Reports

Florida Submergence Curve Revised: Its Relation to Coastal Sedimentation Rates

Abstract. *New data substantiate as well as modify the south Florida submergence curve, which indicates that eustatic sea level has risen continuously, although at a generally decreasing rate, during the last 6500 to 7000 sidereal years (5500 standard radiocarbon years) to reach its present position. Accumulation rates of coastal deposits are similar to the rate of sea-level rise, thus supporting the generalization that submergence rates largely determine as well as limit rates of coastal sedimentation in lagoonal and estuarine areas.*

Scholl and Stuiver (*1*) have shown that during late Holocene time the coastal mangrove swamps and adjoining Everglades of southwestern Florida (Fig. 1) underwent continuous marine submergence. During the last 4500 radiocarbon years, the rate of submergence steadily decreased and sea level did not rise above its present position or hold a fixed level that lasted longer than several hundred years. Submergence was attributed to a eustatic rise in sea level (*1*). The Florida submergence curve has since proved useful in assessment of the eustatic and tectonic implications of submergence data collected along other coasts (*2, 3*).

New data now confirm the younger and modify the older portions of the Florida submergence curve. In addition, investigations to improve the accuracy of radiocarbon dating have established a more precise half-life for radiocarbon years and have disclosed a generally linear divergence between radiocarbon years and true earth (sidereal) years beginning about 2200 years ago. An approximate conversion of radiocarbon years (determined in the standard way) to sidereal years can be made for the period from 2200 to 6000 years ago (*4*). Unless noted, all radiocarbon ages used in this paper have been converted to approximate calendar years. The application of these corrections significantly modifies the original Florida submergence curve.

As originally constructed, the Florida submergence curve (*1*) was based on specially selected sediment samples. The ages of the samples were plotted on the submergence diagram to indicate the elevation (relative to modern sea level) of sea level at a corresponding time. This procedure necessarily involved making decisions regarding actual position of sea level when the dated sediment was deposited—decisions which, unfortunately, also qualified the accuracy of the resulting submergence curve (*5*).

In order to assess the accuracy, we used different criteria to construct a revised submergence curve (Fig. 2). We plotted the ages of 72 dated sediment samples against their elevation *in situ* relative to present sea level, making no correction for the distance above or below sea level at which the dated sediment was actually deposited. The data points, however, are identified with respect to whether the sediment formed at or above mean sea level (freshwater and brackish water types) or at or below mean sea level (marine types), as indicated by the presence or close stratigraphic association of a freshwater or marine fauna or flora. The revised submergence curve (Fig. 2) has been fitted to the plotted data in accordance with the following assumptions.

1) Because sea level must have occupied a position equal to or lower than a dated freshwater sediment, and equal to or higher than a coeval marine sediment, the submergence curve has been drawn to separate them.

2) The large number of dated freshwater sediments from below sea level (*6*) from southern Florida makes it likely that the lowest (in elevation) sediment found for any particular age will have originally been deposited close to the minimum elevation of freshwater sedimentation, which, in southern Florida, is essentially mean sea level. Accordingly, the submergence curve has been drawn to fall generally below the lowest freshwater data points. It should be noted that the curve in Fig. 2 does not follow in detail the base of the freshwater data. This is because errors inherent in determining field elevations and in calculating radiocarbon ages do not justify precise adherence to the data points (*7*).

3) Deposits of peat occur directly over bedrock but beneath 2 to 4 m of marine sediment forming small islands (Crane Key and Man-O-War Key) in Florida Bay (Fig. 1), and over the

