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Apparently the terranes are not only behaving independently from one another, but also relative sea level varies within each block. Such variations suggest that the terranes are composites of smaller structural units not yet defined by geologic mapping. Although our understanding of the dynamics of plate motions and strength of tectonic blocks is limited, tide-gauge results suggest sub-plate scale motions may prevail over continental margins. These observations clearly point to future research to help clarify some of these patterns.

Uncertainties in the tectonic relationships between terranes may be resolved by expanding the tide-gauge network or alternatively by applying new geodetic measurement techniques. Although repeated level surveys have the potential for providing some of these data, systematic errors have decreased the accuracy of this method (Braatz and Aubrey in press). Alternatives to tide gauges center on relatively new geodetic techniques such as *V*ery *L*ong *B*aseline *I*nterferometry (VLBI) and differential *G*lobal *P*ositioning *S*ystem (GPS; Carter et al. 1986). These new techniques offer substantial promise towards resolving issues raised here over time scales of a decade or more.

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rocks of unknown age intruded by Cretaceous granite; 1.3 mm/yr). Excluding station 25 (−1.8 mm/yr; Long Beach, where fluid withdrawal dominates land subsidence), the Cortes-Baja terrane complex composed of Precambrian basement and metamorphosed Paleozoic continental margin strata in southern California and scattered Upper Paleozoic limestone outcrops and Lower Mesozoic clastics capped by Upper Mesozoic volcanics and latest Cretaceous sandstone in Baja, California displays gradual subsidence to the south. This southerly dip of the land also is present in the offshore region with the sills of the continental borderland basins becoming deeper southward (Emery 1960, p. 51). The southerly drop is present more strongly in the original data (Emery and Aubrey 1987), where large scale (plate-wide) trends were not removed from the data.

CONCLUDING REMARKS

The divergent (eastern margin) and convergent (western margin) edges of the North American plate consist of a mosaic of terranes that have been welded to the North American craton. Those on the eastern side were transported to their position during the opening and closing of the Paleozoic Altantic. As Africa and North America separated in the Mesozoic segments of Africa were left behind. During the separation and opening of the present Atlantic these terranes underwent considerable extension and subsidence, a sinking that was accentuated by concurrent and subsequent sedimentation. This margin thus displays a long history of subsidence that may vary along the strike as one crosses from one terrane to another. Sea-level trends from tide gauges appear to document this differential motion, but given a 1 mm/yr accuracy of the tide gauge data, the differences may not be statistically significant. Additional complications to this trend include the result of isostatic adjustment due to ice unloading, effects of which can only be approximated, and local effects such as excessive fresh water withdrawal (see Braatz and Aubrey in press). Whereas the tide-gauge data indicate subsidence, paleontological data from the Coastal Plain in the Carolinas show net vertical uplift rates of 1 to 3 to possibly as high as 5 to 10 cm/1000 yrs (Cronin 1981). The differences between the two data sets may be a reflection of scale: the tide-gauge data records at the most a 100 yr trend whereas the geology records a thousands of years trend.

Along the west coast, blocks that have been welded onto the North American craton during the Mesozoic and Cenozoic also behave independently from one another. Here the along strike differences do appear to be statistically significant, with the blocks north of 55°N subsiding and those from 55°N to 48° generally rising; from 48° to about 38°N (where only 2 data points are available) terranes appear to be stable, from 38° to 35°N the terranes are rising, and in southern California-Baja California, the terranes are subsiding gradually southward. This complex motion of the blocks is the product of westerly motion of the North American plate against the northward moving terranes as they became accreted to the margin. As described by Coney et al. (1980), tectonism along the margin began with the initiation of sea-floor spreading of the North Atlantic in mid-Jurassic as the North American plate first moved northwestward then more westerly against the northerly-moving allochthonous terranes, resulting in intra-block thrust faulting and clockwise rotation of the blocks. Since mid-Tertiary the tectonic regime has been complicated further by the overriding of Pacific spreading axes by the North American plate, producing a complex transform tectonic setting within the belt of accreted terranes, a setting that is active today.

Differential vertical land motion along the east and west coasts may result from non-uniform stresses by differential relative plate movement as well as unequal response by dissimilar and partly decoupled geologic terranes forming the margins. Differential response to glacial load/unloading undoubtedly contributes to the variable signals observed in tide-gauge records. Details of the differing dynamics responsible for non-uniform response to margin stresses are not discussed here. Although tide-gauge data contain several types of errors, particularly related to short record length, trends of relative sea levels exhibited along strike are insensitive to analysis methodology. Small differences between tide gauges may reflect methodological rather than physical processes, yet geographic trends clearly persist and may be due to the independent motion of these terranes.

