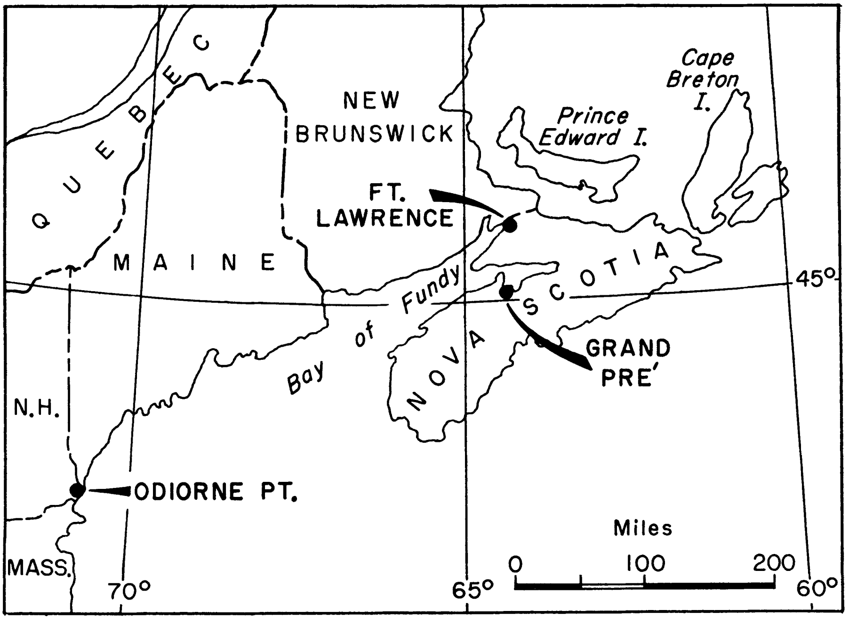

FIG. 1.—Locations of drowned forests

THE DROWNED FORESTS

Odiorne Point, New Hampshire.—This drowned forest is located near lat. 43° 02′ N. and long. 70° 44′ W. (fig. 1). It was described briefly by Lyon and Goldthwait (1934), who used cross sections of the stumps in a vain effort to measure the rate of submergence of the trees by correlating growth rings. The forest site consists of the remains of a largely coniferous stand whose short stumps and fallen logs are found within a small cove. The stumps are partially protected from storms by offshore ledges (fig. 2). Remnants of the trees are rooted in a firm woodland peat that ranges from 2.5 to 4.0 feet in thickness under the dated stumps.

The firm nature of the peat, particularly between the stumps, may be interpreted as indicating compaction by a former barrier beach that was driven landward over its own lagoonal deposits. It is possible that beach sediments have covered the wood until quite recently, because the exposed stump field has been eroded rapidly since Lyon and Goldthwait studied it in 1931. The thickness of peat under each sampled stump is indicated in figure 2. Because these thicknesses of peat vary so little, the stump-base altitudes of the four trees are believed to be valid indicators of relative altitudinal relationships, assuming that compaction has indeed occurred.

The location of the sampled stumps—well to one side of the gap in the bedrock ledges (fig. 2)—reduces the likelihood that the original trees were killed by infrequent storm waters, as opposed to actual submergence. And there was undoubtedly sufficient fresh groundwater in the peat and till substrate to necessitate repeated flooding of the pines by high tides before their death and preservation by salt water. (It should be noted that, although our results are plotted relative to mean tide levels in figs. 5 and 6, we assume that the trees were killed and preserved at the level of high tides.)

