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Coastal Uplift and Mortality of Coralline Algae Caused by a 6.3Mw Earthquake, Oaxaca, Mexico

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ABSTRACT

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Mortality of coralline algae proved to be a useful indicator of rapid coastal uplift produced by a strong shallow-focus earthquake. Because these encrusting algae can not survive desiccation, they can provide estimates of coseismic uplift. After the Mw 6.3, February 2, 1998, Puerto Angel earthquake, southern Mexico, a bleached white belt appeared along the Puerto Angel coast. We measured this white belt two weeks and, again, two months after the earthquake, when coralline algae had experienced low tide sequences. Detailed measurements at 15 sites allowed us to determine the extent of the uplifted coastal zone and to reconstruct the amount of coseismic uplift along the Puerto Angel coast. The width of the dead algal belt varied from 0.07 to 0.50 m. The largest observed values are related to local parameters (exposition to wave splash, geometric disposition, and morphology of the coast) that account for an amplification of the width of the dead algal belt. A detailed survey indicates that coastal coseismic uplift was recorded for ca. 70 km along the Oaxaca coast from Puerto Angel, which is near the epicentral area. The maximum coseismic uplift recorded 0.3 m at La Boquilla and Ixtacahuite, near Puerto Angel, and at Agua Blanca.

ADDITIONAL INDEX WORDS: *Coseismic uplift, tectonic deformation, crustose algae.*

CORALLINE ALGAE AND COASTAL UPLIFT

Mortality of intertidal organisms and upper subtidal algae has been used to document coastal uplift, particularly in the case of coseismic local deformation (PLAFKER, 1964; JOHANSEN, 1971; BODIN and KLINGER, 1986; ORTLIEB *et al.*, 1996, PELLETIER *et al.*, 2000). Coralline algae (family Corallinacaea) secret calcium carbonate in their cell walls, which confers to most of them the ability to encrust bedrock, hence their name of "crustose algae". They depend on light for photosynthesis, and thus are commonly found between intertidal and subtidal zone to a depth of about 100 meters (ADEY, 1986; LÜNING, 1990). Vertical zonation of intertidal species is determined by biotic and abiotic factors that are ultimately related to tidal cycles. The upper limit of the coralline belt is strictly determined as the area that never desiccates completely (Figure 1). Because of extreme sensitivity to desiccation, algae may die rapidly if subject to sudden desiccation even of short duration (LÜNING, 1990; ORTLIEB *et al.*, 1996).

Sudden uplift by earthquakes will, therefore, induce mortality among coralline algae and other intertidal organisms whose upper limits are determined by duration of emergence at low tide. The death of algae is commonly accompanied by whitening (bleaching) of the dead material producing a white belt that contrasts sharply with the reddish or pink encrustment of living algae immediately below (JOHANSEN, 1971; LEBEDNIK, 1973; ORTLIEB *et al.*, 1996). This white belt of dead coralline algae, which is formed within a few days following the earthquake, may be visible for weeks or a few months (PLAFKER, 1964; BODIN and KLINGER, 1986; ORTLIEB *et al.*, 1996). The width of the white belt, measured from the elevation differences between the upper limits of the living and the dead organisms, indicates the extent of the resultant mortality. This width reflects the magnitude of the local vertical component of tectonic deformation.

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THE PUERTO ANGEL MW 6.3 EARTHQUAKE

The Puerto Angel earthquake of February 2, 1998, with a magnitude 6.3 Mw, a depth of 16 km, and an epicenter located near the Puerto Angel coast, ruptured a portion of the northeastward dipping thrust fault lying between the Cocos Plate and the North American plate, (Figure 2). Fourteen magnitude 4.0–4.7 aftershocks were produced within a week of the main shock (SERVICIO SISMOLÓGICO NACIONAL, 1998). Several major earthquakes M>7 have occurred within the borders of Oaxaca during this century (KOSTOGLODOV and PONCE, 1994). The Puerto Angel earthquake occurred within the rupture zone of the November 29 1978, M = 7.6 earthquake. We estimated the rupture zone area using: $\log S = M - 4.0$, where S is the ruptured area in km^2, and M the magnitude (Mw). The rupture zone was about 20 km long and 12.5 km wide, with an ellipsoidal form ratio ~ 1.6 earthquake (Figure 2).