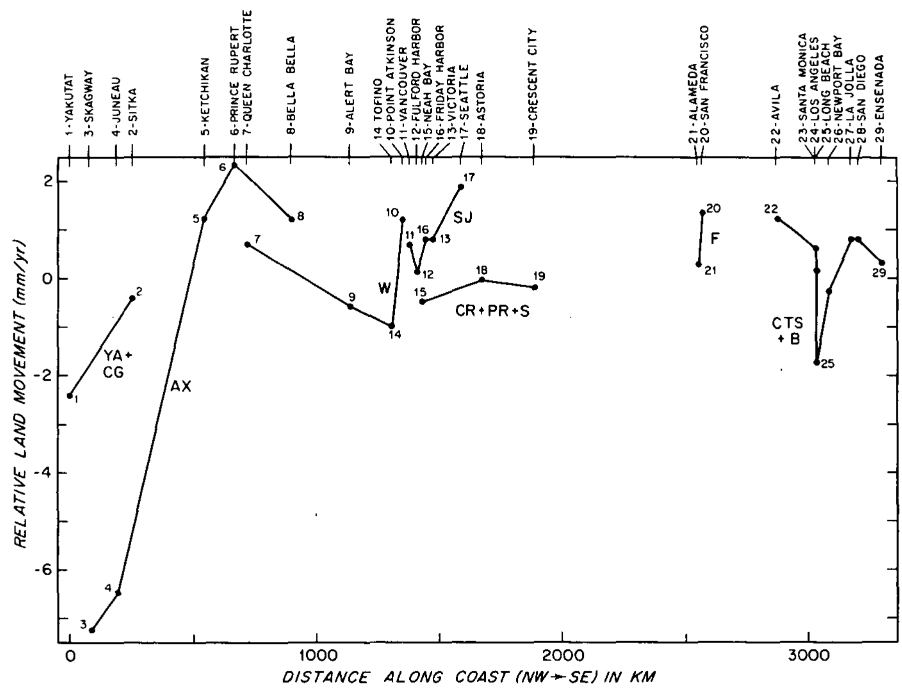

FIG. 6.—Annual relative land levels in the region of figure 4. Data for the western North American margin are derived from Emery and Aubrey (1987). Data similarly are derived from eigenanalysis; however isostatic adjustments were not made because of doubts about their validity in this region. A rigid plate adjustment has been applied to the data, to remove plate-wide tilt.

also varies within individual terranes, a variation that is as much if not more than the variation between blocks. This suggests that the blocks are composites of several smaller terranes. In Alaska both the Yakutat (YA), containing marine Mesozoic and continental Cenozoic rocks, and the Chugach (CG) terrane, composed of Upper Mesozoic flysch and mélange units and lower Cenozoic flysch and clastics (stations 1 and 2), are subsiding with the rate of subsidence being greater in the north (figs. 5 and 6). The Alexander (AX) terrane west of the Yakutat and Chugach, composed of Precambrian (?) and Paleozoic rocks, and Mesozoic volcanics, clastics, and limestone, is subsiding to the north (stations 3 and 4) and uplifting to the south (stations 5, 6, and 8). The stations on the Wrangellia (W) block, a complex of Upper Paleozoic volcanic rocks capped by Mesozoic limestones, clastics, chert, and pillowed and subaerial basalt flows overlain by limestones, cherty limestones and clastic rocks, display a complex sea-level signal. At stations 7 and 10 the terrane is rising, and at station 9 the block is subsiding. Maximum uplift is along the eastern boundary of the block where the terrane is rising at a rate of 1.0 mm/yr at station 10. Stations 11, 12, 13, 16, and 17 on the San Juan terrane (SJ), an intensely deformed mélange containing both Mesozoic and Paleozoic components, indicate that the block is rising with the rate increasing to the south (station 17; 1.9 mm/yr). Crescent (CR; basalt flows, pillow lava, comagmatic mafic dikes, tuff, and breccia), Pacific Rim (PR; tectonically disrupted Late Jurassic to Early Cretaceous deep-marine sedimentary and volcanic rocks), and the volcanic block west of the Cascades (S; Lower Cenozoic volcanic and sedimentary rocks) terranes (stations 15, 18, and 19) do not appear to be undergoing any significant vertical motion. Stations 20 and 21 at the southern end of the Franciscan terrane (T; consisting of Upper Mesozoic Great Valley sequence and rocks of the Franciscan complex above) display a record of stability at station 20 within the Franciscan (0.2 mm/yr) and rising at station 21 near the Franciscan/Salinia boundary (SA; metamorphic