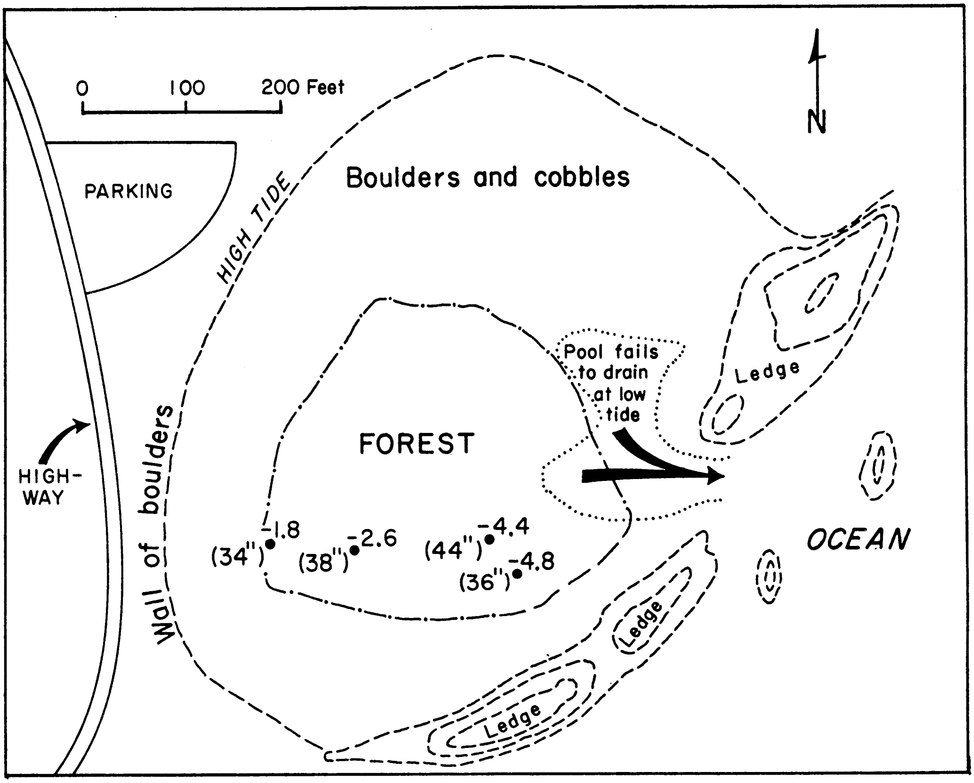

FIG. 2.—Plan view showing positions and altitudes (in feet) below mean tide level of stumps sampled at Odiorne Point, New Hampshire. Thickness of peat beneath each stump, in inches, shown in parentheses.

Fort Lawrence, Nova Scotia.—This well-known drowned forest (Goldthwait, 1924; Johnson, 1925, p. 578), near lat. 45° 50′ N., long. 64° 17′ W. (fig. 1), was first described over a hundred years ago by Dawson (1856, p. 440). Since Dawson's time it has lost most of its exposed soil and the stumps rooted in it. Comparing Dawson's data with our measurements of the distances of stumps from shore and from low water, it seems probable that the stumps seen today have been exposed by tidal scour only in recent decades. Much of the stump field seen by Dawson has been eroded away.

Stumps sampled at this site were rooted in a 6-inch layer of clay loam that is underlain by an 8–9-inch subsoil consisting of red sandy loam. Till underlies this subsoil. The distribution and altitudes of the sampled stumps are shown in figure 3.

Grand Pré, Nova Scotia.—Remains of a forest that extends over at least 100 acres of mud flats are exposed at low tide on the north and shoreward sides of Boot Island (lat. 45° 08′ N., long. 64° 17′ W.; fig. 1). The forest has been described by Goldthwait (1924), who concluded that it extended under the Grand Pré marshland. An unpublished chart that shows the stumps and logs examined in 1931 is now useless, due to the changes produced by tidal scour and deposition. The samples taken for radiocarbon dating came from a small group of stumps near the mainland, selected for maximum range of altitude. Distribution of the stumps and altitudes below mean tide level are shown in figure 4; the stumps occurred on the Grand Pré side of the tidal "Guzzle," just offshore. Stump roots were imbedded in 15–18 inches of a gray clay soil that rests upon 12–24 inches of a pale-red clay subsoil that lies on stony till.

C^{14} AND ALTITUDINAL DETERMINATIONS

Wood samples.—Wood samples used for C^{14} determinations were cut from the outer several rings of four white pine (*Pinus strobus*) stumps or large roots at each forest site (figs. 1–4). In taking each sample, a thin layer of the exposed wood was removed to provide assurance that all wood submitted for dating would be free from contamination by marine organisms or recent deposits of any kind. The utmost precautions were taken in both field and laboratory to assure that the samples were not contaminated with recent C^{14}.

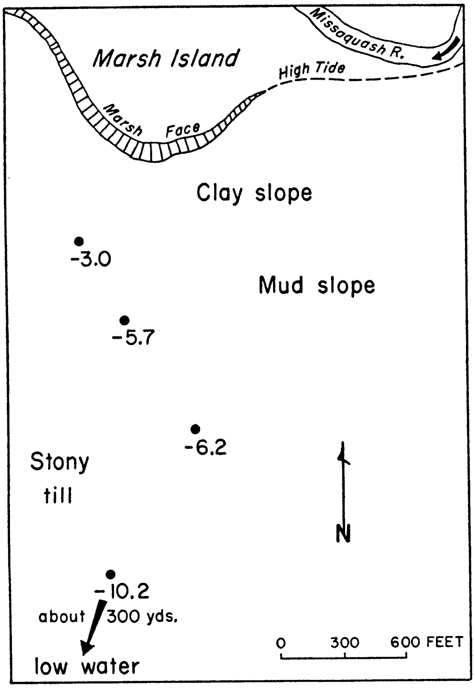

FIG. 3.—Plan view showing positions and altitudes (in feet) below mean tide level of stumps sampled at Fort Lawrence, Nova Scotia.