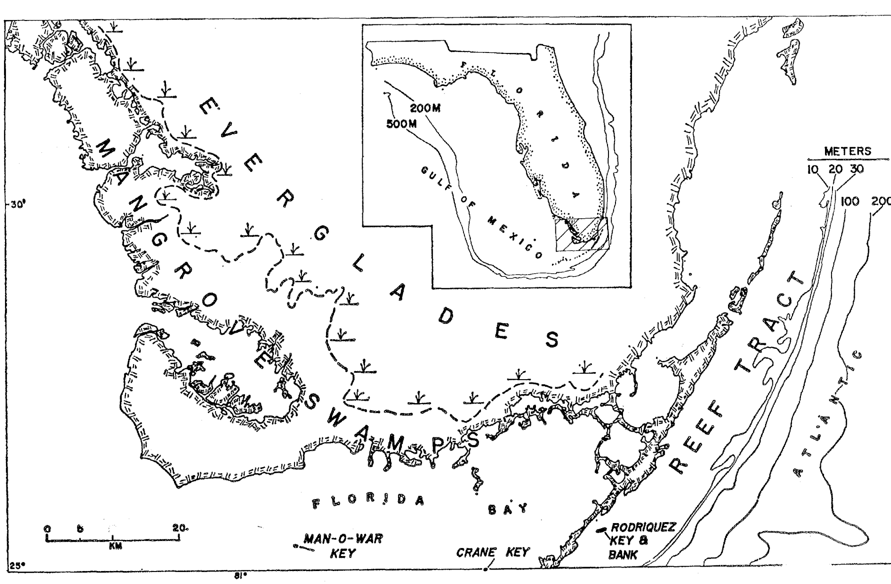

Fig. 1. Location of coastal mangrove (paralic) swamps and Everglades (freshwater) of southwestern Florida. Most of the radiocarbon-dated sediment samples reported in this paper were collected in this area or in the vicinity of Man-O-War, Crane, and Rodriquez keys.

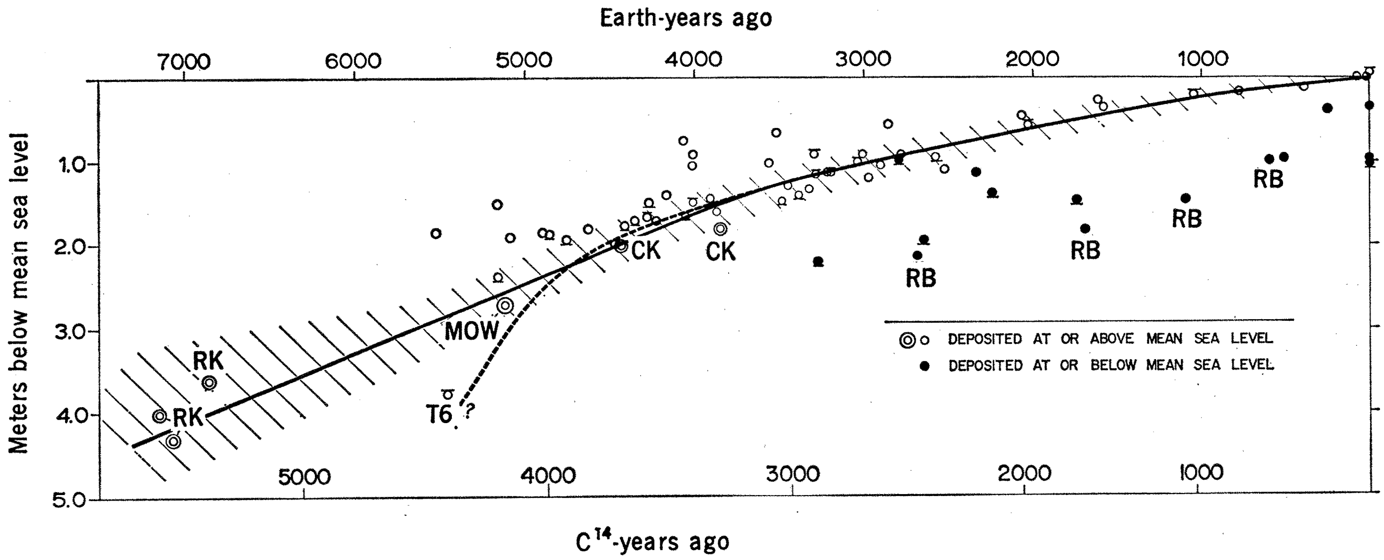

Fig. 2. Unbroken curve is the revised submergence curve for south Florida; dashed curve is a previously published version (*1*). Short bar above or below data points identifies original data used to construct the dashed curve. Data accuracy has been discussed in detail elsewhere (*1, 11*) and is briefly described in reference (*7*). Width of hatched zone indicates the vertical uncertainty in the position of any portion of the revised submergence curve. The accuracy of the data justifies only the construction of a smooth or generalized submergence curve, which should not, therefore, be construed to mean the absence of minor "oscillations" in the late Holocene eustatic rise in sea level. Doubly circled points are dated peat deposits underlying Crane Key (*CK*), Man-O-War Key (*MOW*), and Rodriquez Key (*RK*); dated marine deposits from Crane Key and Rodriquez Bank (*RB*) are also identified (*8, 14*). Upper time scale represents approximate true earth (sidereal) years (*4*), lower scale is in standard radiocarbon years.

