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COSEISMIC COASTAL UPLIFT AND CORALLINE ALGAE RECORD IN NORTHERN CHILE: THE 1995 ANTOFAGASTA EARTHQUAKE CASE

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Abstract — Coralline algae that may be predominant in the upper part of the infralittoral zone along rocky shorelines proved to be a useful indicator of rapid coastal uplift. As these encrusting algae cannot survive desiccation, even for short periods at low tide, they can provide estimates of positive vertical motions like those which may accompany seismic events. The desiccation of a fringe of the algal encrustment, at the base of the intertidal area (=infralittoral fringe), combined with effects of solar radiation rapidly kills the organisms. This mortality results in a conspicuous alteration of the pigmentation from pink/beige/reddish to white. After the July 30, 1995 Antofagasta earthquake (M_w 8.1), in northern Chile, such a white fringe appeared in some parts of the bay of Antofagasta and surroundings. The width of the dead algae fringe varied from 0 to more than 1.8 m. The widest observed widths are related to local parametres (exposition to wave splash, geometric disposition) that account for an amplification of the width of the dead algae fringe, and must be identified. Thus, a careful study of each locality led us to determine the extent of the coastal areas that had been uplifted, and to reconstruct, with a precision of the order of 2 cm, the amount of the vertical deformation along the Antofagasta Bay and southern Mejillones Peninsula.

It was thus shown that the coastline bordering the town of Antofagasta suffered practically no coseismic uplift, while areas to the south and to the west of Antofagasta Bay proved to have been uplifted by as much as 25 and 40 cm, respectively. The maximum uplift (80 cm) was seen at the southwestern tip of the peninsula of Mejillones. These precise reconstructions are of great help for the calibration of geodetic studies performed independently and for the modelling of the coseismic deformation at a regional scale. Copyright © 1996 Elsevier Science Ltd

CORALLINE ALGAE AND COASTAL INSTABILITY

For almost one and a half centuries (Darwin, 1846), intertidal organisms and upper subtidal algae have been used, although not systematically, to document coastal uplift, particularly in the case of coseismic motions (Plafker, 1964; Johansen, 1971; Lebednik, 1973; Bodin and Klinger, 1986). In Chile, studies performed in relation to the 3 March 1985, M_s 7.8 earthquake focused on the post-seismic displacement of cirripeds, molluscs and kelp algae (*Lessonia nigrescens*), giving major importance to the subsequent reorganisation of the vertical zonation in the intertidal area (Castilla, 1988; Castilla and Oliva, 1990). In these papers there was only a brief mention of the death and bleaching of 'lithothamnioid algae' that preceded the downward shift of the lower level of kelp beds (*L. nigrescens*). It must be noted that for the March 1985 Chilean earthquake, unlike the cases of the Alaskan (Plafker, 1964; Johansen, 1971) and Mexican (Bodin and Klinger, 1986) earthquakes, coralline algae were not actually used to evaluate the amount of coseismic uplift.

The group of coralline algae pertain to the Corallinacaea family (Rhodophyta, Cryptonemiales). This family is characterised by the presence of calcium carbonate in the cell walls that confers to most of the genus the possibility to encrust bedrock, hence their other name of 'crustose algae'. Their latitudinal distribution is very wide, from polar seas to the Equator (Littler, 1972). The tropical species associated with coral reefs are probably the best known, but the group is represented by many genus and species in temperate and cold oceanic environments as well. As algae, they depend on light for their photosynthetic activity, and thus are commonly found between the intertidal zone downward to a depth of the order of 100 m or so. In terms of vertical zonation, in many coastal areas the most common genus found in the uppermost subtidal area are *Porolithon* and *Neogoniolithon*, while the genus *Lithothamnium*, *Mesophyllum* and *Archaeolithothamnium* are dominant at greater depths (50–80 m; Adey, 1986).

Coralline algae are known under a variety of names: Corallinacea, Melobesioids, crustose algae, lithothamnium s.l. (or 'lithothamnion'). Not many authors are able to differentiate the distinct subfamilies, genus and species within this family (e.g. *Lithophyllum* spp., *Pseudolithophyllum* spp., *Mesophyllum* spp., *Porolithon* spp., etc.). The determination of specimens, even at the generic