Laboratory work.—C^{14} age determinations for the twelve samples were made by Isotopes, Inc., Westwood, New Jersey. The laboratory corrected for the Suess effect, or the addition to the atmosphere—since about 1900—of ancient CO_2 by the industrial use of fossil fuels. The laboratory correction for the Suess effect involved the selection of a modern comparison standard; the standard used for our first six samples (Lyon and Harrison, 1960, fig. 1) was 1900 A.D. wood, while an oxalic acid standard was used for the intermediate samples (fig. 5, this study). Thus the correction for the Suess effect was not a correction of the radiocarbon age.

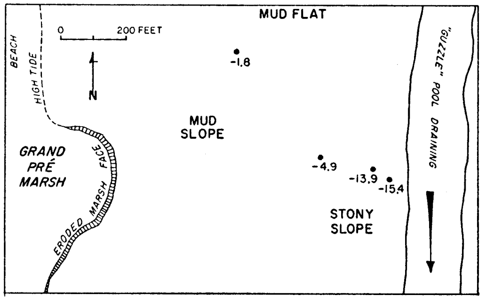

FIG. 4.—Plan view showing positions and altitudes (in feet) below mean tide level of stumps sampled at Grand Pré, Nova Scotia.

Stump altitudes.—Altitudes of the bases of the stumps were determined by standard leveling techniques, using an engineer's level. Stump altitudes were related to the mean tide level at each site, as determined from tide-table data and the observed high-tide mark for the date of the field work. Mean tide level (also known as half tide level) is a plane midway between mean low water and mean high water at a given place. It is not to be confused with mean sea level. We were unable to relate our measurements to mean sea level because of the absence of bench marks or tide-gauge stations in the vicinities of the three drowned forests. The computed mean tide levels were available,

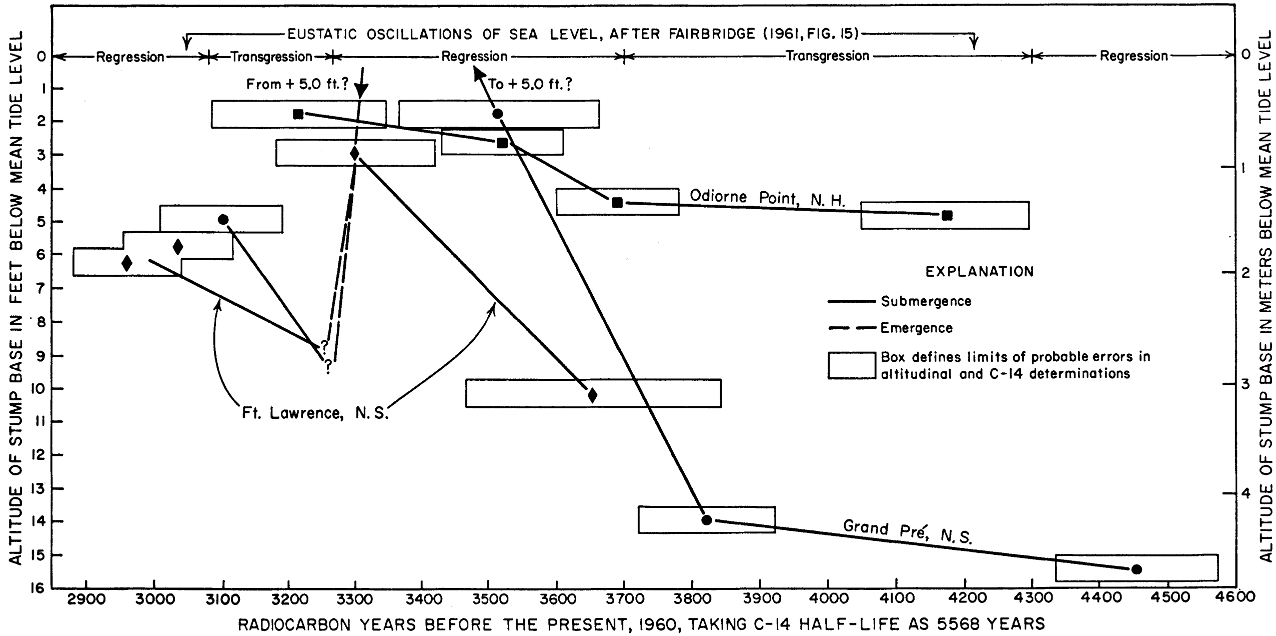

FIG. 5.—Altitude versus age for four stumps at each of three drowned-forest sites, and inferred history of submergence and emergence at each site. (Radiocarbon ages have been corrected for the Suess effect.)

however, for points within about 2 miles of each site, from the U.S. Department of Commerce Tide Tables (1959). Because the altitudinal determinations were referable, ultimately, to high-tide marks as datum planes, all level lines were run on calm days. In this way, discrepancies between the computed high-tide values of the tide tables and the observed high-tide marks in the field were minimal.