nearshore portion (Rodriquez Key) of the Florida Reef Tract (*8*) (Fig. 2). Because of their close stratigraphic association with several meters of overlying marine deposits, the peats must have formed near, though probably a little above, sea level (*9*); they are therefore good guides (*7*) to the general positions of former sea level stands. The submergence curve on Fig. 2 has accordingly been drawn close to them.

The unbroken curve in Fig. 2 should represent the approximate average eustatic position of sea level during the last 6500 to 7000 years (approximately 5500 radiocarbon years). For the last 4800 years the revised curve is coincident with the published submergence curve, which is the dashed curve on Fig. 2. The two curves, however, are not in close agreement before this time. Sample T6 (Fig. 2), a fresh- to brackish-water peat of questioned significance (*5*), was used to position the lower segment of the original curve (*1*).

However, the position and slope of the submergence curve indicated by the distribution of newly acquired freshwater data and the data from Man-O-War, Crane, and Rodriquez keys suggest to us that sample T6 is in error (we recognize that T6 may yet prove to be a valid control point; confirmation would imply the submergence curve flattens between 5500 and 7000 years ago). The expanded time scale (resulting from age correcting) and the rejection of sample T6 allow us to remove the sharp downward inflection from the revised submergence curve. However, a definite, slope increase (factor of 2.4) still remains. The indicated change in rate of sea-level rise is from about 3.5 cm/100 years after 3500 years ago to about 8.3 cm/100 years before this time.

The decrease in rate of rise was earlier (*1*) correlated tentatively with probable global cooling associated with the beginning of the neoglacial period. Although this correlation may prove correct, the inflection is in part dependent upon data collected at Rodriquez Bank (Fig. 1). Because this site is located near relatively deep water east of the Florida Reef Tract, it may have undergone isostatic subsidence in response to the water-loading effect described by Bloom (*3*). The amount of isostatic subsidence is difficult to assess because of the proximity of Rodriquez Bank to the continental slope, a region of crustal transition and uncertain load response. However, general considerations suggest that during the last 7000 years isostatic subsidence on the order of 1 to 2 m, a correction for which would reduce, although not eliminate, the inflection, could have taken place. Accordingly, the cause of the downward inflection in the submergence curve remains in doubt.

The submergence curve for the last 4000 to 5000 years, which includes the inflection point, is based mostly on data from the coastal swamps bordering the inner edge of the wide shelf off southwestern Florida (Fig. 1). The shallowly submerged coastal region could not have been significantly downwarped by water loading (*3*). This portion of the submergence curve, therefore, is regarded as a good measure of the position of sea level during the last five millenniums.

Although a number of factors control rates of coastal sedimentation, rate of coastal submergence should be the chief factor in lagoonal or estuarine areas where the rate is not extremely low and where the sediment supply remains approximately the same during submergence (*10*). These conditions would seem to be met in southwestern Florida, which has been submerged at an average rate close to 3.5 cm/100 years during the last 4000 years, and receives most of its sediment from biological sources (chiefly mollusks, algae, and rooted vegetation). Therefore, the rate of coastal sedimentation during this time should also have averaged close to 3.5 cm/100 years. Actually, the average rate of coastal marine deposits (based on 11 determinations) during the last 4000 years has been 3.0 cm/100 years (Fig. 3). In contrast, calcitic mud formation in nearby coastal freshwater swamps has averaged

