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# Changing coastal levels of South America and the Caribbean region from tide-gauge records *

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## Abstract

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Tide-gauge records from southern Mexico, the Caribbean Islands, and Central and South America that span the interval 1940–1970 reveal long-term changes of relative sea level according to regression analysis and eigenanalysis. The results indicate such large variations in both direction and rate of secular movement as to rule out changes in volume of ocean water as being more than a subordinate factor. The only satisfactory explanation is that the land level beneath the tide gauges is rising in some places and sinking in others.

Complex spatial patterns of relative seal-level change in southern Mexico and the Caribbean mirror the tectonic regime of these regions, exhibiting both submergence and emergence of the land. Central American tide-gauge records similarly show considerable complexity, responding to relative movement along plate boundaries. The Pacific coast of South America appears to correlate with the depth of the Benioff zone; subduction of aseismic ridges produces local highs in the Benioff zone, flanked by troughs at either side. Near the Benioff highs, relative land level is rising; between these ridges relative land level is falling. Sea-level trends in southern and Atlantic coasts of South America are closely linked with continental crustal rifting and subsidence. Data do not allow unambiguous separation of changes in ocean level from changes in land level, and no simple eustatic ocean level change can be estimated accurately from these data.

## 1. Introduction

Tide gauges reveal diurnal, seasonal, and episodic variations in water level, and especially long-term secular changes. Many of the latter have been ascribed to long-term modifications of sea level by return of glacial melt-water and steric expansion. On the other hand, most coasts contain topographic evidences of large changes of land level, both higher and lower than at present. The correct interpretation is important because, although we expect the volume of ocean water to increase as glaciers melt and oceans expand because of increased air temperature caused by the carbon-dioxide greenhouse effect (National Research Council, 1983; Committee on the Relationship between Land Ice and Seal Level, 1985), we also must expect changes in levels of continental margins caused by isostatic adjustment and tectonism associated with movements of the land surfaces beneath the tide gauges. This question is especially important for South America where there are only 28 useful stations, of which only nine are along coasts of the huge Pacific Ocean.

On the tectonic side of the question is the evidence of effects upon tide-gauge records of slow subsidence along divergent (pull-apart) continental margins revealed by analyses for eastern

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North America (Aubrey and Emery, 1983; Braatz and Aubrey, 1987) and off Australia (Aubrey and Emery, 1986a). Along convergent continental margins changes of coastal levels range from extreme subsidence caused by tectonic erosion during underthrusting (southern Japan—Aubrey and Emery, 1986b) to moderate subsidence and/or uplift caused by incorporation of thick continental margin sediments carried on subducted layers (western North America—Emery and Aubrey, 1986b) and northern Japan—Aubrey and Emery, 1986b). Along some coasts having little lateral plate movement vertical sinking or sliding is attributable to compaction of sediments of continental basin formation (eastern Asia—Emery and Aubrey, 1986a) or to coastal rebound and sinking associated with melt of glacial masses (northern Europe—Emery and Aubrey, 1985; eastern North America—Braatz and Aubrey, 1987). South America, Central America, and the Caribbean Sea contain belts of most of these kinds of tectonism; accordingly, we have tried to investigate the important question of how well tide-gauge records in that region can distinguish between continuing tectonism and increase in volume of ocean water.

Our data base is mainly that of the Permanent Service for Mean Sea Level in England. Of 55 records from within Fig. 1 that are longer than 10 years, only 14 (9 from Argentina, 3 from Mexico, and 2 from Puerto Rico) extend to later than 1970. The paucity of data more recent than 15 years limits some interpretations, and it is to be hoped that unprocessed measurements have been filed and await eventual processing in many of the countries.

## Results and discussion

### *Long-period trends examined by regression*

Most of the tide-gauge data show subsiding land level (increasing relative water level), but some stations have the opposite trend; moreover, trends in either direction are far from coherent nor do they change systematically with latitude or region. These characteristics imply that steric expansion and increased volume of ocean water from glaciers and streams cannot be the sole cause (although such additions may be included). We must look, instead, for regional or local changes of land level and try to identify their contribution to tide-gauge records. Because changes of land level dominate, the tide-gauge results are expressed so that (+) means relative rise of land and (−) means relative fall of land level (Fig. 1).

The simplest means of determining the long-term trend is to analyze separately by linear regression the series of mean annual sea levels at each station. Short records are useless (because of the spectral richness of the signals), but 55 stations within Fig. 1 include at least 10 years (Table 1). Some records, especially short ones, yield erratic trends having low *t*-confidence levels (the *t*-confidence represents roughly the probability that the measured slope is within ±1 mm/year of the true slope). Those having confidence levels lower than 0.80 were eliminated arbitrarily leaving 47 potentially useful records, of which *t*-confidence levels for 30 are higher than 0.90 and for 38 are higher than 0.85. Frequency distribution of *t*-confidence levels is similar for the 27 stations along South America and the 20 along Central America and islands of the Caribbean Sea.

The mean changes of level obtained by regression analysis are best viewed when superimposed on tectonic maps and as profiles along the four major tectonic provinces of the region (Figs. 2 and 3). The tectonic province along northwest and west coasts of South America is addressed first (panel A of Fig. 3). The structural setting in western Venezuela and in Colombia (Fig. 3A) is one of a relatively stable platform, the Maracaibo block to the east and a late accretionary wedge to the west. This wedge consists of two structural elements. Inboard next to the Maracaibo block is the middle Eocene San Jacinto belt, and outboard—the Pleistocene–Holocene Sinu belt (Duque-Caro, 1979). Deformation of turbidites at the base of the continental slope in Colombia Basin indicates that the Sinu belt still is moving. The belt off northwestern Colombia is interpreted by Vitali et al. (1985) as the remains of the N–S oriented western South America subduction zone recently isolated by collision of the Panama block with western Colombia (Wadge and Burke, 1983). The