The precise altitudes, relative to mean tide levels, of the dated stumps are not critical to the determination of rates of submergence or emergence of the forest sites; only the relative differences in altitudes between stumps at each site are critical. These relative altitude values are believed accurate to ± 0.4 foot, an estimate that takes into account both the very small instrumental errors and the relatively large errors of determination of the "bases" of the stumps.

INTERPRETATIONS OF DATA

SUBMERGENCES AND EMERGENCES OF SITES

Odiorne Point.—The C^{14} and altitudinal determinations for each of the stumps at Odiorne Point are sufficiently distinct to permit the construction of a curve of submergence for this site (fig. 5). In spite of the small range of altitudes and of the short distances between the stumps, only the one that dates at 3,690 $\pm$ 90 B.P. overlaps the limits in the probable errors for either age or altitude of adjacent stumps.

The simple picture of progressive submergence (fig. 5) of the drowned forest at Odiorne Point was a pleasing one to find, because we had conditioned ourselves to believe that a continuous progression of tree deaths by rising salt water was the logical and expectable picture. We were surprised, therefore, when the dates for stumps at intermediate altitudes at the other two sites revealed a discontinuous pattern of tree death relative to stump altitude.

Fort Lawrence.—We fully expected that the additional C^{14} dates (fig. 5) for the Fort Lawrence stumps, at the intermediate altitudes of -5.7 and -6.2 feet, would fall *between* 3,655 and 3,300 years B.P. (the respective dates of the lowest and highest dated stumps at this site). If dates within the 3,655–3,300 B.P. range had been obtained, our concept of successively higher stumps of the drowned forest being killed by a single, progressive transgression of the sea would have been verified.

The actual dates obtained, both more recent than 3,300 B.P., raised several questions. The first two questions are considered the most important:

1. What happened to the stumps of the older trees that had once been growing at the intermediate altitudes?

2. How could the stump at the highest altitude (-3.0 feet) be preserved for perhaps five centuries during regression of the sea, while another forest grew at lower altitudes (to -9.0 feet?) and until the sea transgressed again?

We suggested that tidal silts 8–30 feet thick (Johnson, 1925, p. 575–577), which had been deposited on the salt marsh over the sloping forest floor during the initial transgression (fig. 5), were eroded again at the intermediate altitudes, during a regression of the sea to possibly -9.0 feet (fig. 5). Stripping of the silts down to the highly resistant till surface would have proceeded rapidly. The stumps and the soil about their roots at the intermediate altitudes would have been subjected to the wave action of neap tides and the plucking and abrasive action of shore ice for many years. Most or all of the stumps at the intermediate altitudes of around -6.0 feet could have been removed in this way, as have others from that same zone since the second forest was photographed by Goldthwait (1924, p. 156) in 1914.

We further suggest that the high stump and others above it were preserved up to five centuries beneath the firm cover of tidal silts and clays during regression of the sea. Such silts and clays are characteristic of the tidal marshes in the Fort Lawrence area (Ganong, 1903, p. 167). We admit that our argument suggests fortuitous preservation in this sequence of events, but we point out that an essentially identical sequence of events may be logically inferred from the Grand Pré data below.

After the stumps at the intermediate altitudes had been removed or reduced to fragments, we propose regression of the maximum high-tide level to below −7.0 feet, to allow for reforestation at the intermediate altitudes, but no farther than −9.0 feet, to allow for preservation of the low stumps. During the time the sea had regressed to below −7.0 feet, a new forest was established. It became established upon tidal silts

TABLE 1

	Feet	Inches	Comment
Marsh mud, reddish..........	2	11	
Marsh mud, bluish-grey.......		9	
Marsh mud, greyish...........	1	8	Full of roots
Marsh mud, bluish...........	2	10	With roots
Marsh mud, dark grey and bluish (a drowned-forest bed).......	1	8	Full of roots and stems
Gravel, sand, and clay..........	1	11	Partially stratified, with roots of shrubs and plants
Boulder clay....	40+		With striated boulders

that overlay the old forest surface at the higher altitudes but *upon the old till surface at the intermediate altitudes.*

Establishment of a younger forest upon the tidal deposits at the higher altitudes is supported by the geologic section described by Chalmers in 1895 (Johnson, 1925, p. 576), exposed at the Fort Lawrence end of the Chignecto ship railway and located above our stumps at intermediate altitudes. The section was described by Chalmers (1895, p. 127M) as shown in table 1. We interpret the two units of marsh mud that overlie the forest bed ("full of roots and stems") to be the materials upon which the second forest developed during regression of the sea. Chalmers (p. 127M) reported *woody* roots in these units that overlie the drowned forest bed.

This second, higher forest was itself killed by the next transgression of the sea (fig. 5). Some of the stumps that were rooted firmly in the till were preserved to the present. Those rooted only in the tidal silts were torn out relatively easily, with the exception of the root system, or were removed entirely as the silts were undermined and eroded away.