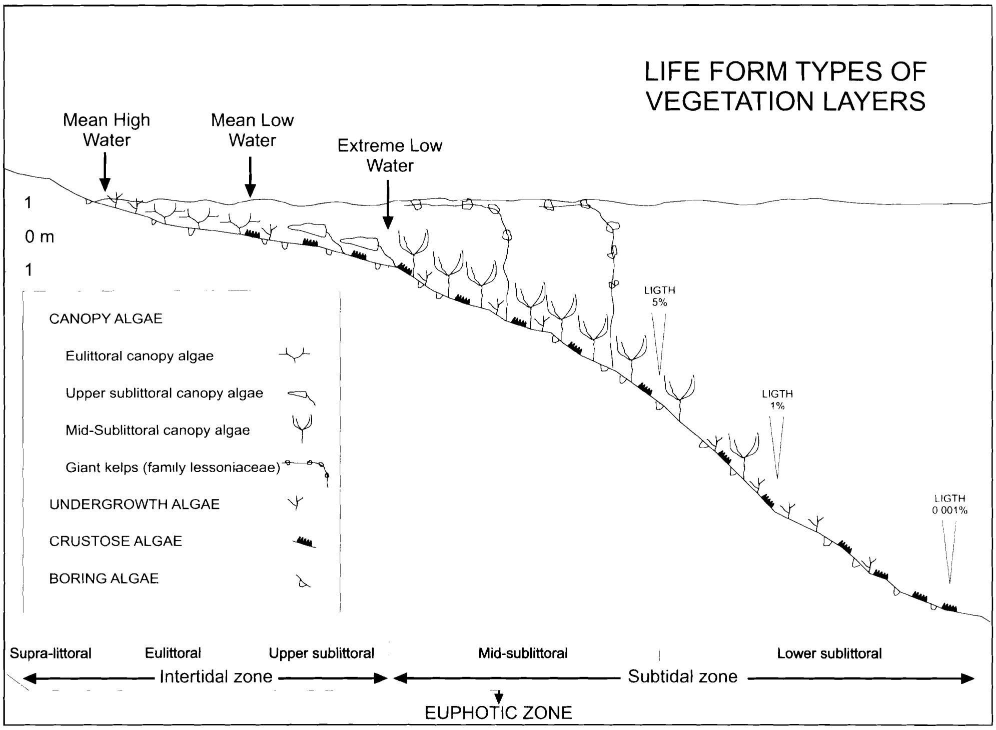


Figure 1. Scheme of algal life form types and their distribution within the euphotic zone. Crustose coralline algae depend on light for their photosynthetic activity, and thus are commonly found between intertidal and subtidal zone to a depth of about 100 m or even deeper. The upper limit of the coralline belt is strictly determined as the area that never desiccates completely. As the algae are extremely sensitive to desiccation, they may die rapidly if subject to sudden desiccation even of short duration. The deepest crustaceous red algae may be found at 268 m or at 0.001% of surface light (Scheme modified from LUNING, 1990).