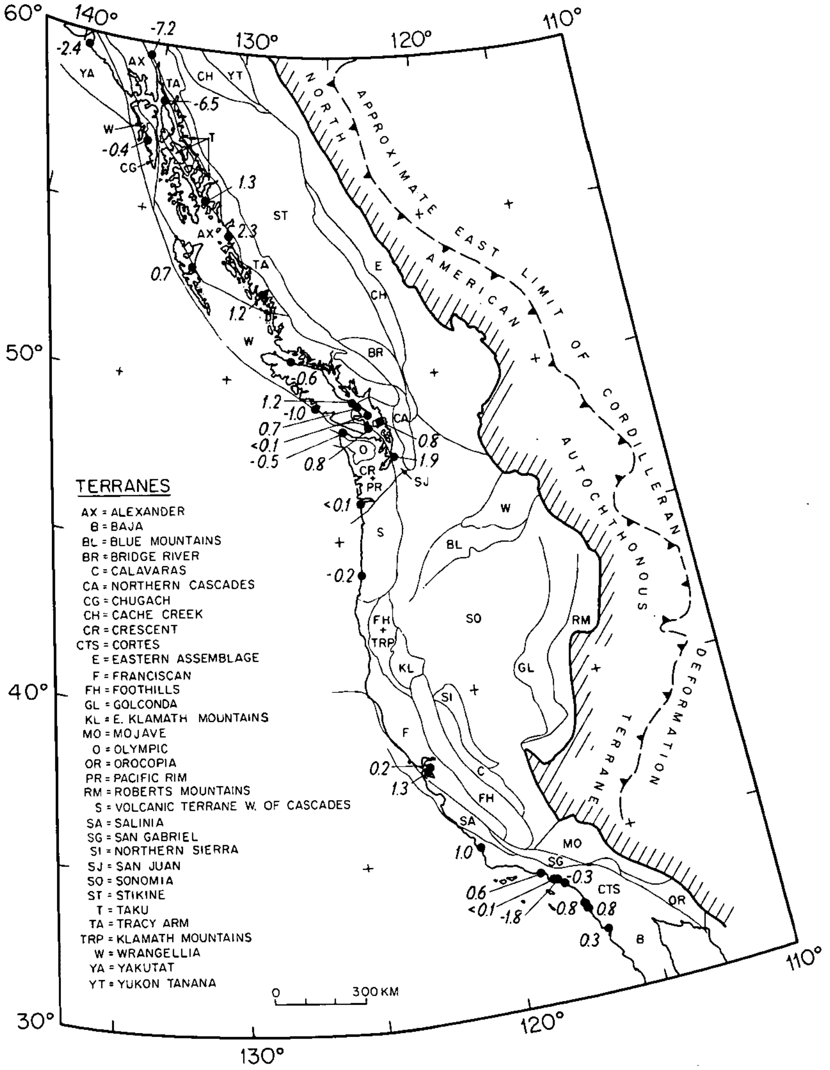

FIG. 5.—Tectonic map of western North America showing rates of sea-level change in mm per yr. As in figure 2 negative numbers indicate subsiding land (or rising sea).

and/or Mesozoic strata deposited far from or at the distal ends of continental influences. Boundaries between the terranes are known or suspected faults. Many are also sutures that have been reactivated by concurrent and post-collision dextral movements. Some terranes contain pieces of oceanic crust of late Paleozoic-early Mesozoic age; others contain fragments of oceanic arcs swept against the Cordilleran margin. Some represent distal parts of continental edges, and still others are fragments from rifting events, intraplate volcanism, or oceanic plateaus. Deposited atop these blocks are superjacent terranes composed of sedimentary and volcanic sequences tying together previously disjunct terranes.

The autochthonous/allochthonous terrane fabric of western North America is also reflected in the sea-level trend constructed from tide-gauge data (figs. 5 and 6). Although the data are sparse, with some terranes having only one or two tide-gauge stations, each block does appear to be characterized by a particular signal in the relative sea-level curve, indicating that the terranes behave independently from one another. The signal

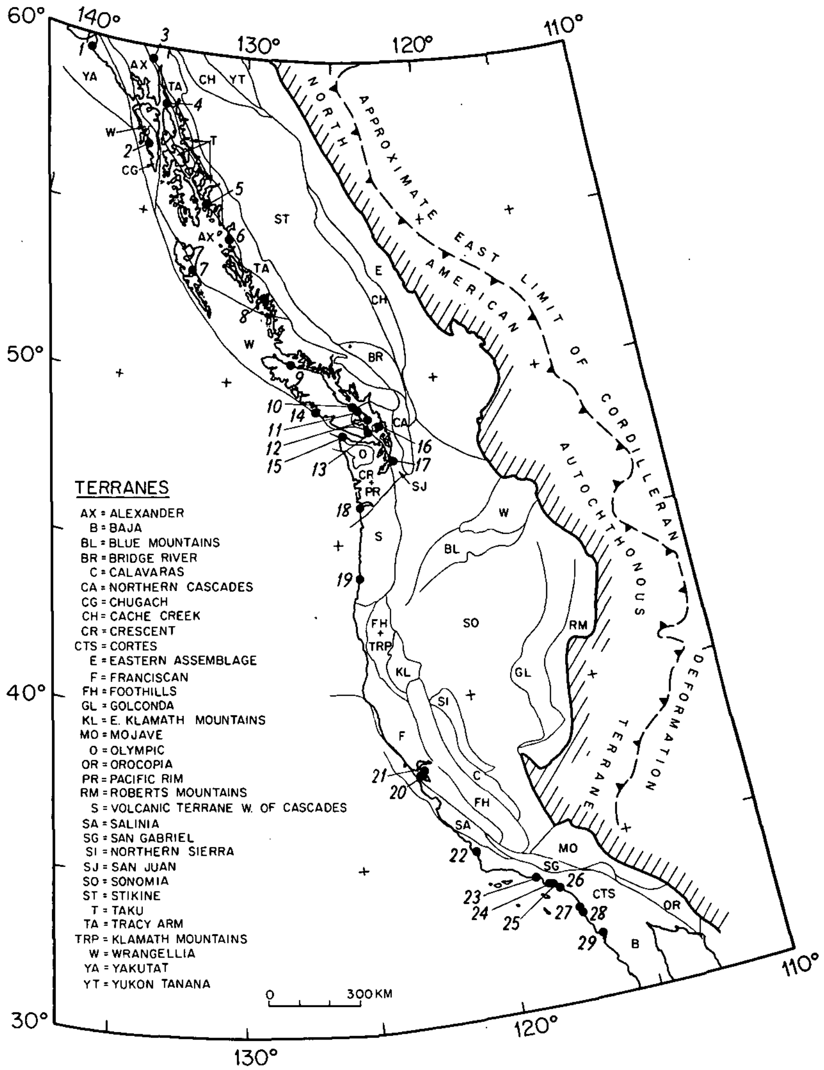

FIG. 4.—Generalized map of terranes welded onto the western margin of the North American craton. Compiled from Coney (1980), Jones et al. (1984), Monger and Berg (1984), Silberling et al. (1984), and Coney and Campa (1984). Also indicated are tide-gauge stations.