In this way we explain the apparent anomaly of the occurrence—across a single, sloping surface—of the remains of a forest belt of relatively younger trees bordered upslope and downslope by the remnants of relatively older trees.

3. Could not the intermediate stumps have been displaced from higher altitudes by some process? This question is answered with confidence in the negative. The stumps at −5.7 and −6.2 feet (figs. 3 and 5) are firmly rooted in a non-compacting type of soil (as described on p. 98). They are movable only after being torn away by tidal scour and shore ice. Stumps now available for sampling appear to have been overlain until recently by tidal silts and clays, which cover other stumps just shoreward of them. Because the soil in which they are rooted was developed from till as a parent material, and because none of the stumps is underlain by peat, there is no chance for differential compaction of stumps at this site. Solifluction or landslide are also ruled out because of the absence of a periglacial climate in the area since the trees grew and because of the relatively gentle slope of the forest floor.

4. Could contamination by younger C^{14} material have affected the ages of the trees? An appreciable error of this type is only a remote possibility, because of the stability of the cellulose and lignin molecules in wood of any age, the selection of wood samples free from contamination by younger carbon compounds, and the impossibility of simple infiltration of the 25-gm. samples by significant weights of soluble younger carbon since the death of the trees. In any case, it is doubtful that any such effect on the ap-

parent ages of the wood samples would have been selective for the trees that grew at the intermediate altitudes.

We conclude that the trees at the intermediate altitudes of −5.7 and −6.2 feet grew on a new soil at a time when the sea had regressed from a previous high at −3.0 feet. We assume that the postulated new forest was later killed by the rising salt water of a transgressing sea.

It appears that at this site there was a relatively rapid transgression, lasting from about 3,700 B.P. to 3,400 B.P. (fig. 5). Immediately after about 3,400 B.P. a fairly rapid regression occurred. A forest then became established in the area down to the altitude of the maximum high tide of this lowered sea level. Then another transgression ensued (fig. 5), and the younger trees at altitudes of −6.2 and −5.7 feet were killed progressively.

Whether or not the two youngest trees at Fort Lawrence were killed by a single, progressive rise of salt water is difficult to say, owing to the considerable overlap in the probable errors in the radiocarbon ages of the stumps and to the lesser overlap of the probable errors in the altitudes of the stumps (fig. 5). For this reason, the curve of submergence of this site was constructed to end at the approximate mean values for the radiocarbon ages and the stump-base altitudes.

Grand Pré.—The picture of submergence and emergence that arises out of the Grand Pré data is identical with that which was obtained for Fort Lawrence. The Grand Pré data are quite reliable; there is no overlap in the probable errors for the C^{14} or for the altitudinal determinations for the four stumps at this site.

Once again, the same questions arise, as arose with the Fort Lawrence data. Here again is a stump (figs. 4 and 5, −4.9 feet), intermediate in altitude between the highest and lowest stumps, whose age is less than that of the highest stump. As before (p. 101), we invoke a protective cover of tidal silts for preservation of the highest stump during a subsequent regression of the sea.

Eustatic versus tectonic sea-level changes.—Fairbridge (1961, fig. 15) has derived a curve for the eustatic oscillations of sea level for the period 10,000 B.P. to the present. His curve shows a total of five eustatic oscillations of the sea during the 1,600-year period covered by our study. The limits of Fairbridge's various transgressions and regressions of the sea are plotted on figure 5, for comparison with the submergence and emergence curves for our three sites. Our curves do not compare favorably with the transgressions and regressions drawn from Fairbridge's curve.

One consideration is that our C^{14} dates have been corrected for the Suess effect, whereas some of the dates that were used by Fairbridge (1961, p. 158) in constructing his curve were not. Should a sample be dated by techniques that do not provide for a correction in view of the Suess effect, the ***apparent*** C^{14} age would be from 0 to 250 years older than the actual age. This consideration raises the possibility that some of the boundaries between Fairbridge's transgressive and regressive events, shown on our graph, could be shifted varying distances—up to 250 radiocarbon years—to the left on our figure 5.

Should it be possible to shift leftward Fairbridge's boundaries (fig. 5) between transgressions and regressions of the sea—even in the most fortuitous manner—only a mediocre correspondence between his and our curves would be achieved. Before commenting further on the lack of correspondence between Fairbridge's and our curves, it would be well to consider the interrelationships of the three curves of figure 5.

CRUSTAL WARPING

Curve analysis.—The best place to begin consideration of the interrelationships of all three curves is in the region 3,650–3,500 B.P. (fig. 5). All three sites clearly were undergoing submergence during this period, and at different rates. The greatest rate of submergence (4.1 feet per century) was at Grand Pré, the next greatest was at Fort Lawrence (2.0 feet per century), and the least rate was at Odiorne Point (1.1 feet per century).