THE PUERTO ANGEL COAST AND CORALLINE ALGAE

Local fishermen and residents of Puerto Angel, Oaxaca, reported the appearance after few days of the earthquake of a white belt along the Puerto Angel rocky coast. In Puerto Angel and surrounding rocky shorelines of Oaxaca, coralline algae are abundant in the shallow subtidal and intertidal zone. However, despite their wide representation on the Oaxaca coast there was practically no published pre-earthquake information on the taxonomy and ecology of coralline algae for the southern Pacific coast of Mexico. C. Mendoza and L. Mateo (Escuela Nacional de Ciencias Biológicas, IPN) investigated the taxonomy of algae that we collected along the Oaxaca coast and provided us with identifications. We used information on the ecology of the identified algae for other parts of the world (STEPHENSON and STEPHENSON, 1972; BAKUS, G. J., 1975; STENECK *et al.*, 1991; GORDON *et al.*, 1976; STENECK, 1986; GARCIA PAMANES and CHEE BARRAGAN, 1976; FRAGOSO TEJAS, 1999; DETHIER, 1987; LEHMAN and TUNNEL, 1992; DIXON, and IRVINE, 1977; ABBOTT, and HOLLENBERG, 1976) to estimate the vertical zonation of coralline and other crustose algae in the study area.

Several algal species of the family Corallinaceae were most abundant in the study area. These are: *Jania pacifica, Hydrolithon samoence, Lithophyllum imitans, Titanoderma pustulatum, Hydrolithon farinosum.* Also abundant are the species *Hildenbrandia* sp., and *Hildenbrandia rubra* (family Hildenbrandiaceae). These algal species normally live in the range of shallow subtidal to the intertidal zone. Although still attached to the rocky shore, coralline and other crustose algae collected in the study area were weathered and abraded by wave erosion, and were completely discolored. Some of the coralline species (*Hydrolithon farinosum, Jania pacifica,* and *Lithophyllum imitans*) were covered by epiphytes (*Acrochaetium microscopicum, Xenococcus acervatus, Dermocarpa hemisphaerica, Hydrolithon farinosum*) and endophytes (*Stylomena alsidii, Blennothrix, Chlorogloea, Xenococcus, Pseudoanabaena,* and *Pleurocapsa enthophysaloides*) indicating that coralline algae were found in conditions inadequate for their development that could be caused by coastal emergence or exceptional low tide stands. Mean tidal range is 52 cm and maximum (extreme) tidal range is 184 cm at the Puerto Angel shore.

METHODS USED TO ESTIMATE COASTAL UPLIFT

Vertical displacements in the Puerto Angel coastal area were determined from measurements of the upper growth and upper death limits of coralline and other crustose algae relative to sea level along the intricately embayed rocky coast. The difference in these vertical elevations (*i.e.* the