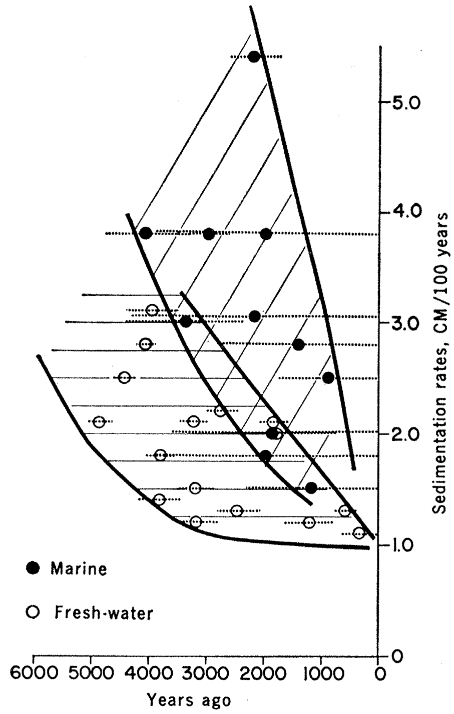

Fig. 3. Sedimentation rates in coastal swamps and nearshore areas of southwestern Florida during the last 5000 sidereal years. Horizontal line through data point indicates the range in sediment ages over which the average value (plotted point) was computed.

only 1.6 cm/100 years. This lower value signifies that submergence was attended by coastal regression and the marine inundation of former freshwater swamps (the Everglades)—a fact emphasized and documented in previous studies (*11*).

Although there is considerable scatter of the data on Fig. 3, they appear to indicate a slight increase in sedimentation rate with age. For example, the rate of calcitic mud formation in coastal freshwater swamps averaged 1.2 cm/100 years from 0 to 1000 years ago, 1.7 cm from 1000 to 2000 years ago, 1.7 cm from 2000 to 3000 years ago, 1.9 cm/100 years from 3000 to 4000 years ago, and 2.8 cm/100 years from 4000 to 5000 years ago. This trend may reflect the slowly decreasing rate of sea-level rise indicated by the submergence curve over the last 5000 years.

Our results indicate that sea level has risen continuously, although at a generally decreasing rate, during the last 5000 sidereal years, and possibly since 7000 years ago, to its present position. Unlike other workers (*12*), we believe that sea level never rose above this level or remained stationary during its slow rise to this position for more than a few hundred years. However, the pronounced change (slowing) in rate of rise beginning about 3500 years ago shown on a previously published submergence curve (*1*) is much reduced on the revised curve presented here (Fig. 2). The similarity of rates of coastal sedimentation with rates, and possibly with changes in rates, of coastal submergence stresses the fundamental geologic relation between these variables.

Inasmuch as geologic and geomorphic evidence (*13, 14*) show that no substantial coastal subsidence has taken place in southwestern Florida during the Holocene, we believe that the revised Florida submergence curve closely (no greater than ± 0.3 m) traces the average eustatic position of sea level during the last 5000 sidereal years. From 5000 to 7000 years ago the submergence curve is based on less certain data, and the curve as drawn is regarded as only a close approximation (± 1.0 m) of former eustatic levels.