Disregarding Odiorne Point for the moment, these rate differences suggest progressive, downward crustal warping from Fort Lawrence southward to Grand Pré (fig. 1). This requires that Grand Pré be submerged by a greater amount than Fort Lawrence during a given period of time. Such a relationship is shown, of course, for the time interval 3,650–3,500 B.P. In figure 5 it is assumed that the submergence trend continues uninterruptedly and at the same rate at Grand Pré, as long as Fort Lawrence is undergoing submergence; that is, until about 3,300 B.P.

Continued submergence of Grand Pré between 3,500 and 3,300 B.P. would require that sea level rise to at least 5.0 feet (fig. 5) above its present level at Grand Pré. Evidence of such a recent rise of sea level should be present somewhere in the vicinity of Grand Pré. Goldthwait (1924, p. 152) mentions miscellaneous river terraces and irregular gravelly deltas on the shore of Minas Basin between Kentville and Windsor, and notes that a good cross section of a delta can be seen in a railway cut beside Halfway River, at Huntsport, some 7 miles from the drowned forest at Grand Pré. The altitude of the top of this delta surface is not given by Goldthwait, but he indicates (1924, p. 152) that "all these deposits lie well below the limits set by the . . . Truro Plain [about 60 feet above mean sea level]." The speculative nature of our correlation of a postulated 5-foot(?) rise above present sea level with the deposits mentioned by Goldthwait is obvious. Neither the ages nor the precise altitudes of the deposits mentioned by Goldthwait are known. Hughes (1957, p. 9), moreover, intimates that the Truro gravel plain mentioned by Goldthwait is glaciolacustrine in origin, in view of "the lack of marine deposits in the valley of Shubenacadie River." Because Shubenacadie Valley is only 40 miles east of the deposits mentioned by Goldthwait, the lack of marine deposits is damaging evidence to our correlation. Goldthwait (1924, p. 152), however, mentions brick clays containing starfish and shells near Middleton, about 40 miles *west* of Grand Pré. On the strength of this evidence it seems reasonable to continue with the present line of reasoning.

Because the sea level must have regressed at both sites shortly after 3,300 B.P., in order to have risen again to kill the trees at intermediate altitudes, there appears to have been a rapid emergence of both sites. The emergence curves of the two Nova Scotian sites (fig. 5) have been constructed according to these assumptions:

1. Emergence began at both sites about 3,300 B.P.
2. Owing to a reversal in the sense of the previous crustal warping, Grand Pré would exhibit the greatest rate of emergence, and the greatest amount of emergence as well.
3. Both Fort Lawrence and Grand Pré stopped emerging at the same time.

These assumptions permitted construction of the emergence curves of figure 5, and the relationship these emergence curves bear to the subsequent submergence curves (post-3,260 B.P., fig. 5) is a measure of their reliability. The final submergence curves, for the period 3,250–2,990 B.P. (fig. 5), are seen to be similar in slope to those found earlier for the period 3,650–3,500 B.P.; that is, the *data* of final submergence *permit* the construction of curves that indicate that the greatest rate and amount of submergence took place at Grand Pré. And because the data of final submergence of these two sites permit the construction of such curves, it is possible that the emergence curves are reliable.

Returning to the problem of eustatic oscillations of sea level, it seems clear that such are not indicated by the data of figure 5. The inferred regression of the sea at the Nova Scotian sites, for example, finds no counterpart in the continued transgression of the sea at Odiorne Point (fig. 5). Nor do our curves correspond well with the curve of eustatic oscillations of the sea offered by Fairbridge (1961, fig. 15), as was mentioned on page 103, or with the curves given by Schofield (1959, fig. 8).

The Nova Scotian curves of figure 5 are

best interpreted in terms of tectonically induced sea-level changes; that is, considering sea-level movements for a given time interval as a constant for the three sites—although apparently a "moving" constant—it becomes reasonable and possible to assess the relative crustal movements between the sites for that time interval. Prior to making such an assessment, however, it would be advantageous to consider an effect heretofore ignored in the presentation of the data and in the analysis of the curves. This is the tidal effect.

Curve adjustment.—A somewhat different interpretation of the Nova Scotian data is possible (fig. 6) if slight adjustments are made in the slopes of the curves of figure 5, based upon differences in the height of the tide at the two sites. As indicated by Goldthwait (1924, fig. 10), the present-day tidal range at Grand Pré is 4 feet greater than at Fort Lawrence, owing to shoreline irregularities that cause a differential funneling of the tidal surge at the two sites. That is, there is a relative difference in a given high tide at the two sites of 2 feet.[4] Assuming that an identical tidal relationship held 3,000–4,000 years B.P., it follows that during coastal submergence a tree at Grand Pré and one positioned 2 feet lower at Fort Lawrence could be killed simultaneously. The submergence curves of figure 5 have been adjusted in figure 6 to satisfy this requirement; they have been spaced a distance of two vertical feet from each other on the graph. Adjustments that have been made in the slopes are based on possible datum points that lie within the limits of the probable errors (figs. 5 and 6, boxes). The slopes of the submergence and emergence curves (fig. 6), having been drawn parallel, indicate identical rates of sea level and (or) crustal movements during this period. These adjustments (fig. 6) eliminate two difficulties; namely, the inadequately evidenced rise of sea level to +5 or more feet at Grand Pré (fig. 5) and the unrealistically steep emergence curves at the two sites (fig. 5).