or alternative controls on non-uniform land movement other than the geological terranes. The data are suggestive of some tectonic control possibly linked to terranes, a situation that needs more exploration with an expanded tide-gauge network or alternative geodetic techniques.

WESTERN NORTH AMERICA

As described by Coney et al. (1980), Jones et al. (1984), Monger and Berg (1984), Silberling et al. (1984), and Coney and Campa (1984), western North America is a vast mosaic of terranes that collided and accreted to the North American craton during the Mesozoic and early Cenozoic (figs. 4 and 5). These blocks appear to have undergone large-scale concurrent and post-accretionary horizontal translations and significant rotations around vertical axes, motions that are continuing to the present. The terranes are characterized by internal homogeneity, continuity of stratigraphy, tectonic style and geologic history. Most display sedimentary and volcanic rock sequences of oceanic affinity, and contain only upper Paleozoic

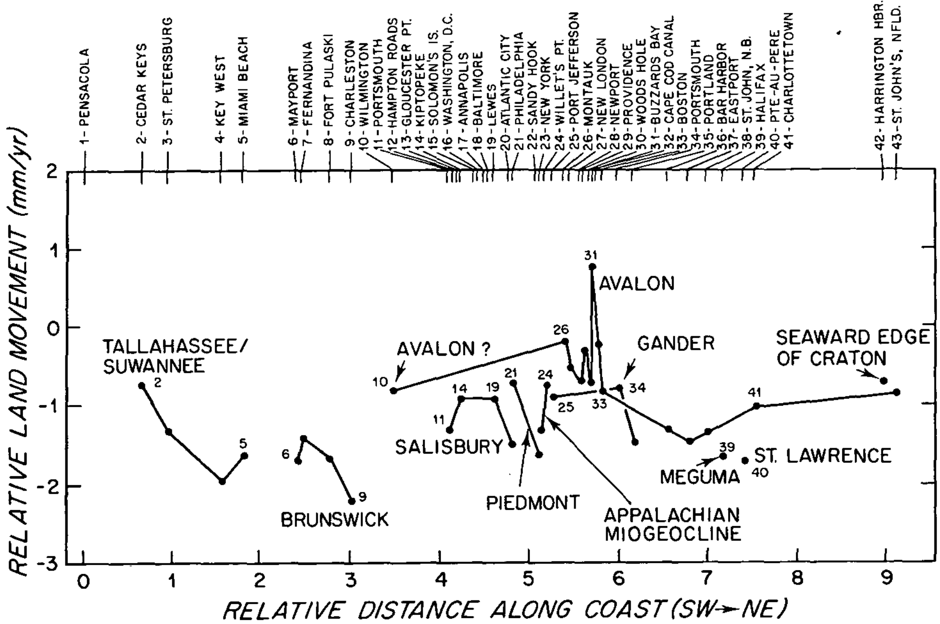

FIG. 3.—Annual relative land levels in the region of figure 1. Data for the eastern North American margin are derived from Braatz and Aubrey (in press). Peltier's (1986) isostatic estimates have been removed from these data. Residual data were analyzed using eigenanalysis; these results then were combined to form estimates of relative land rise. Emphasis is placed on relative changes between stations, rather than absolute magnitude. The uncertainty in base level for zero tectonic movement relative to the center of the earth results from the inability to separate local tectonic motion from global (eustatic) ocean changes.

explain. That this is the only region of uplift in a domain of sinking would tend to place the data in question, possibly a bias resulting from the short record length of 20 yrs at the station. Rates of subsidence within the Salisbury embayment, the structural low southwest of the Avalon, in places exceed 1.0 mm/yr. This trend of basement sinking is disrupted by a northwest-trending belt in the middle of the embayment where subsidence rates are less than 1 mm/yr. Subsidence at stations 21 and 22 on the Piedmont terrane tends to increase sharply to the northeast from 0.8 to 1.6 mm/yr. On the Gander terrane (station 25, 34, and 35) subsidence rates range from 0.8 to 1.6 mm/yr. The sharp difference between the rates at 34 (0.8 mm/yr) and 35 (1.6 mm/yr) may result from station 34 being at the southern end of the Ottawa-Boston trend, a zone of Jurassic-Cretaceous intrusives and present-day seismic activity (Sbar and Sykes 1973). Along the northern edge of the St. Lawrence terrane (station 40) relative rate of subsidence is 1.7 mm/yr. Such an unusually high rate may be a result of the station's location along the contact between the allochthonous block and the autochtonous Paleozoic miogeocline. This area also is along a belt of seismic activity extending from the St. Lawrence Valley to eastern Kansas with the St. Lawrence Valley representing a rift zone along the contact between the craton and the Paleozoic orogen (Kumarapeli and Saull 1966). A much lower value (0.7 mm/yr; station 42) occurs along the contact between the exposed craton and the segment of the craton covered by Paleozoic platform deposits. Along the seaward edge of the Meguma block the rate of subsidence (station 39) is 1.7 mm/yr, nearly twice that on the Avalon platform at station 43. This difference may reflect the proximity of station 39 to the hinge zone whereas station 43 is well within the Avalon terrane (figs. 1 and 2).