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References and Notes

1. D. W. Scholl and M. Stuiver, *Bull. Geol. Soc. Amer.* **78**, 437 (1967).
2. A. C. Redfield, *Science* **157**, 687 (1967).
3. A. L. Bloom, *Bull. Geol. Soc. Amer.* **78**, 1477 (1967).
4. The sidereal correction equation, $T = (1.4) \cdot (R) - 900$, was modified from another equation [M. Stuiver and H. E. Suess, *Radiocarbon* **8**, 534 (1966)], where T is true age and R is the standard radiocarbon age. Also applied was an initial correction factor of 1.029 from the ratio (5930:5568) of the newly established ^{14}C half-life to the older value used for standard age computations. Recent tree-ring measurements indicate that the actual sidereal correction may be somewhat smaller than as computed here; however, a better formula is not yet available.
5. W. G. Smith and J. M. Coleman, *Bull. Geol. Soc. Amer.* **78**, 1191 (1967); D. W. Scholl and M. Stuiver, *ibid.*, p. 1195.
6. Some of the dated freshwater sediment plotted on Fig. 2 is peat (22 samples), but most is calcitic mud sampled from cores collected beneath brackish and marine waterways and bays in the coastal mangrove swamps and in freshwater ponds in the Everglades immediately landward of these swamps. The calcitic mud is precipitated in shallow freshwater ponds (0.5 to 1.0 m deep) by the action of floating or attached algal masses; the floor of these ponds is at or above sea level.
7. Field positioning and dating errors of sediment samples from south Florida are discussed in D. W. Scholl and M. Stuiver, *Bull Geol. Soc. Amer.* **78**, 437 (1967) and D. W. Scholl, *Marine Geol.* **1**, 344 (1964). The typical uncertainty about age that results from all sources is estimated to be from 100 to 300 years; the typical error involved in determining the elevation of dated samples is about 0.3 m. However, somewhat larger errors must be attributed to samples of peat collected above bedrock but beneath several meters of deposits forming offshore islands (keys) and banks. This error reflects uncertainties in making the proper correction for peat compaction, which is probably as much as 0.5 m for thick (1.0 or more) peat layers.
8. Samples of peat from Crane Key and overlying marine carbonate material, specifically the finger coral *Porites divaricata* and the red algal *Goniolithon* sp., from Rodriquez Bank were dated by the Shell Oil Company (*13*). Some of these dated samples appeared in K. W. Stockman, R. N. Ginsburg, E. A. Shinn, *J. Sediment. Petrology* **37**, 633 (1967).
9. Calculations based on average accumulation rates of marine carbonate in Florida Bay indicate that the age of the base of the marine section is essentially equivalent to that of the underlying peat. Hence deposition of marine carbonate began shortly after cessation of peat accumulation. The determined age of the peat is therefore the approximate age of a former stand of sea level at the field elevation of the peat-carbonate sediment contact. Peat below Rodriquez Key is thought to have been derived from the red mangrove (*Rhizophora mangle*) which forms close to mean sea level (R. Turmel, personal communication). Peat beneath Man-O-War Key is closely associated with freshwater sediments and apparently formed at or just above sea level. See (*7*) for comments on probable compaction of these basal peats.
10. G. A. Rusnak, in *Estuaries*, G. H. Lauff, Ed. (AAAS, Washington, D.C., 1967), p. 180; K. W. Stockman, R. N. Ginsburg, E. A. Shinn, *J. Sediment. Petrology* **37**, 633 (1967).
11. D. W. Scholl, *Marine Geol.* **1**, 344 (1964); *ibid.* **2**, 343 (1965); W. Spackman, C. P. Dolsen, W. Riegel, *Palaeontographica B* **117**, 135 (1966).
12. R. W. Fairbridge, in *Physics and Chemistry of the Earth*, L. H. Ahrens, F. Press, K. Rankama, S. K. Runcorn, Eds. (Pergamon Press, New York, 1961), vol. 4, pp. 99–185; J. M. Coleman and W. G. Smith, *Bull. Geol. Soc. Amer.* **75**, 833 (1964).
13. J. H. Davis, Jr., *Bull. Fla. Geol. Surv.* **25**, 311 (1943); G. G. Parker and C. W. Cooke, *ibid.* **27**, 119 (1944); S. F. MacNeil, *U.S. Geol. Surv. Prof. Pap. 221-F* (1950), p. 95; D. Alt and H. K. Brooks, *J. Geol.* **73**, 406 (1965); J. H. Hoyt, in *Annu. Mtg. Geol. Soc. Amer. Abstr.* New Orleans, La., 1967, p. 104.
14. Stratigraphic data compiled by Applin and Applin [*U.S. Geol. Surv. Prof. Pap.* **447**, 84 (1965)] indicate that since Early Cretaceous time the average rate of tectonic subsidence in southern Florida has been about 0.3 cm/100 years. Their data also show a systemic decrease in the rate of subsidence with time. For example, average values are 0.9 cm/100 years for the Late Cretaceous, 0.3 cm/100 years for the early Tertiary, and 0.09 cm/100 years since Eocene time. For our study, the implication of this trend is that during the late Holocene the rate of subsidence in southern Florida may well have been less than 0.1 cm/100 years—a value 35 times lower than the average submergence rate we measured for the last 4000–5000 years. In southern Florida the large difference between subsidence and submergence rates is good evidence that the submergence measured here is largely due to changes in sea level.
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