As seen in figure 6, the flex points in the two Nova Scotian curves, at 3,375 B.P., fall in a region not covered by the Odiorne Point data. If, in fact, the curve for Odiorne Point were similar to the curves postulated in figure 6 for the other two sites, it would be possible to make a good case for differential warping—of the same sense but different magnitude—for the three sites.

A portion of the curve for the eustatic rise of sea level along the relatively stable Texas coast, derived by Shepard (1960, fig. 3), is plotted on figure 6. The slope of Shepard's curve compares very favorably with the over-all slope of the curve for Odiorne Point and with the segment of the Grand Pré curve for the period 4,500–3,800 B.P. (fig. 6). Evidently, the submergence history of Odiorne Point shown in figure 6 is related, almost entirely, to a gradual, eustatic rise of sea level. The slightly accelerated submergence of Odiorne Point between about 3,700 and 3,500 B.P. (fig. 6) is interpreted as being of tectonic origin and corresponds to the accelerated submergence of the Nova Scotian sites, also believed to be tectonically induced (see below).

Finally, it is probable that the divergence of the submergence curves for the Nova Scotian sites, between 3,500 and 3,650 B.P. (fig. 5) is a reflection, however slight, of a real condition. It is also probable that the tidal effect just mentioned was also operative in those times. If, then, both sets of curves (figs. 5 and 6) are to be taken as approximations of the truth, it seems advisable to think in terms of differential crustal warping both between west-central Nova Scotia and coastal New Hampshire and between the two Nova Scotian sites as well.

SYNTHESIS OF INTERPRETATIONS

The following interpretations of the drowned-forest data seem warranted, *assuming absolute accuracy for the C^{14} ages of the twelve stumps.*

[4] A more detailed analysis, based upon computed mean tide ranges, spring tide ranges, and mean tide levels for the two sites (U.S. Department of Commerce, 1959, p. 193, nos. 571 and 583), indicates that the minimum difference in a given high tide would be about 1.9 feet, and the maximum 2.2 feet.

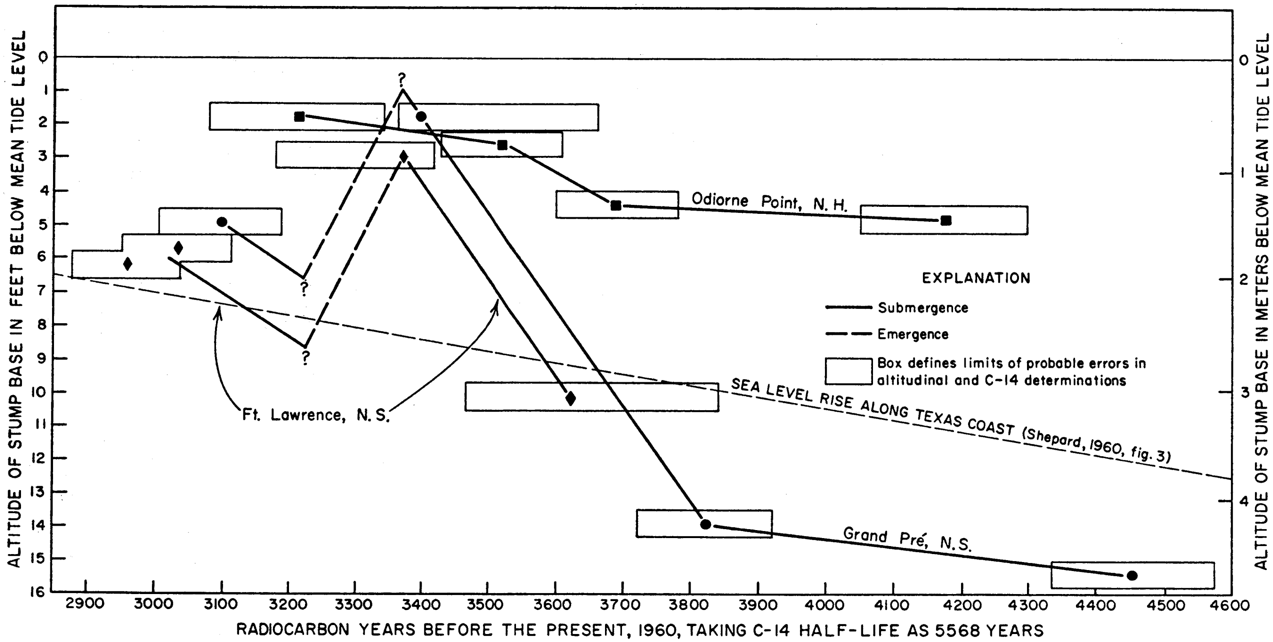

FIG. 6.—Altitude versus age for four stumps at each of three drowned-forest sites. Curves for Nova Scotian sites have been adjusted relative to those of fig. 5 for tidal effect (see text, p. 104).