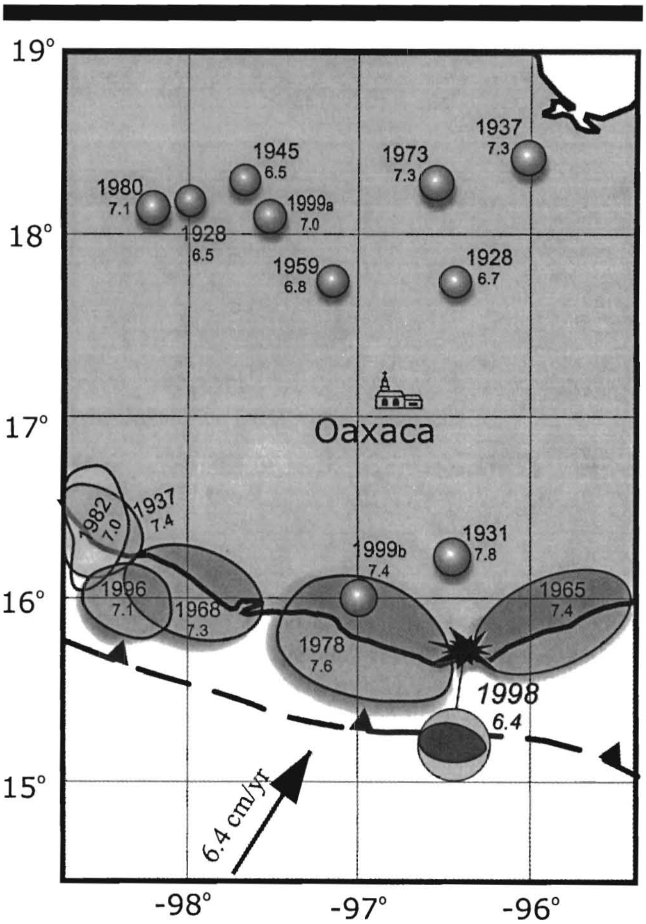


Figure 2. Seismicty of Oaxaca. The Puerto Angel earthquake of February 2, 1998 (Mw = 6.3, depth = 16 km) ruptured a portion of the northeastward dipping thrust fault lying between the Cocos Plate and the North American plate. Major earthquakes M ≥ 6.5 have occurred within the borders of the Oaxaca state during this century. Earthquake magnitudes are shown as surface magnitudes (Ms), and the 1998 earthquake is shown in moment magnitude (Mw). Circles indicate location of earthquakes, filled ellipsoids show rupture zones. Fault-plane solution shows a thrust faulting earthquake.

width of the dead algal belt) reflects the amount of coseismic coastal uplift. Detailed accounts of the method can be find in PLAFKER (1964), BODIN and KLINGER (1986), and in ORTLIEB *et al.* (1996).

We surveyed the epicentral region related to the February 2, 1998 Puerto Angel earthquake in two field seasons, two weeks and two months after the earthquake occurrence, when the dead algal belt was visible and when coralline algae had experienced low tide sequences. The survey had to be performed during maximum low tide, which limited our field work to a few hours each day. We made measurements along the shore except in those places where cliffs, heavy surf, or braking waves prevented boat landing or where the upper growth limits were not well-defined, or on sandy shores where no evidence was left. The total surveyed shoreline extends for about 128 km

We used the presence, or absence, of the white belt of dead algae and the width of this belt to determine the extent of the uplifted area and the amount of coseismic uplift. The width of the dead algal belt along the coast was almost uniform. However, some areas showed lateral variations up to 40% within a few tens of meters. These variations were mostly caused by the degree of exposure to strong waves and the resulting wave splash, which, in turn, is related to differences in the orientation of the coast and to variations in microtopography. Local geometric and microtopographic variations at each locality were considered when evaluating the amount of coastal uplift, applying a series of criteria established by ORTLIEB *et al.* (1996). We measured the width of the dead algal belt with a tape measure along vertical surfaces and with a centimeter-scale stadia rod along sloping surfaces.

RESULTS

We measured the dead algal belt at 15 sites along the Oaxaca coast (Figure 3). Eleven of fifteen measured values satisfy quality criteria (ORTLIEB *et al.*, 1996). Although of lower quality, four values are the only evaluations possible on the extent of coralline algae mortality at those sites. They are from localities where the shore was exposed to splash effects, or to areas where the limits of the dead algal belt were not clearly defined, or they were made before or after maximum low tide.

Our results demonstrate that the uplift produced by the Puerto Angel earthquake was limited to an area between Agua Blanca and Palo Santo (Figure 3). West of Agua Blanca, there was no evidence of algae mortality. We made observations farther east, as far as El Arrocito, on the Huatulco bays; however this area did not show a clear dead algal belt. Our easternmost site, Palo Santo, is highly exposed to wave action and lacked clearly defined parallel dead algal belt, leaving some doubts regarding the extension toward the east of the uplifted area. Evidence of widespread algal mortality was very obvious at La Boquilla, Ixtacahuite, and at Agua Blanca (Figure 3). The width of dead algal belt ranged from 0.07 up to 0.50 m along the surveyed area. The largest observed values are related to local parameters (wave splash, geometric disposition, and coastal morphology) that account for an amplification of the width of the dead algal belt.