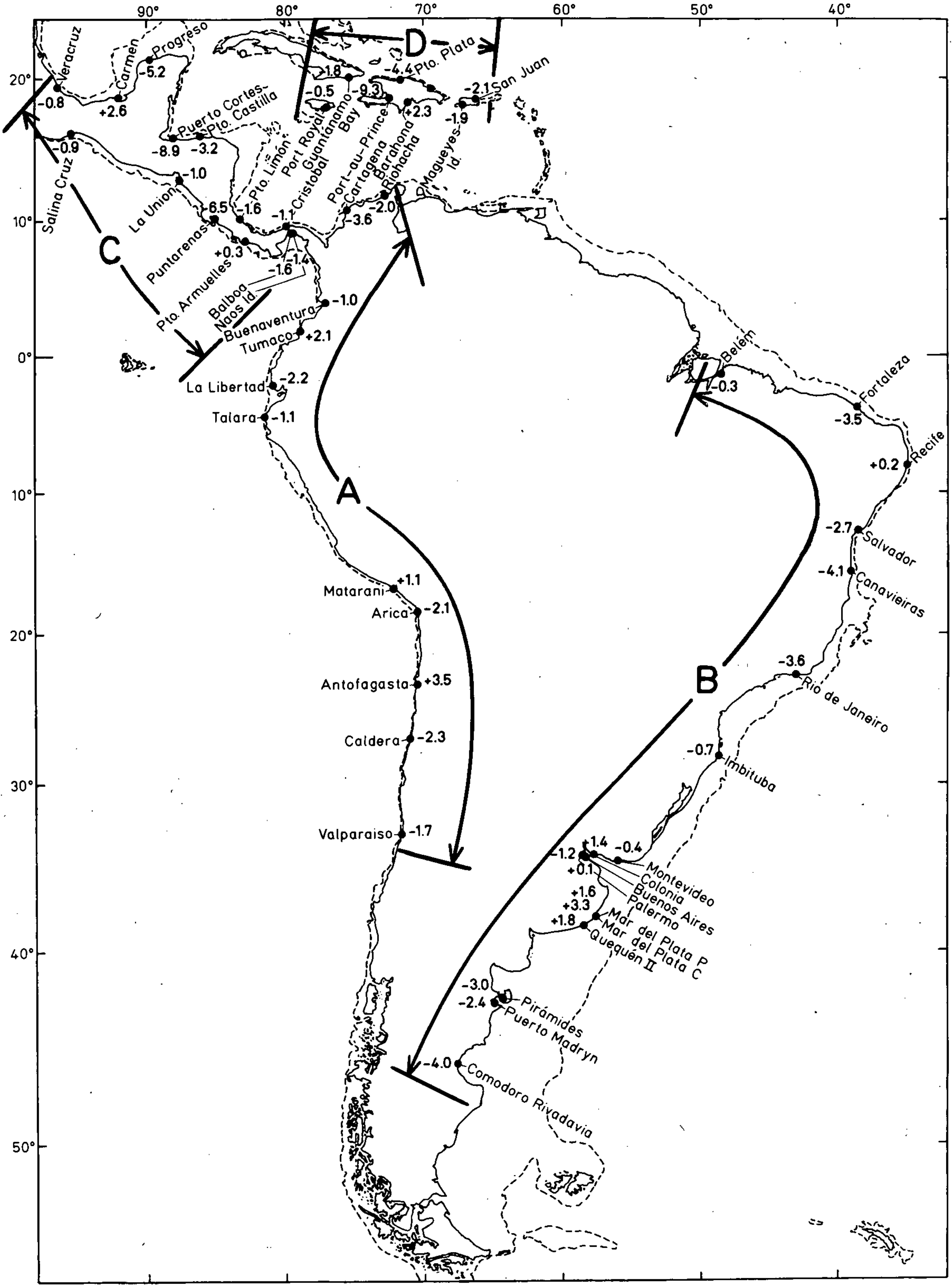

Fig. 1. Positions of tide-gauge stations of South America, Central America, and the Caribbean islands whose records are longer than 10 years. Dots and names indicate stations having 95% confidence levels higher than 0.80 for slopes of trend lines drawn by regression analysis through data points for mean annual relative sea-levels. Negative values indicate areas where land is sinking relative to sea level, whereas the positive values indicate areas where land is rising. Shorelines and 100-fm (183-m) contour (dashed) are from Defense Mapping Agency chart (1982). *A–D*—structural regions (see Fig. 3).

TABLE 1

Tide-gauge stations

| Station name | Location | | Begin year | End year | Total years | Regression slope (mm/yr) |
|---|---|---|---|---|---|---|
| | lat. | long. | | | | |
| *Mexico (Pacific)*—(North of Fig. 1) | | | | | | |
| Ensenada | 31°51′N | 116°38′W | 1956 | 1982 | 25 | −1.1 |
| La Paz | 24°10′N | 110°21′W | 1952 | 1966 | 15 | −1.7 |
| Guaymas | 27°55′N | 110°54′W | 1952 | 1965 | 14 | −3.0 |
| Manzanillo | 19°03′N | 104°20′W | 1954 | 1982 | 26 | −3.1 |
| Salina Cruz | 16°10′N | 095°12′W | 1952 | 1979 | 27 | −0.9 |
| *Guatemala (Pacific)* | | | | | | |
| San Jose | 13°55′N | 090°50′W | 1960 | 1969 | 10 | −0.9 |
| *El Salvador (Pacific)* | | | | | | |
| La Union | 13°20′N | 87°49′W | 1948 | 1968 | 21 | −1.0 |
| *Costa Rica (Pacific)* | | | | | | |
| Puntarenas | 09°58′N | 084°50′W | 1941 | 1966 | 26 | −6.5 |
| Quepos | 09°24′N | 084°10′W | 1957 | 1969 | 13 | +1.6 |
| *Panama (Pacific)* | | | | | | |
| Puerto Armuelles | 08°16′N | 082°52′W | 1951 | 1968 | 18 | +0.3 |
| Balboa | 08°58′N | 079°34′W | 1908 | 1969 | 62 | −1.6 |
| Naos Island | 08°55′N | 079°32′W | 1949 | 1968 | 20 | −1.4 |
| *Colombia (Pacific)* | | | | | | |
| Buenaventura | 03°54′N | 077°06′W | 1941 | 1969 | 28 | −1.0 |
| Tumaco | 01°50′N | 078°44′W | 1953 | 1968 | 16 | +2.1 |
| *Ecuador (Pacific)* | | | | | | |
| La Libertad | 02°12′S | 080°55′W | 1948 | 1969 | 22 | −2.2 |
| *Peru (Pacific)* | | | | | | |
| Talara | 04°37′S | 081°17′W | 1942 | 1969 | 28 | −1.1 |
| Chimbote | 09°05′S | 078°38′W | 1955 | 1968 | 14 | +5.6 |
| Matarani | 17°00′S | 072°07′W | 1941 | 1969 | 28 | +1.1 |
| *Chile (Pacific)* | | | | | | |
| Arica | 18°28′S | 070°20′W | 1950 | 1970 | 21 | −2.1 |
| Antofagasta | 23°39′S | 070°25′W | 1946 | 1970 | 25 | +3.5 |
| Caldera | 27°04′S | 070°50′W | 1950 | 1969 | 21 | −2.3 |
| Valparaiso | 33°02′S | 071°38′W | 1958 | 1969 | 13 | −1.7 |
| *Argentina (Atlantic)* | | | | | | |
| Ushuaia I | 54°49′S | 068°13′W | 1957 | 1969 | 13 | −6.2 |
| Comodoro Rivadavia | 45°52′S | 067°29′W | 1959 | 1980 | 20 | −4.0 |
| Puerto Madryn | 42°46′S | 065°02′W | 1944 | 1979 | 28 | −2.4 |
| Piramides | 42°35′S | 064°17′W | 1957 | 1972 | 16 | −3.0 |
| Quequén II | 38°35′S | 0.58°42′W | 1968 | 1980 | 13 | +1.8 |
| Mar Del Plata P | 38°03′S | 057°33′W | 1957 | 1979 | 21 | +1.6 |
| Mar Del Plata C | 38°03′S | 057°33′W | 1957 | 1979 | 24 | +3.3 |
| Buenos Aires | 34°36′S | 058°22′W | 1957 | 1979 | 23 | +0.1 |
| Palermo | 34°34′S | 058°24′W | 1957 | 1979 | 24 | −1.2 |
| Isla Martin Garcia | 34°11′S | 058°15′W | 1957 | 1976 | 20 | +9.9 |
| *Uruguay (Atlantic)* | | | | | | |
| Colonia | 34°28′S | 057°51′W | 1954 | 1970 | 17 | +1.4 |
| Montevideo | 34°55′S | 056°13′W | 1938 | 1970 | 26 | −0.4 |
| La Paloma | 34°39′S | 054°09′W | 1955 | 1969 | 15 | −2.6 |