1. A continuous, probably eustatic, rise in sea level of about 0.31 foot per century was in progress along the New England–Acadian shore between about 4,500 and 3,200 years ago. This rate value is based on the slope of a straight line joining the lowest and highest stump data reported in figures 5 and 6 for Odiorne Point. Such a line is nearly parallel to Shepard's curve for eustatic sea-level rise (fig. 6) and to the Grand Pré curve between 4,450 and 3,800 B.P. Crustal stability of all three sites prior to 3,800 B.P. is indicated.

2. Between about 3,800 and 3,400 years ago crustal downwarping occurred in west-central Nova Scotia, at the approximate rate of 2.6 feet per century. This rate value is derived from the slopes of the submergence curves in figure 6, minus the value of 0.31 foot per century for the eustatic rise. A possible hinge for this warping trend would have lain to the north of Fort Lawrence (fig. 1), because Grand Pré, 50 miles south of Fort Lawrence, may have been submerged at a slightly greater rate than Fort Lawrence (p. 104). Odiorne Point lay on the fringe of the downwarped area, as indicated by its slightly accelerated rate of submergence during this period (fig. 6).

3. Upwarping of north-central Nova Scotia took place in the following century and a half (3,400–3,250 B.P.) at the approximate rate of 4 feet per century (fig. 6). The crust beneath the southern New England shore was stable during this time, while Odiorne Point continued to undergo eustatic transgression by the sea of about 0.32 foot per century.

4. Renewed crustal downwarping commenced in west-central Nova Scotia after about 3,250 B.P. and continued until at least 3,000 B.P. The rate of downwarping may have approximated 0.88 foot per century (fig. 6).

The greatest rates of upwarping (4 feet per century) and downwarping (2.6 feet per century) given above may seem excessive. Jenness (1960, p. 177), however, presents evidence that the coast of Newfoundland around Bonavista Bay is at present being upwarped at the (maximum) rate of 3 feet per century. The Newfoundland coast 100 miles to the southeast, at St. Johns, on the other hand, is undergoing downwarping at the approximate rate of 1 foot per century (Jenness, 1960, n. 6). The values for these modern rates of crustal warping in Newfoundland are comparable to the values inferred in this study for west-central Nova Scotia 3,000–4,500 years ago.

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SOLUTION CAVES IN GYPSUM, NORTH CENTRAL TEXAS[1]

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ABSTRACT

The thirteen gypsum solution caves in north central Texas here described occur within the Permian Blaine Formation. Four are of vadose origin, four were developed by solution in the phreatic zone, and five were not studied in sufficient detail to determine their origin. Diagnostic features and histories of two caves, one representative of those having a vadose origin and one representative of a phreatic origin, are discussed.

INTRODUCTION

This investigation was made in conjunction with a series of zoölogical studies of *Myotis velifer*, a species of bat that inhabits most of the gypsum caves in north central Texas and southwestern Oklahoma. Through co-operation with the Department of Biology of Texas Technological College, the writers accompanied field parties in the exploration and investigation of many of the gypsum caves and have been permitted to re-enter all of the caves for further study.

Very little has been published concerning the location, morphology, and origin of gypsum caves. The gypsum caves in north central Texas provide a unique area for the study of solution features found in gypsum compared with those of limestone and dolomite caverns.

LOCATION

Location of thirteen gypsum caves in the north central Texas region is given in figure 1. Locality data for the caves serve as a reference for future investigators and point out the relative abundance of solutional features previously reported as rare. Furthermore, the caves typify two schools of thought—namely one-cycle (vadose) and two-cycle (phreatic to vadose) history of development—and hence constitute a valuable correlation between solutional features observed in gypsum and carbonate caverns. The low incidence of banded-bat recovery in this area (Patterson, 1961, p. 33) and reports by local residents of additional caves suggest the presence in this region of many other gypsum caves now concealed by debris fill and collapse of numerous sinkholes.

Area I is located near the Hardeman-Cottle County line approximately 14 miles southwest of Quanah, Texas. Three of the largest caves investigated occur in this area: Walkup Cave, on the R. W. Walkup Ranch; Panther Cave, 2 miles west of Walkup Cave on the Floyd Richardson Ranch; and Collapse Cave, 1 mile west of Panther Cave on the Richardson Ranch.

Four caves on the Sam Vest Ranch, 25

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