The dead algal belt at La Boquilla (site 6) was 26 to 40 cm wide (32 cm mean value). The higher value corresponds to an exposed area where the upper limits of the dead and the live organisms are not parallel (Figure 4.a). Values of 30 cm are considered most representative because they are from areas protected from wave splash (Figure 4.b). The extent of algae mortality decreased to the east and west of La Boquilla. To the west, at Ixtacahuite, the shore forms two half-moon bays. The cliffs of the eastern bay face to the southwest and are highly exposed to the action of strong waves. This shore effect is associated with a dramatic increase in the dead algal belt, with measured widths up to 100 cm and a mean value of 64 cm. In contrast, on the shore at the more protected western bay at Ixtacahuite (site 9), the belt was 12 to 37 cm wide (19 cm mean value) (Figure 5).

At Puerto Angel (site 17) beach access was difficult because of rocky cliffs, but boulders long the shore showed a distinct

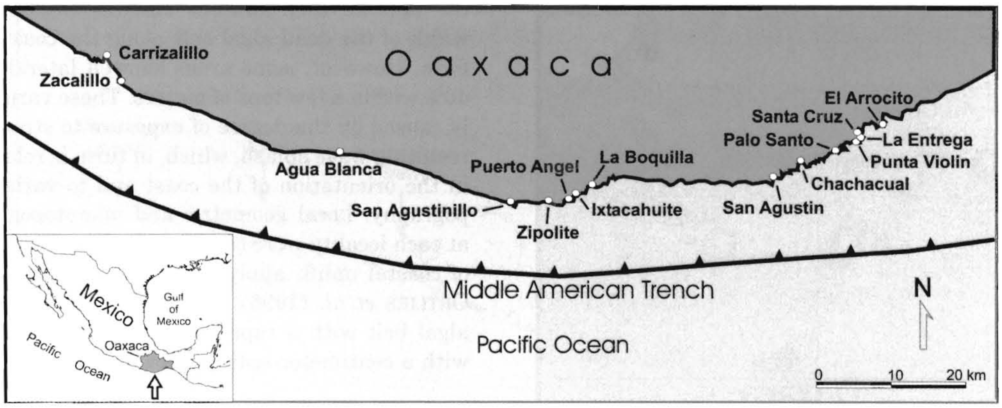
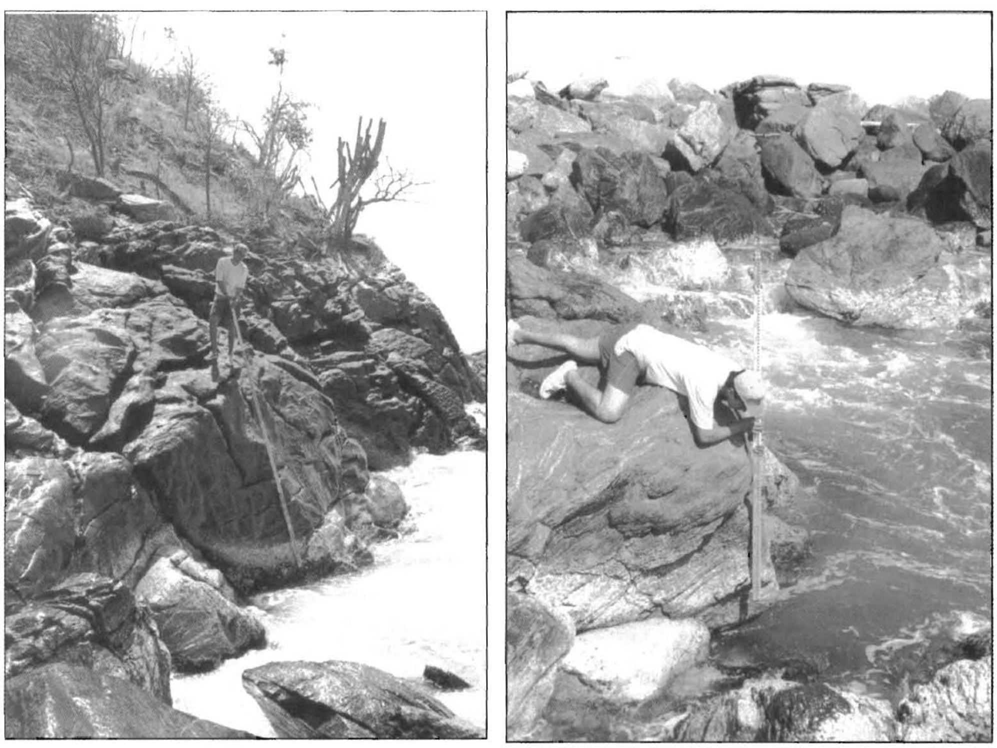