TABLE 1 (continued)

| Station name | Location | | Begin year | End year | Total years | Regression slope (mm/yr) |
|---|---|---|---|---|---|---|
| | lat. | long. | | | | |
| *Brazil (Atlantic)* | | | | | | |
| Imbituba | 28°14′S | 048°39′W | 1948 | 1968 | 21 | −0.7 |
| Rio de Janeiro | 22°56′S | 043°08′W | 1949 | 1968 | 20 | −3.6 |
| Canavieiras | 15°40′S | 038°58′W | 1952 | 1963 | 12 | −4.1 |
| Salvador | 12°58′S | 038°31′W | 1949 | 1968 | 20 | −2.7 |
| Recife | 08°03′S | 034°52′W | 1948 | 1968 | 21 | +0.2 |
| Fortaleza | 03°43′S | 038°29′W | 1948 | 1968 | 19 | +3.4 |
| Belém | 01°27′S | 048°30′W | 1949 | 1968 | 20 | −0.3 |
| *Colombia (Caribbean)* | | | | | | |
| Riohacha | 11°33′N | 072°55′W | 1953 | 1969 | 17 | −2.0 |
| Cartagena | 10°24′N | 075°33′W | 1949 | 1969 | 21 | −3.6 |
| *Panama (Caribbean)* | | | | | | |
| Cristobal | 09°21′N | 079°55′W | 1909 | 1969 | 61 | −1.1 |
| *Costa Rica (Caribbean)* | | | | | | |
| Puerto Limon | 10°00′N | 083°02′W | 1948 | 1969 | 21 | −1.6 |
| *Honduras (Caribbean)* | | | | | | |
| Puerto Castilla | 16°01′N | 086°02′W | 1955 | 1968 | 14 | −3.2 |
| Puerto Cortes | 15°50′N | 087°57′W | 1948 | 1968 | 21 | −8.9 |
| *Mexico (Gulf)* | | | | | | |
| Progreso | 21°18′N | 089°40′W | 1952 | 1982 | 30 | −5.2 |
| Carmen | 18°38′N | 091°51′W | 1956 | 1966 | 11 | +2.6 |
| Alvarado | 18°46′N | 095°46′W | 1955 | 1966 | 12 | +5.3 |
| Veracruz | 19°11′N | 096°07′W | 1953 | 1982 | 29 | −0.8 |
| *Cuba (Caribbean)* | | | | | | |
| Guantanamo Bay | 19°54′N | 075°09′W | 1937 | 1968 | 31 | −1.8 |
| *Jamaica (Caribbean)* | | | | | | |
| Port Royal | 17°56′N | 076°51′W | 1954 | 1969 | 16 | −0.5 |
| *Haiti (Caribbean)* | | | | | | |
| Port-Au-Prince | 18°34′N | 072°21′W | 1949 | 1961 | 13 | −9.3 |
| *Dominican Republic (Caribbean)* | | | | | | |
| Barahona | 18°12′N | 071°05′W | 1954 | 1969 | 11 | +2.3 |
| Puerto Plata | 19°49′N | 070°42′W | 1949 | 1969 | 16 | −4.4 |
| *Puerto Rico (Caribbean)* | | | | | | |
| Magueyes Island | 17°58′N | 067°03′W | 1955 | 1978 | 23 | −1.9 |
| San Juan | 18°27′N | 066°05′W | 1962 | 1974 | 13 | −2.1 |

Sinu belt terminates at Cartagena with no apparent deformation on the upper Magdalena Fan (Lu and McMillen, 1982; Kolla et al., 1984; Vitali et al., 1985). It reappears north of the fan and continues along the rest of the Colombian margin and the Venezuela margin (Lu and McMillen, 1982). Interruption of the deformed belt probably indicates displacement by a strike-slip fault, possibly a seaward extension of the right-lateral Oca fault, beneath the Magdalena Fan (Lu and McMillen, 1982). In Cartagena at the northern end of the deformed belt south of the Magdalena delta, and is sinking at a rate of 0.36 mm/year. On the Guajira plain covered by Quaternary deposits