The data do not exhibit a unique correspondence between relative sea levels and the suspect terranes, although terrane-wide averages in general differ from one another. This ambiguity in interpretation may reflect errors in tide-gauge data, complex interterrane differential movement, and rifting related to the opening of the present Atlantic,

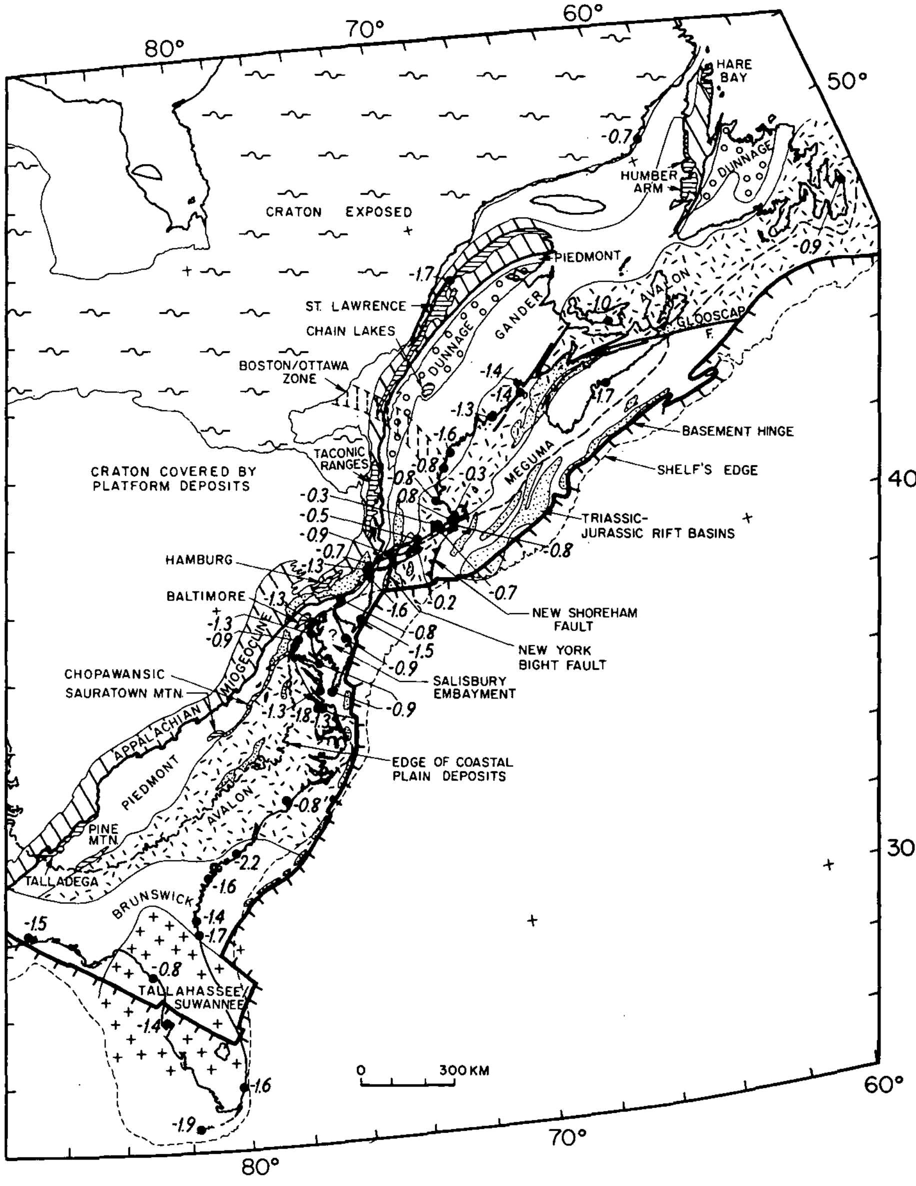

FIG. 2.—Tectonic map of eastern North America showing rates of sea-level change in mm per yr. Negative numbers indicate subsiding land (or rising sea).

0.8 mm/yr. Farther north along the northwest edge of the Avalon terrane (stations 26 to 33; 36 to 38; 41 and 43) subsidence rates range from 0.2 to 1.4. The highest values of 1.4 mm/yr are in coastal Maine. According to Anderson et al. (1984), subsidence in this region is associated with seismic activity that has persisted since at least the 1800s. Anderson et al. state that with respect to Portland, the land in Eastport, Maine has subsided at a rate of 1.8 mm/yr between 1927 and 1966 and at a rate of 7.8 mm/yr between 1942 and 1966. Thus the rate of subsidence has not remained constant, with the period of increased subsidence correlating with the post-1940 increase in seismic activity as described by Shakal and Toksoz (1977). The unusual value at station 31 (+0.8 mm/yr; land is rising) is difficult to