Figure 3. Surveyed region related to the 6.3Mw Puerto Angel earthquake. Total coastal area surveyed is ca. 128 km long, between Carrizalillo and El Arrocito. Scattering of measurements is produced by the absence of rocky shores along the coast. Insert shows location of study area within Mexico.

dead algal belt exposed above mean sea level. Although inaccessible the Puerto Angel pier showed a band of dead oysters. At Puerto Angel measured values ranged from 11 to 23 cm (16 cm mean value).

At Zipolite (site 3), strong waves prevented us from measuring the dead algal belt although it was present. Farther west, along the San Agustinillo shore (site 10), most rocky cliffs are exposed to wave action; nevertheless, the white belt was well-defined and continuous with measured values ranging from 7 to 20 cm. At Agua Blanca, west of San Agustinillo (site 4), the dead algal belt was conspicuous and up to 40 cm wide (Figure 6). However, here the shore was highly exposed



A B

Figure 4. Dead algal belt at la Boquilla: a) differences in exposure and microtopography increase the width of dead algal belt as illustrated in this picture; b) dead algal belt exposed above mean sea level. Stadia rod is in centimeter scale.

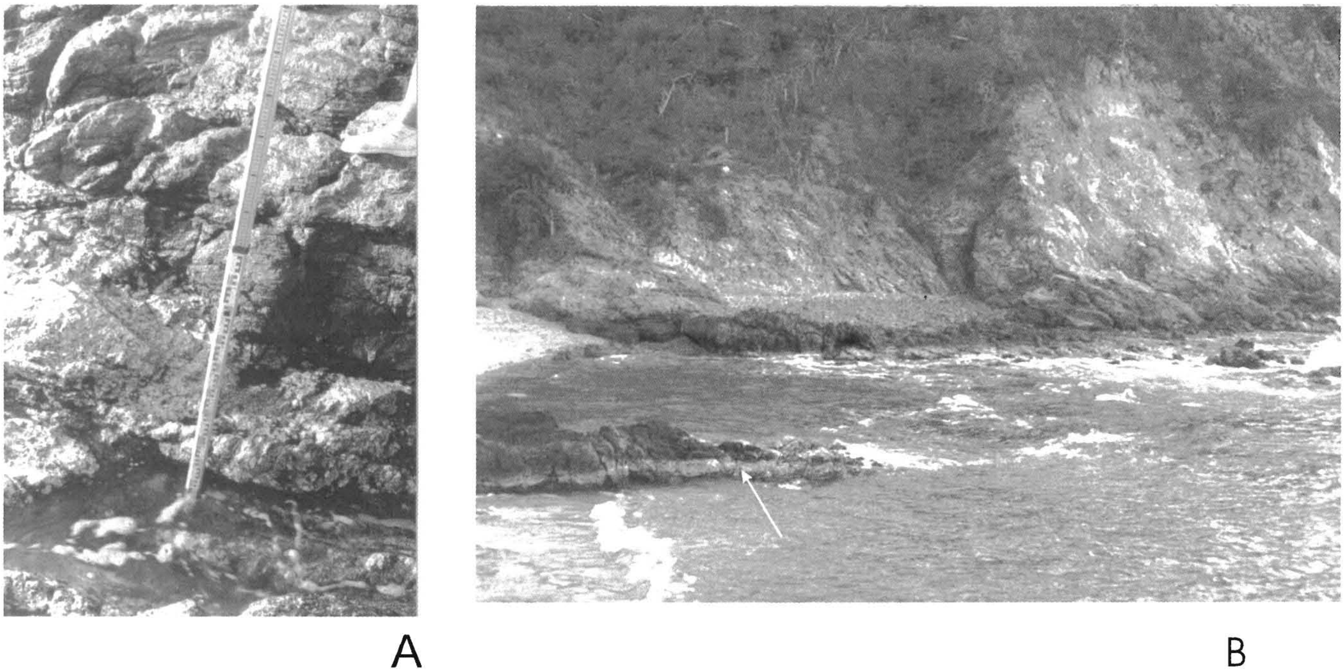


Figure 5. Dead algal belt at Ixtacahuite: a) Detail of the dead coralline algal belt at Ixtacahuite. Measurement precision is 1 cm; b) Parallel white belt of dead algae exposed on a relatively protected shore at Ixtacahuite.

and we only consider the lower values (30 cm) measured in protected areas to be representative. At the westernmost end of the area, at Zacalillo and Carrizalillo, coralline algae were present, but there was no white dead algal belt. This observation suggests that uplift was minimal, perhaps less than a few centimeters, or not at all.