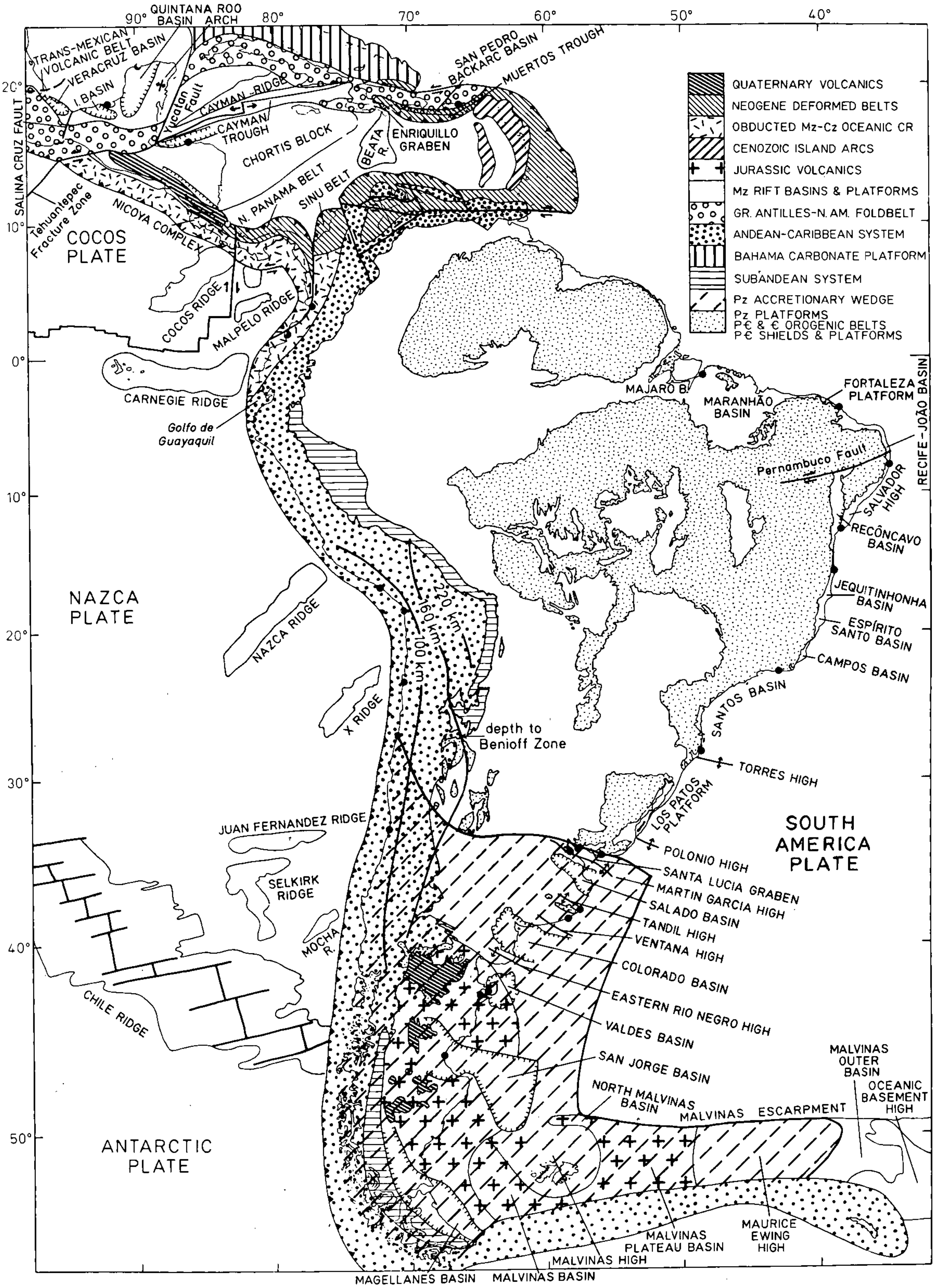

Fig. 2. Tectonic map of the region compiled from King (1969), Bowin (1975), Ponte and Asmus (1976), Herz (1977), De Almeida et al. (1978), Case and Holcombe (1980), Urien et al. (1981), Aubouin et al. (1982). Biju-Duval et al. (1982a), and Bovis and Isacks (1984). Although not so indicated, Mexico, Yucatan, and the Chortis block are allochthonous terranes that were attached to North America during the Mesozoic. Important structural units are identified by patterns according to geological ages and are named.

north of the Santa Marta massif the land is sinking at a lower rate of −2.0 mm/year at Riohacha. This station is seaward of a terrace atop which lower Tertiary strata are exposed (Martin, 1978). Thus the region appears to consist of a series of highs and lows that are undergoing differential