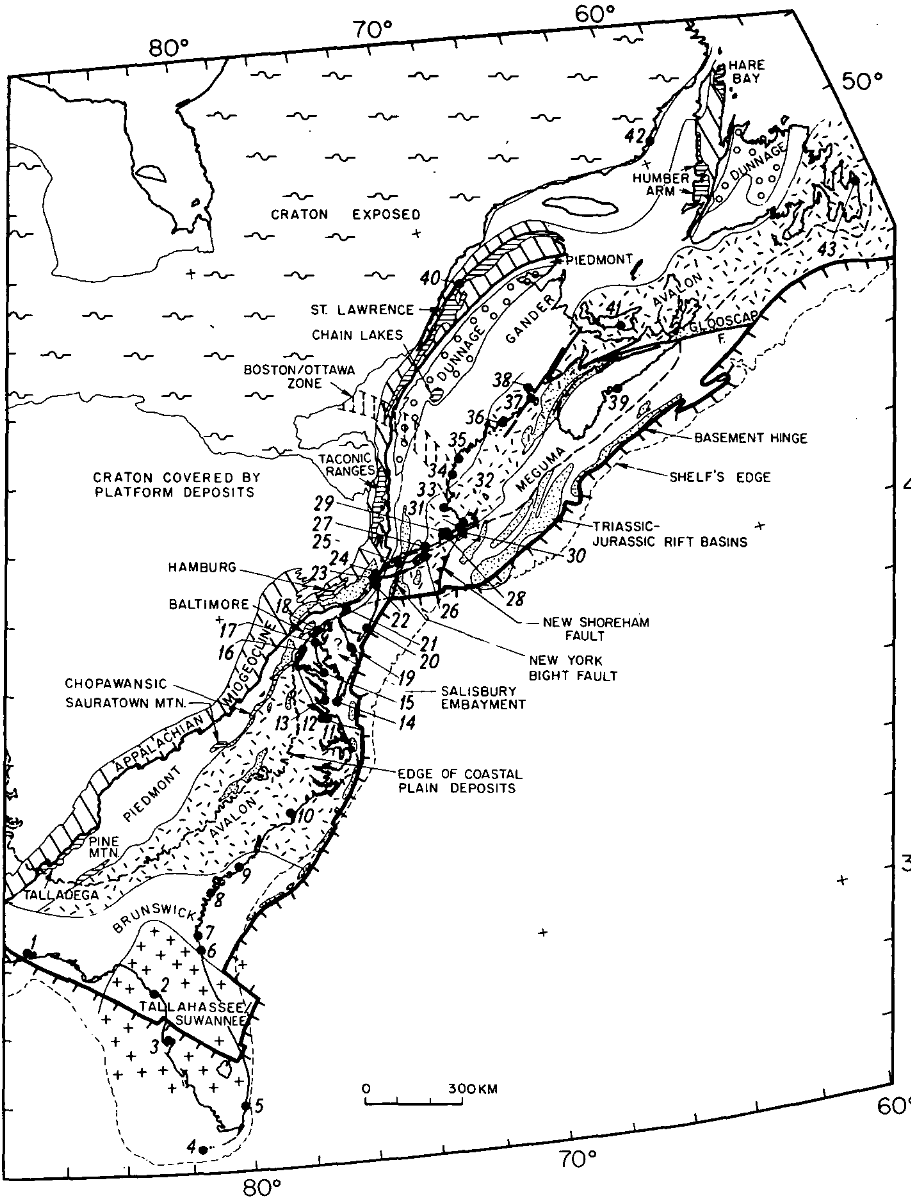

FIG. 1.—Tectonic map of the eastern North American margin. Compiled from King (1969), Williams and Hatcher (1982), an unpublished tectonic map by K. Klitgord of the U.S. Geological Survey Marine Geology Branch at Woods Hole, MA, Ballard and Uchupi (1975), Emery and Uchupi (1984), Hutchinson and Grow (1985), and Hutchinson et al. (1986). Also indicated are tide-gauge stations; numbers are as on figure 3.

Tide Gauge Data.—To some degree, relative sea-level trends obtained from tide gauges on eastern North America appear to reflect the basement terranes described above (figs. 1, 2, and 3). For example, stations 2 to 6 located in the Tallahassee/Suwannee terrane display the maximum relative subsidence seaward of the basement hinge (stations 3–5), with subsidence increasing away from the hinge. High subsidence values also occur in the Brunswick terrane, reaching a value of 2.2 mm/yr at station 9. The lowest rate of subsidence (0.8 mm/yr) in the region occurs at the crest of the Tallahassee/Suwannee terrane. Northeast of the Brunswick terrane along the front of the possible southern extension of the Avalon terrane the rate of subsidence (station 10) is only dle Ordovician graptolite shale. The Gander terrane consists of volcanic rocks and shale above a gneiss dome in New England and pre-Middle Ordovician clastic rocks in Canada. This terrane developed on the opposite side of the Iapetus with its long history of mid-Paleozoic deformation and intrusion resulting from horizontal displacement along a mega-shear (Williams and Hatcher 1982, 1983).