East of La Boquilla, at San Agustin and Chachacaual (site 7 and 16) there was no clear dead algal belt, but further east, at Palo Santo (site 12) we found visible patches and in few areas a more continuous dead algal belt. The rocky cliffs on this shore are highly exposed to wave action and the dead algal belt, up to 30 cm in width, is not parallel. However, in nearby protected areas the dead algal belt was 11 to 15 cm wide. At the locality farthest east of Palo Santo, El Arrocito, the only evidence of recent vertical motion was small patches of a discontinuous light pink belt and a yellow-greenish belt. The yellow-greenish patches were identified as new colonizing cyanophyte algae. We suggest that El Arrocito bay was located at the eastern limit of the coseismically deformed region. Further to the east of El Arrocito at Tangolunda bay, no evidence of uplifted coralline algae was found.

Figure 6 summarizes the distribution and amount of uplift (mean values) estimated from the dead coralline algal belt. We have used mean values only to graphically represent the

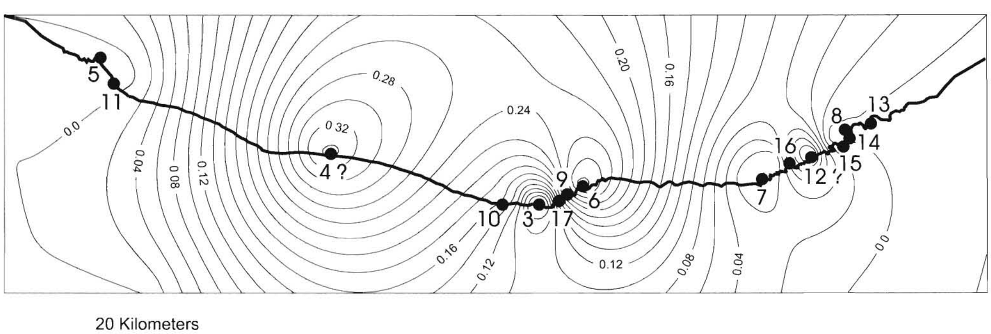


Figure 6. Distribution of coastal uplift. Coseismic deformation produced by the Puerto Angel earthquake is limited to an area between Agua Blanca and Palo Santo. Maximum uplift occurred at La Boquilla (site 6) and Agua Blanca (site 4). Sites are indicated in bold numbers, isolines show uplift values in meters (See text for site numbers).

width of the dead algal belt along the Oaxaca coast. Plotted values are conservative estimates of absolute uplift. Only values that might best represent the uplift were plotted. We did not include values for localities highly exposed to waves and splash effects. The plotted values indicate a maximum uplift of 0.3 m at La Boquilla, near Puerto Angel, and at Agua Blanca. Uplift represented by coralline algae mortality extended 33 km west of Puerto Angel. We are unsure about the precise location of the eastern limit of the uplifted area; however, we estimated it as approximately 38 km east of Puerto Angel. Values of uplift vary along the coast, suggesting greater vertical motion at sites located nearest to the epicenter. Differences in vertical motion might indicate that the rupture zone is shallower under La Boquilla-Agua Blanca, and that local faults in the overriding plate were reactivated. However, further research is necessary to confirm the presence of local faults.