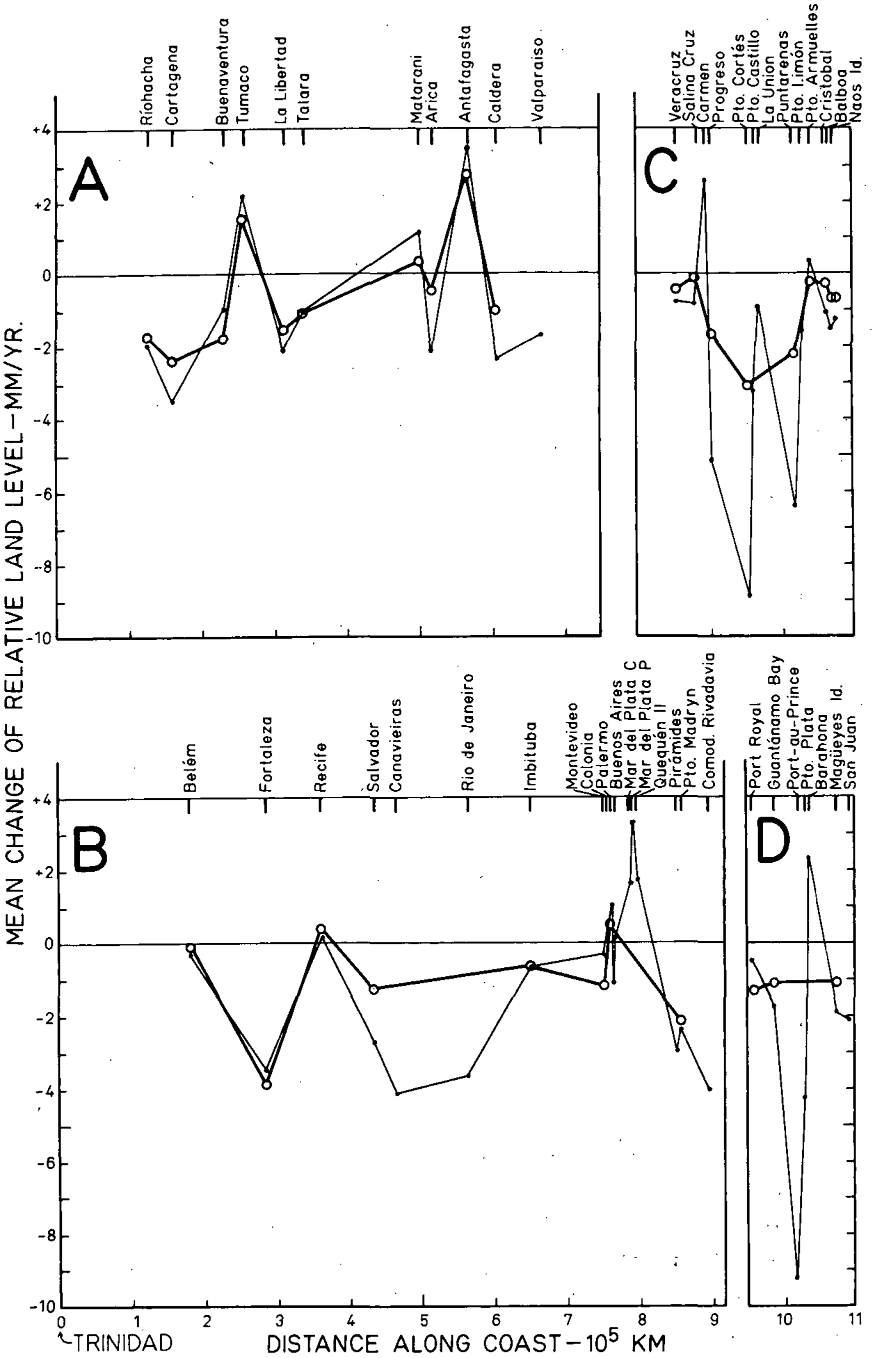

Fig. 3. Results of regression (narrow lines) and eigenanalysis (wide lines) and their differences in four regions. A. Tectonized belt of South America between Trinidad Island and Valparaiso—mostly Pacific coast. B. Continental platform of South America from Trinidad Island to Comodoro Rivadavia—Atlantic coast. C. Central America from northwest to southeast. D. Caribbean Islands from west to east. See Fig. 1 for locations of regions.

vertical motion. For example, uplift of 1.5 mm/year has been reported from the Venezuelan Andes and the Sierra de Perija southeast of the Guajira plain (Kellog and Bonini, 1982), whereas the plain and Lake Maracaibo are sites of subsidence. Uplift and concurrent subsidence are produced by N–S compression due to a combination of translation and underthrusting of the continental margin by oceanic crust at the Venezuela Basin (Biju-Duval et al., 1982b). According to Stienstra (1983), the rate of uplift of the Netherland Antilles Ridge off Venezuela during the last 500,000 years has been on the order of 10 cm/1000 years (0.1 mm/year).

Seismic data indicate that the dip of the Benioff Zone along the west coast of South America varies along strike from flat to moderately-inclined segments. Barazangi and Isacks (1979) proposed that the transitions between flat to dipping segments are marked by tears in the descending slab. Recent analyses of microearthquake data obtained with a local seismograph network yield no evidence for such tear faults, and Hasegawa and Sacks (1981) and Bovis and Isacks (1984) proposed that segmentation is achieved by flexures rather than tear faults. Uplift of the Benioff Zone is believed to result from the subduction of the Malpeno, Carnegie, Nazca, and Juan Fernandez aseismic ridges. They add buoyancy to the shallow-dipping plate segment that in turn uplifts the overriding South America plate. Where the northern edge of the Carnegie Ridge intersects the coast of South America at Tumaco the coast is rising at a rate of +2.1 mm/year, whereas in a structural low south of the high at Golfo de Guayaquil the land is sinking at rates of −2.2 (La Libertad) and −1.1 (Talara) mm/year. Uplift at Tumaco also may be the result of motion along the right-lateral fault that separates the North-Panama deformed belt at the west from the Sinu belt at the east. The region between the Carnegie and Malpeno ridges is subsiding at a rate of −1.0 mm/year (Buenaventura). Farther south in the vicinity of Nazca Ridge and the unnamed ridge at the south the coast is being uplifted at rates of +5.6 (Chimbote —Table 1, but confidence level too low for Fig. 1), +1.1 (Matarani), and +3.5 (Antofagasta) mm/year. The region between the ridges at Arica is subsiding at −2.1 mm/year and that between the unnamed ridge and the Juan Fernandez, Selkirk, and Mocha ridges (at Caldera) is subsiding at a rate of −2.3 mm/year. The rate of subsidence at Valparaiso where the Juan Fernandez Ridge is entering the subduction zone has decreased to −1.7 mm/year.

The next tectonic division (panel B of Fig. 3) consists of the east coast of South America. The tip of South America between lat. 37°S and Cape Horn may be a Paleozoic to Triassic accretionary wedge welded onto South America as a result of semi-continuous subduction of the ancestral Pacific plate from Middle Devonian to the Triassic (Forsythe, 1982; Fig. 2). As the wedge was accreted onto South America, the subduction zone migrated progressively westward, changing its trend from northwest to its present N–S one. Superimposed on this terrain is a mesozoic rift system formed during the separation of Africa and South America. Associated in time and space with these NNW-trending rifts is a Middle to Late Jurassic igneous event that affected an area of more than 1,000,000 km$^2$ (Güst et al., 1985). This region again experienced an extensive magmatic episode during the Quaternary (De Almeida et al., 1978). Proximity of the rift system to the subduction zone along the west coast may account for the magnitude of the igneous event. The tide-gauge recordings from the San Jorge basin (Comodoro Rivadavia) and Valdes Basin (Puerto Madryn and Piramides) display evidence of subsidence ranging from −4.0 to −2.4 mm/year.

Positive values (+1.8 mm/year at Quequén II, and +1.6 and +3.3 mm/year at Mar del Plata P and C) characterize the Ventana and Tandil highs. The Martin Garcia high in the Rio de la Plata estuary appears to be rising at a rate +1.4 mm/year at Colonia and is quite stable at Buenos Aires rising +0.1 mm/year, and sinking at a rate of −1.2 mm/year at Palermo. Montevideo along the southern edge of the Santa Lucia graben is relatively stable subsiding at a rate of −0.4 mm/year. Imbituba north of the Torres high, a half horst along the northern edge of the Torres syncline, appears to be sinking at a rate of −0.7 mm/year. Rio de Janeiro at the northern end of a coastal alkalic belt that was active between 72 and

51 m.y. ago (Herz, 1977) is sinking at a rate of −3.6 mm/year. Such subsidence may be thermal in origin. Rio de Janeiro also is on an E–W lineament that separates Santos basin at the south from Campos basin at the north. South of the lineament, basement descends rapidly from 1 to 5 km along a basement hinge (Leyden et al., 1971). Thus, subsidence in Rio de Janeiro also may be due to movement along the hinge. Canavieiras at the northern end of the Jequitinhonha basin where basement descends rather abruptly from 1.5 to 3 km below sea level is sinking at a rate of −4.1 mm/year. Salvador on the Salvador fault separating the Recôncavo basin to the west from the Salvador high to the east is sinking at a rate of −2.7 mm/year. The station at Recife at the eastern end of the right-lateral Pernambuco fault shows minor uplift of +0.2 mm/year. Along northern Brazil, where magmatic activity took place as recently as 30 m.y. ago (Ponte and Asmus, 1976), subsidence at a rate of −3.4 mm/year at Fortaleza may be thermal in origin. The Belem station, documenting minor subsidence at a rate of −0.3 mm/year, is on a structural low (Gorini, 1977) marked by continuing subsidence.