The Avalon terrane contains alternating belts of late Precambrian sedimentary and volcanic rocks atop Cambrian shallow-water marine sediments containing an Atlantic realm trilobite fauna all of which are intruded by mid-Paleozoic batholiths. These deposits are coeval with the Pan-African sequences in North Africa (O'Brien et al. 1983). The Avalon, which is unaffected by the Taconic (Ordovician) orogeny, was welded onto the North American craton during mid-Paleozoic (Acadian orogeny). In Canada the Gander-Avalon boundary and the Avalon-Meguma boundaries are marked by steep zones of mylonite and high angle brittle material. In southern Maine the Gander-Avalon boundary may represent a mid-Paleozoic oceanic suture zone. Off New York we have tentatively placed the boundary between the Avalon and Meguma terranes along the New Shoreham and New York Bight faults described by McMaster (1971) and Hutchinson and Grow (1985). This has yet to be verified. Williams and Hatcher (1982, 1983) have included within the Avalon terrane the eastern Piedmont and Carolina Slate belt. Although these southern units do have an Atlantic trilobite fauna, the stratigraphic succession (the thick sequence of Cambrian felsic volcanics in the Carolinas is not matched in Canada, and the limestones and red and black shales present in Canada are not known in the Carolina Slate belt) suggests that the southern units may represent a different allochthonous terrane (Secor et al. 1983).

South of and in fault contact (Glooscap and New Shoreham faults) with the Avalon platform is the Meguma, a terrane characterized by Cambro-Ordovician deep-water fans, Ordovician glaciomarine tillite, and Early Devonian paralic sediments. This allochthonous terrane of probable northwest African parentage became attached to North America during late Paleozoic (Schenk 1981). Atop the Meguma-Avalon boundary is a Carboniferous rift system that extends from southern New England to Newfoundland. At the southwest end of the Paleozoic accretionary wedge is a suture zone-magmatic complex (the Brunswick terrane) beneath the Coastal Plain that is characterized by low gradient magnetic and gravity zones (Klitgord and Popenoe 1983). A similar zone may exist beneath the Coastal Plain in the Salisbury embayment.

Outboard of the Brunswick is the Tallahassee/Suwuannee or Florida terrane consisting of Paleozoic granites, diorites, and rhyolites in the central Florida basement complex, relatively undeformed Paleozoic rocks in northern Florida, and block-faulted sedimentary rocks in western Florida (Barnett 1975; Klitgord et al. 1984). Paleozoic rocks in northern Florida consist of Ordovician quartzite sandstone and Silurian-Devonian black shale which are similar to those in the Bove basin of western Africa. This terrane probably docked onto the North American terrane in late Paleozoic after lateral motion along a megashear.

Superimposed on all of these basement terranes is a northeast-trending Late Triassic-Early Jurassic rift system filled with continental and shallow marine (including evaporites) sediments (Ballard and Uchupi 1975; Van Houten 1977; Hutchinson et al. 1986). These tensional structures were formed in response to the separation of Africa and North America in the Mesozoic. During this separation segments of Africa and Paleozoic oceanic plateaus were left behind. As a result, North America became wider than during the Paleozoic and Africa relatively narrower. The Mesozoic rifts and suspect terranes are truncated on the eastern side by a hinge zone which marks the thinning of crust from normal continental values of 30–40 km to a thinned crust 10–20 km thick (Watts 1981; Emery and Uchupi 1984, p. 369). Resting uncomformably on all of these provinces is the drift supersequence (Coastal Plain deposits) emplaced since seafloor spreading began in mid-Jurassic 180 m.y. ago. Its thickness ranges from less than a few kilometers landward of the hinge to as much as 18 km in the offshore basins seaward of the hinge on the outer shelf to the upper continental rise.

plate-wide trends and their response to tectonic stresses.

In this brief report we compare the relative sea-level changes from tide-gauge records from eastern and western North America from 1900 to the present with the second-order lithotectonic terranes accreted to the North American craton during the Paleozoic in eastern North America, and during the Mesozoic and early Cenozoic in western North America. Data and techniques used in this analysis are presented in Emery and Aubrey (1986*a*).

Tide-gauge data are subject to many sources of error. Short record length, installation in harbors, and uncertainties in datums all contribute to errors in estimating low-frequency relative sea-level trends. In addition to errors in the data, analysis methodology can introduce bias or increased errors. Quantification of these various errors is complex; error estimates for the data used in this report average about ± 1 mm/yr (geographical averaging can reduce these errors). As a result, small differences between stations may not be significant; general trends, however, are more likely to be real (Aubrey and Emery 1983; Aubrey and Emery 1986*a*).

EASTERN NORTH AMERICA

The structural fabric of the eastern seaboard is the result of sea-floor spreading, subduction and continental collision in the Paleozoic, and continental rifting, sea-floor spreading, and development of the continental margin that began in the Mesozoic and is continuing to date. Inboard of the Paleozoic's shelf's edge is the North American Precambrian craton (exposed to the north and buried by Paleozoic platform deposits to the south). East of the craton is the deformed Appalachian miogeocline, the western shelf and slope of the Paleozoic Iapetus Ocean. Outboard of the miogeocline is a complex of allochthonous terranes that were welded onto the North American margin during the closing of the Iapetus (Cook et al. 1981; Williams and Hatcher 1982, 1983). Although difficult to map in ancient mountain belts (Zen 1983), these terranes can be distinguished from one another by their contrasting stratigraphy, structure, metamorphic histories, faunas, mineral deposits, and paleomagnetic characters. Contrast between early and late accretionary boundaries tends to suggest that some transcurrent motion took place during the latest cycle of accretion (Gates et al. 1980).