CONCLUSIONS

Vertical motions that produced coastal uplift and could be recorded by the extent of coralline algae mortality accompanied the magnitude 6.3 Mw Puerto Angel earthquake. A white belt, formed by the sudden death of the algae, appeared along the Oaxaca coastline, and was visible after a few days and for at least two months after the earthquake. The width of the belt varied along the coast. It best represented the amplitude of vertical deformation long protected coasts. Values at areas more exposed to strong wave action record wave splash, as well as coseismic uplift.

Interpretation of the amount of coastal uplift is based on the most representative values of the width of dead coralline algal belt. A few values might be underestimated because the white belt may have already being partially covered by colonizing *cyanophyte* that appeared two months after the earthquake. The hypothesis that coralline algae mortality was produced by extremely low tides is rejected, because we surveyed localities when coralline algae had experienced low tide sequences. Therefore, the dead coralline algal belt reliably recorded the uplift that occurred on the coast as result of the 1998 Puerto Angel earthquake. It is likely that most of the observed uplift occurred coseismically. However, postseismic readjustments might be responsive for part of the observed values.

Values for the width of dead coralline algal belt indicate that maximum uplift occurred at La Boquilla, near Puerto Angel, and at Agua Blanca. The uplift extended 33 km west and approximately 38 km east of Puerto Angel. The presence of the dead algal belt at most sites along the coast and its generally uniform width indicate that the magnitude of uplift is well represented by the belt of dead coralline algae.

No tide gauge or pre-and post-earthquake GPS data were available for this study. However, the presence of marine terraces at the Puerto Angel, Carrizalillo and Agua Blanca indicates long-term coastal uplift and might represent residual uplift from large earthquakes produced periodically on the underlying megathrust in southern Mexico. However, because there are no published ages for the marine terraces, uplift rates during the Pleistocene-Holocene can not be determined.

We demonstrate that an earthquake with a moderate magnitude (Mw 6.3) and shallow epicenter ($\sim$ 16 km) was capable of producing significant uplift along the coast of Oaxaca. The mortality of coralline algae proved to be a reliable indicator of coastal uplift.

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□ RESUMEN □

La mortalidad de algas coralinas se utilizó como indicador del levantamiento rápido de la costa, producido por un sismo con foco somero. Debido a que estas algas costrosas no sobreviven a largos periodos de desecación, pueden proporcionar una idea sobre el levantamiento cosísmico. Después del sismo de 6.3 Mw, del 2 de febrero de 1998, en Puerto Angel, Oaxaca, apareció una franja blanca a lo largo de la costa. Las mediciones de detalle en 15 sitios nos permitieron determinar la extensión de la costa emergida y la magnitud del levantamiento cosísmico a lo largo de la costa de Oaxaca. El ancho de la franja de algas muertas varía de 0.07 a 0.50 m. Los valores mayores corresponden a los sitios con parámetros locales (exposición al efecto del rompimiento de las olas, la disposición geométrica y la morfología de la costa) que amplifican el ancho de la franja de algas muertas. El reconocimiento detallado indica que el levantamiento cosísmico fue registrado ca. 70 km a lo largo de la costa de Oaxaca, alrededor de Puerto Angel, ubicado cerca de la zona del epicentro. El máximo levantamiento cosísmico regristrado es 0.3 m en La Boquilla y en Ixtacahuite, cerca de Puerto Angel, y en Agua Blanca.