Data from the PSMSL can be compared with that reported by Brandani et al. (1985). With data extending over larger time intervals (from 1906 to 1984 for Buenos Aires, for example), Brandani et al. (1985) determined regression slopes significantly different from the present estimates. They determined slopes of −1.4 versus +0.1 mm/year at Buenos Aires, −1.8 versus +3.3 mm/year at Mar del Plata Club, −3.1 versus −2.4 for Puerto Madryn, and −7.4 versus −4.0 mm/year at Comodoro Rivadavia. Without having the Brandani et al. (1985) data to analyze, the authors cannot determine which data are more representative of long-term changes in relative sea level. This disagreement underlines the need for caution when interpreting short tide-gauge data from a geological perspective.

The tectonic province along Central America and the southern part of North America is addressed in panel C (Fig. 3). The negative value at Veracruz (land is sinking at a rate of −0.8 mm/year) is in Veracruz Cruz basin, a structural low south of the Trans-Mexican Volcanic belt, a seismically active trans-tensional left-lateral mega-shear that separates the allochthonous Yaqui and Maya West blocks (Martin and Case, 1975; Anderson and Schmidt, 1983). The mega-shear along which the Trans-Mexican volcanic edifices were constructed during the Quaternary may be an eastward prolongation of the Tamayo transform fault developed with the opening of the Gulf of California during the Pliocene (Aubouin et al., 1982). Although the volcanic lineament is separated from the Cocos plate by 400 to 600 km, and it is not parallel with the Middle America Trench, the calc-alkaline composition of the Trans-Mexican volcanics has led some scientists to associate the volcanic axis with the subduction of the Cocos plate (Aubouin et al., 1982). The positive (rising) value of +2.6 mm/year at Carmen in the Gulf of Campeche is on a structural high along the eastern margin of the Macuspana–Compeche basin (Locker and Sahagian, 1984). In contrast, a structural low between the Quintana Roo arch to the east and a high along the western side of the Yucatan peninsula (Viniegra, 1971; Locker and Sahagian, 1984) is characterized by submergence (−5.2 mm/year at Progreso). Progreso also was a site of igneous activity during the Late Cretaceous, so possibly subsidence here may be a product of thermal decay.

The southern terminus of the North American continent is along the Guatamala Transverse zone abutting the Caribbean nappes displaced by the Yucatan fault scarp near the eastern edge of the Quintana–Roo arch (Aubouin et al., 1982). Superimposed on this nappe complex is the seismically active Motagua fault zone along which Central America is being displaced eastward. Associated with this sinistral motion is noticeable horizontal displacement. For example, in the Guatemala earthquake of 1976 of magnitude 7.5 the average horizontal displacement of 108 cm along the Motagua fault was accompanied by vertical offsets of as much as 50% of the horizontal on the eastern end with the displacement down to the north (Plafker, 1976). Evidence of this uplift also can be seen in the Bay and Swan islands on the emergent crests of narrow ridges along the southern side of the Cayman Trough (United

States Geological Survey, 1967; McBirney and Bass, 1969). Vertical movements in the Bay Islands have caused uplift and southward tilting of the islands in very recent times. Puerto Cortés north of the Bay Islands and Puerto Castilla south of the islands are within the 150-km-wide northern boundary of the Caribbean plate. Puerto Cortés is along the Motagua fault. Pliocene-Quaternary strike-slip motion along this fault has created a series of horsts and pull-apart basins (Manton, 1987) comparable to the structures described by Crowell (1974) from southern California. Puerto Cortés on one of these lows is subsiding at a rate of $-8.9$ mm/year. Puerto Castilla south of the Bay Islands is along the La Ceiba fault (Manton, 1987), whose motion has fragmented the Honduran continental margin into a series of irregular ridges and basins (Pinet, 1975). Like the low at Puerto Cortés the one at Puerto Castilla is subsiding, at a rate of $-3.2$ mm/year.

Central America contains two allochthonous blocks, the oceanic Panama block at the southeast and the Chortis block or Nicaraguan Rise having continental affinities at the northwest. These blocks became attached to North America during the Mesozoic (Emery and Uchupi, 1984, and references therein). Final closure of the Central America Isthmus apparently occurred as recently as the late Pliocene (Keigwin, 1978). The oceanic Panama block (Costa Rica and Panama) consists of Pliocene–Quaternary volcanic edifices and oceanic terrains of Pacific origin thrust over the Caribbean plate (Bowin, 1975) deforming the sediments in front of it (Lu and McMillen, 1982). Present motion of the Panama block may be clockwise, with compression along the northern edge and translation along the southern boundary (Vitali et al., 1985). The northern edge of the block appears to be undergoing subsidence, with tide-gauge data at Puerto Limon and Cristobal recording rates of $-1.6$ and 1.1 mm/year respectively. Similar subsidence occurs on the Pacific side of the Panama block at Balboa ($-1.6$ mm/year) and Naos Island ($-1.4$ mm year). Tide-gauge results at Puerto Armuelles, near the edge of a collapsed segment of the Panama block, document minor uplift of $+0.3$ mm/year. The highest subsidence at a rate of $-6.5$ mm/year is recorded at Puntarenas, Costa Rica along the continental Chortis block. This region is on a graben (King, 1969) landward of the obducted ophiolitic Nicoya complex high composed of Late Jurassic (?) and Cretaceous rocks (Aubouin et al., 1982). Away from the obducted high at La Union subsidence is only $-1.0$ mm/year. Consumption of the Tehuantepec Ridge produces only slight offset of coastal structures with tide-gauge recordings at the Isthmus of Tehuantepec (San Jose) displaying only minor subsidence, at a rate of $-0.9$ mm/year.