Suspect Terranes.—Included within these suspect terranes are the Taconic allochthons (Hamburg, Taconic Ranges, St. Lawrence, Humber Arm, and Hare Bay) consisting of lower structural slices of sedimentary rocks and upper slices of volcanic rocks, igneous rocks, and ophiolite facies which originally lay on the slope and rise (Williams and Hatcher 1982, 1983). They were transported westward onto the upper slope and shelf of the miogeocline as a result of eastward subduction of the North American margin beneath an overriding oceanic plate.

The Talladega terrane of the southern Appalachians consists of a Paleozoic succession containing chert capped by mafic volcanic rocks (distal product of island-arc volcanism).

Rocks of the Piedmont terrane are predominantly late Precambrian-early Paleozoic metaclastics resting on Precambrian Grenville basement metamorphosed to upper greenschist and amphibolite facies (Williams and Hatcher 1982, 1983). From New York north the Piedmont is considered to be the deformed and metamorphosed rocks (Taconic Ordovician orogeny) of the eastern edge of the miogeocline. In the south the Piedmont is a subhorizontal crystalline slice emplaced above the North American miogeocline during Alleghanian (Permian-Carboniferous) tectonism (Cook et al. 1981; Williams and Hatcher 1982, 1983).

The Dunnage terrane consists of early Paleozoic mafic rocks and marine sedimentary rocks resting on an ophiolite complex. Deformation of this terrane is much less than on the adjacent Piedmont and Gander terranes. It and the Gander were welded onto the miogeocline and with one another during the Middle Ordovician (Taconic orogeny). The Chain Lakes are bordered by a steeply-dipping Ordovician ophiolite complex to the south, intruded by Paleozoic granite to the east, and capped unconformably by Silurian sediments consisting of 1500 m.y. old quartz-feldspar gneisses (Williams and Hatcher 1982, 1983). The Chopawamsic terrane is composed of mafic plutonic rocks intruded by a 500 m.y. old granite pluton overlain by Mid-

GEOLOGICAL NOTES

SUSPECT TERRANES IN THE NORTH AMERICAN MARGINS AND RELATIVE SEA-LEVELS[1,2]

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ABSTRACT

Sea-level trends deduced from tide gauges show considerable variation along strike both on the convergent (western) and divergent (eastern) edges of the North American plate. That portion of the variation unrelated to Quaternary glaciation and deglaciation may reflect the differential reaction to extension and sediment loading in the east, and in the west subduction and translation of terranes welded onto the North American craton. These autonomous blocks appear to impart distinct signatures on records of relative sea levels, suggesting promise in deducing complex terrane topography of other margins using tide-gauge data. Uncertainties in these deductions can be reduced only with expanded tide gauge coverage or by application of new geodetic techniques (*V*ery *L*ong *B*aseline Interferometry or differential Global Positioning *S*ystem).

INTRODUCTION

Analyses of yearly averages from tide-gauge records from various parts of the world reveal variable spatial and temporal patterns of relative sea-level movements. These patterns are so variable along the strike that they are believed to be primarily of tectonic and secondarily of oceanographic origin. The tectonic signal is so strong that the available data are insufficient to permit the separation of tectonic and eustatic effects on relative sea levels. In Japan, for example, low frequency patterns (periods longer than 10 yrs) in sea level best can be explained as the result of the subduction of the Pacific and Philippine plates beneath Japan (Aubrey and Emery 1986*a*). Relative sea-level changes in the eastern Asia mainland reflect rising of massifs and ancient foldbelts and subsidence of Cenozoic basins and foldbelts (low frequency), and Kuroshio Current and freshwater inflow onto the shelf (higher frequency; 2–25 yr periods; Emery and Aubrey 1986*a*). In Australia low-frequency (period of 20 yrs and greater) changes in relative sea levels are ascribed to such tectonic factors as subsidence due to sediment and water loading, thermal cooling of oceanic crust, and uplift along a convergent plate boundary (Aubrey and Emery 1986*b*). In the Fennoscandian region changes in sea level are due to isostatic rebound following the last glaciation (Emery and Aubrey 1985). Long term changes in relative sea level in South and Central America and the Caribbean islands are ascribed to general subsidence along the Atlantic margin, subduction along the Pacific margin, and block development in the Caribbean plate (Aubrey et al. unpub. data).

Sea-level movements along the eastern margin of North America result from post-glacial isostatic adjustments (long wavelength spatial patterns; thousands of kilometers), and tilts of the land surface, regional warpings in Florida, Georgia, and the Carolinas, subsidence in the Chesapeake area, and fault reactivation in northern New England (short wavelength spatial patterns; tens to hundreds of kilometers; Aubrey and Emery 1983; Braatz and Aubrey in press). Relative sea-level changes in western North America are due to vertical movements caused by horizontal movements of oceanic plates; subduction at the east end of the Aleutian Trench; translation and secondary subduction between Sitka, Alaska and the Mendocino Fracture Zone; translation west of the San Andreas fault; and subsidence along northwestern Mexico (Emery and Aubrey 1986*b*). This earlier work concentrated on first-order

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