The Caribbean tectonic province is the last province to be described (panel D of Fig. 3). Nicaragua Rise (Chortis block), eastern Cuba, and Hispaniola are sites of emergence. Elevated and tilted Pleistocene coral reefs and terraces in this part of the Caribbean attest to this emergence of the land (Horsfield, 1975, 1976). For example, the crest of the Cayman Ridge is uplifted toward the east with Misteriosa Bank at the western end of the ridge being at a depth of 30 to 40 m below sea level, Grand Cayman at an elevation of 20 m, and Cayman Brac farther east at an elevation of 40 m (Emery and Uchupi, 1984, p. 538). On Grand Cayman terraces range in elevation from 2 to 15 m (Emery, 1981). In Jamaica are seven terraces tilted southward with the highest ones on the north coast reaching an elevation of 180 m. On Navassa Island between Jamaica and Haiti is a terrace at 15 m elevation surrounding a Tertiary limestone plateau. In eastern Cuba, ten terraces reach elevations of 400 m and are tilted up northward; in western Haiti 28 terraces on which Pleistocene reef limestone are present rise as much as 500 to 600 m (Horsfield, 1975). In the Dominican Republic are five or six terraces that reach elevations of 300 m. The Windward Passage between Cuba and Haiti (having the greatest number and highest terraces) and the Hispanola Quaternary volcanic centers and rifts is the area of most rapid uplift. From here the terraces dip northward in Cuba, eastward along the Cayman Ridge and Hispaniola, and southward in Jamaica. This uplift is the result of translation and secondary subduction motions along the Cayman Trough, an uplift that $^{14}C$ measurements (Taylor, 1980) indicate is on the order of $+0.5$ mm/year along the north coast of Hispaniola. Uplift along the north coast of Hispaniola has exhumed a Paleogene subduction complex buried beneath Upper Eocene and Pleistocene sediments (Bowin and Nagle, 1983). Within this broad uplifted area are small isolated structural lows that are undergoing subsidence—such as Port Royal, Jamaica that is sinking at a rate of −0.5 mm/year, Guantanamo Bay in Cuba at a rate of −1.8 mm/year, and Puerto Plata at the north coast of Hispaniola at a rate of −4.4 mm/year.

Barahona at the south coast of the Dominican Republic is rising at a rate of +2.3 mm/year. It is south of the eastern end of the Enriquillo graben, a westward extension of the Muertos Trough. The sierras de Nieba and El Numero and San Cristobal basin north of the graben represent westward extensions of the tectonic accretionary wedge north of the trough (Biju-Duval et al., 1982a). Uplift of the region farther south may be due to collision of the Beata Ridge with the subduction complex. Subsidence of the Enriquillo graben has caused parts of the low to sink more than 200 m below sea level (Goreau, 1981). At its eastern end near Port-au-Prince the low is sinking now at a rate of −9.3 mm/year. In Puerto Rico both Magueyes Island in the south and San Juan in the north of the island are undergoing subsidence of −1.9 and −2.1 mm/year that is due to eastward motion of the Caribbean plate with respect to the Americas coupled with a small amount of convergence of the Americas (Ladd et al., 1977; 1981; Ladd and Watkins, 1979). According to Sykes et al. (1982), the relative motion of the Caribbean plate during the last 7 m.y. has been $3.7 \pm 0.5$ cm/year. Based on the 390-km length of the seismic zone and a thermal equilibrium of 10 m.y., Kellog and Bonini (1982) estimated that the Caribbean—South America convergence rate is on the order of $1.9 \pm 0.3$ cm/year. This convergence has been accommodated by deformation of the Caribbean plate producing a pattern of faults that resemble slip lines in a modified Prandtl cell (Cummings, 1976; Burke et al., 1978). Whereas the northern and southern coasts of Puerto Rico are sinking, the rest of the island is rising. This uplift is documented by terraces whose elevations range from 1.5 to at least 70 m (Kaye, 1959; Monroe, 1968; Weaver, 1968).

A basis for comparing the tectonic regions besides local reversals in direction of vertical movement is the average rates at which sites that are sinking most rapidly are moving. The seven fastest sinking stations of the Atlantic divergent margin average −3.3 mm/year; the six fastest of the mainly Pacific tectonized belt average −2.3 mm/year; and the six fastest of Central America and the Caribbean islands average −6.2 mm/year (Fig. 3). This kind of analysis is limited by the fact that the average dimensions of the blocks in all regions appear to be smaller than the average spacings between stations, a situation that is unlikely ever to improve.

### *Long-period trends examined by eigenanalysis*

Regression analysis of tide-gauge records has the advantage of being able to scrutinize each record on an independent basis, but the computed mean changes of level may be representative of different dates if the records are for different time spans. Eigenanalysis, on the other hand, has the capability of simultaneously comparing records from many sites in a region using parts of the records that have identical time spans, making allowance for gaps in the records, and identifying aberrant records (see Aubrey and Emery, 1986b). For this study we set a lower limit of 15 years for eigenanalysis (as compared with 10 years arbitrarily set for regression analysis). Data at some of the stations were found to differ enough from those at other stations that the 32 stations acceptable for regression analysis were reduced to only 18 for South America (including one, Colonia, that was unsatisfactory for regression), and the 23 stations for Central America and the Caribbean islands were reduced to 12. Expected differences in records from these two groups led to separate eigenanalysis for the groups.

The first three eigenfunctions plotted for the time span between 1940 and 1970 (Fig. 4) show that for South America the first, second, and third functions contain 40.2, 18.3, and 11.9 percent of the total energy of the fluctuations in level; those for Central America and the Caribbean islands have 50.8, 22.7, and 9.2%.

The results from synthesis of eigenfunctions

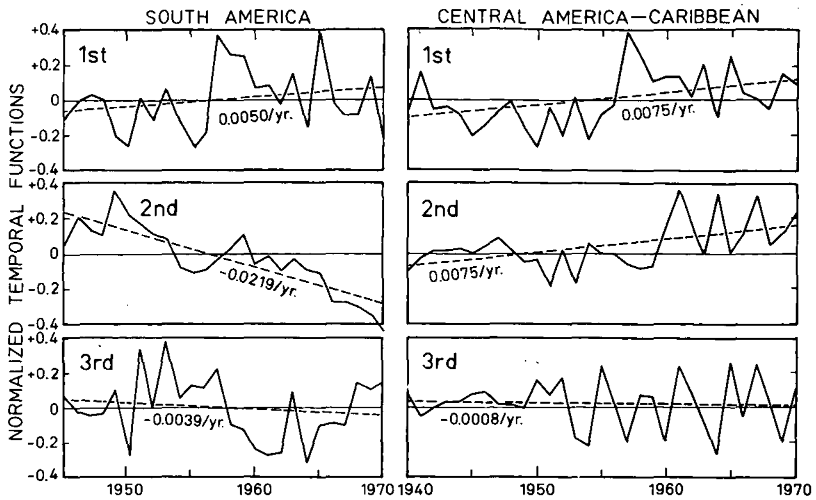

Fig. 4. Temporal eigenfunctions for the periods between 1945 and 1970 for South America and 1940 and 1970 for Central America and the Caribbean islands at eigenanalysis stations indicated on Fig. 3. Data for 1940–1945 were eliminated for South America because of sparsity.

plotted on Fig. 3 are less frequent than those obtained by regression, but they exhibit similar trends. In fact, the points from the few surviving tide-gauge stations are near those for the regression analysis, with differences caused mainly by the use of the sum of only the first three eigenfunctions (accounting for less than 100%) to compute the synthetic changes of level and because of biases introduced by the eigenanalysis methodology. Direct comparison of regression and eigen results reveals a scatter plot (Fig. 5) that is nearly symmetrical with the axis of a 1 : 1 correlation for both coasts of South America but contains much higher regression thus higher results for three Central American stations. Further comparison of results in terms of averages for different regions (Table 2) confirms Fig. 5 in showing faster subsidence of land by regression than by eigenanalyses.

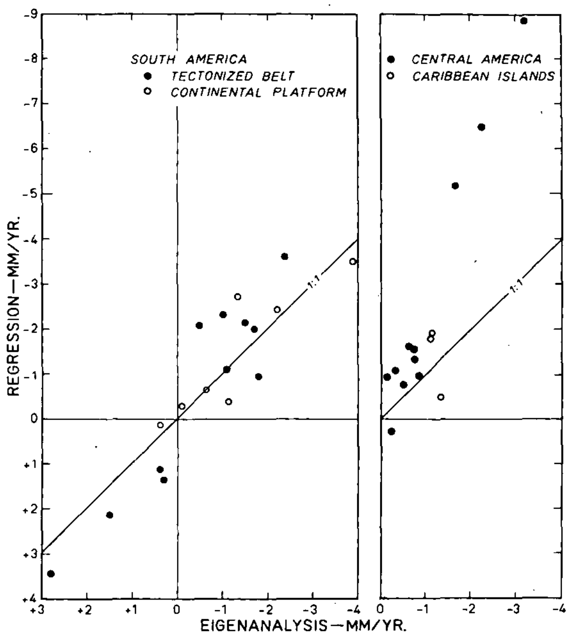

Fig. 5. Scatter plots for regression versus eigenanalysis where both were available for the same station. The 1 : 1 straight line is the relationship that would have existed if both methods of analysis had yielded identical results.

TABLE 2

Average annual change of relative land level

| | Regression * (mm/yr) | Eigenanalysis * (mm/yr) |
|---|---|---|
| Central America | | |
| Tectonized | −2.29 (13) | −1.03 (11) |
| Caribbean islands | | |
| Tectonized | −2.52 (7) | −1.19 (3) |
| South America | | |
| Tectonized | −0.83 (11) | −0.52 (10) |
| Basin or Platform | −2.15 (12) | −1.03 (8) |
| Massif | +1.69 (4) | (0) |
| Total Central American and Caribbean | −2.37 (20) | −1.06 (14) |
| Total South America | −1.05 (27) | −0.75 (18) |
| Overall total | −1.61 (47) | −0.89 (32) |

* Number of stations between parentheses.

These biases result from eigenanalysis of records having different durations.

Isostatic adjustment following Pleistocene deglaciation is a possible source of spatial differences in secular trends of relative sea levels. Clark et al. (1978) illustrated little spatial variability in isostatic adjustment compared with observed levels. Details of isostatic adjustment in South America in Clark et al. (1978) are lacking; more recent work (Peltier, 1986) does not clarify this data gap. Given the insufficient density of isostatic adjustment estimates in South America, we made no attempt to subtract these effects to calculate a residual signal.

## Conclusions

Secular trends differ from station to station mainly in rate but partly in direction of vertical movement of relative land or sea level. If tide-gauge data are assumed to represent change in relative sea levels, they must be recording mainly changes of land level that are large enough to obscure changes of sea level caused by additions to volume of the ocean produced by influx of new glacial meltwater or by heating of ocean water. Isostatic adjustment following Pleistocene deglaciation is another possible source of spatial differences in secular trends of relative sea levels. Clark et al. (1978) illustrated little spatial variability in isostatic adjustment compared to observed levels. Details of isostatic adjustment in South America in Clark et al. (1978) are lacking; more recent work (Peltier, 1986) does not clarify this data gap. Given the insufficient density of isostatic adjustment estimates in South America, we made no attempt to subtract these effects to calculate a residual signal.

The trends of secular changes of land level examined by both regression and eigenanalysis exhibit regional patterns that correlate with vertical movements of continental margins expected from tectonism associated with lateral movements of continental and oceanic plates. Widely-spaced tide-gauges and lack of adequate complementary elevation-change data preclude identification of tectonic movements without ambiguity. Data, however, correlate well with the tectonics of the region, having senses of relative motion that agree with other geological evidence. For instance, the complex spatial patterns of uplift and subsidence in the Caribbean region is reflected in the patterns of tide-gauge results and terrace elevations.

Tide-gauge records of Central America document the complex tectonics of plate boundaries in the form of volcanism, faulting, and transform motion. Western South American tide-gauge data correlate well with depth to the Benioff zone. High rates of uplift coincide with subduction of aseismic ridges; adjacent areas exhibit lower rates of uplift or even subsidence, as normal sea floor is subducted. The Atlantic coast of South America exhibits correlated patterns of relative motion, ascribed to varying terrains and possible thermal effects. Again, tide-gauge data correlate well with geological evidence for relative motion.

Tide-gauge data may exhibit some variability caused by uncertainties in datums. However, extensive screening by the PSMSL and the authors identified stations having obvious datum problems. Although a couple of stations having possible datum problems may remain, the overwhelming correspondence between tide-gauge data and geological evidence suggests this is not the case. Lacking independent measurements of relative land movement, however, we are left with some concern over the validity of these correlations. Future studies involving use of Very Long Baseline Interferometry and differential Global Positioning satellites may reduce the uncertainty in these correlations.

If the tectonic correlations are indeed correct, the use of tide-gauge records to separate unambiguously the movement of the land from the rise in ocean level is fraught with difficulty. If ocean level over the past half century has been rising at a rate of about 1 mm/year, as many workers have assumed, the movements of land level in South America must be even larger. The complex signature of tectonics clearly can be ignored no longer in studies of sea-level change.

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