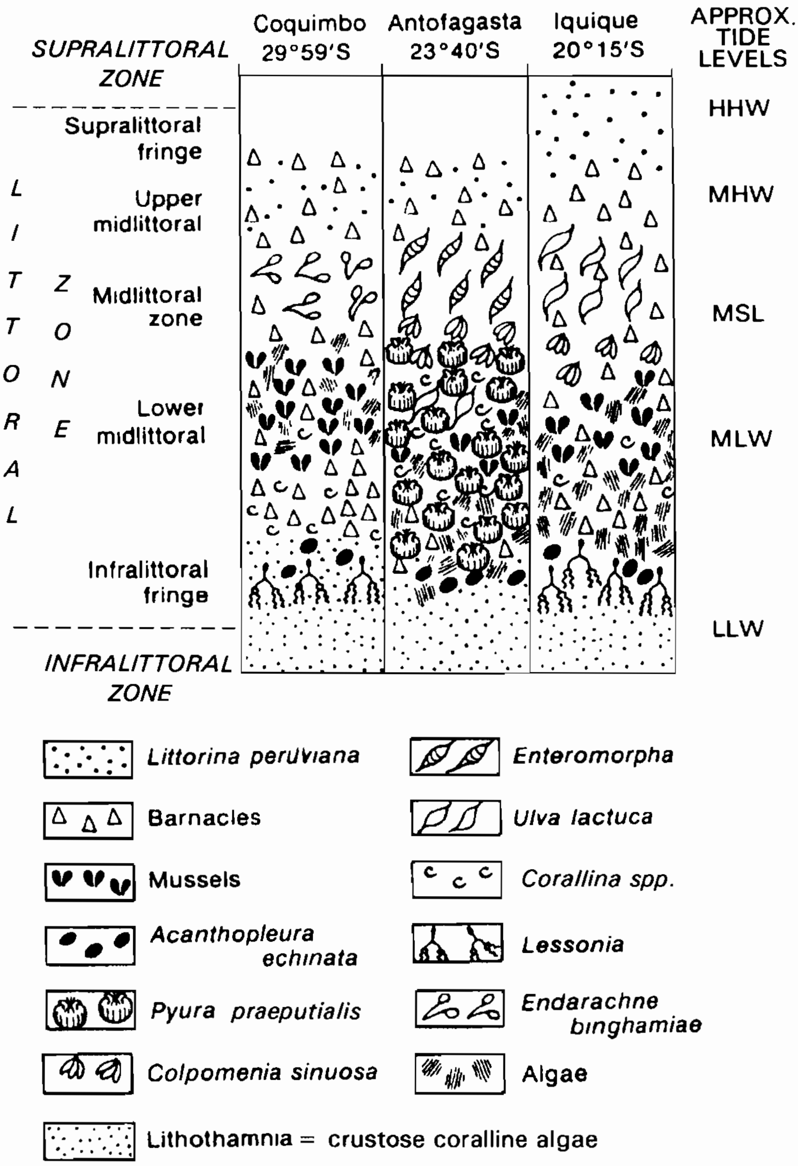

FIG. 1. Sketch of the biological vertical zonation of the littoral area in northern Chile (including Antofagasta), modified from Guiler (1959) and Stephenson and Stephenson (1972) with indication of the tidal levels (only valid in quiet and protected areas).

level, cannot be made in the field and normally requires ground sections and scanning electron microscope analysis. The taxonomic identification is based on the cell size, location of heterocysts, type of hypothallium, presence and diameter of multispored conceptacles and/or sporangial sori size (Johansen, 1971; Adey and Johansen, 1972; Adey, 1986; Meneses, 1986).

In a review on the studies concerning this group, Meneses (1986) emphasised that, in spite of their wide representation along the Chilean coasts, practically no taxonomic studies had been conducted (except in the Magellan region, to the south, at the beginning of the century) and that much work was still needed to understand the ecology, distribution and characteristics of each species along the Pacific coast of South America. This implies that nowadays it is practically impossible to identify the distinct species of coralline algae in Chile.

In central and northern Chile, the coralline algae are abundant and may form a belt at the limit of the intertidal and subtidal zones (Guiler, 1959; Stephenson and Stephenson, 1972; Meneses, 1986). In the area of Iquique (20°S), Guiler (1959) distinguished, without identifying them, 'three obvious species of *Lithothamnia*, a purple-red coloured species, a deep red and a pink, the latter being the most common'. In the area of Antofagasta, where rocky shorelines are predominant, coralline algae are abundant in the subtidal zone and in the lowermost ponds and hollows of the intertidal area (Fig. 1). Their presence is apparently weakly controlled by the lithology of the rocky substrate, since they grow without visible differences on volcanic rocks (La Negra Formation), granite (Bolfin Formation) or conglomerates (Caleta Coloso Formation). Much more important is the exposition to the wave action, as indicated by most authors (e.g. Adey and Vassar, 1975; Raffaelli, 1979; Johansen, 1971). The water motion plays a role in the calcification process, and also in the protection from some grazers and/or in limiting the competition with other organisms. The upper limit of the coralline algae belt is strictly determined as the area which never desiccates completely. Because of splash action, this level may be several cm, or dm, above the lowest tide mark. Furthermore, the survival of the algae does not require submergence, but (at least) permanent wetness. Well-exposed areas that are almost permanently subjected to strong waves (all year long), and where the biological zonation is displaced upward, may thus exhibit an upper limit of the algal belt that stands significantly higher than the mean low water mark. In general though, along most of the protected sectors of the coastline, this upper limit is found near, or slightly above, the mean low water line At Antofagasta, the tides are of the mixed semi-diurnal type, the mean tidal range is about 0.8 m, with extremes of 0.6 and 1.6 m.

The well defined upper limit of the coralline algae belt in the Antofagasta area often coincides with the lower limit of extension of the *Pyura praeputialis*, an endemic species of ascidians (Chordata) only found in the bay of Antofagasta (Guiler, 1959; Gutierrez and Lay, 1965; in both ref., *P. praeputialis* is erroneously identified as *P. chilensis*, an infralittoral species). In the areas most exposed to the ocean swell, particularly on the southern and western coast of Mejillones Peninsula, kelp algae are abundant, and a near coincidence is observed in the respective upper limits of the coralline algae belt and that of *L. nigrescens*. Both algae can be used to define the limit between the sublittoral zone and the infralittoral fringe (Fig. 1).

The line which is defined by the top of the coralline algae belt in the infralittoral fringe provides one of the most precise bioindicators related to sea level in that region. Actually this line, perfectly horizontal in the open protected environments, is so well defined that it can be used to evaluate the amplitude of exceptional low tide stands and of sudden uplift motions produced by seismic activity. As the algae is extremely sensitive to desiccation, it may die rapidly if subjected to sudden desiccation, even of short duration (i.e. an hour or so, during the low tide hemicycle). The death of the algae is commonly accompanied by a whitening of the dead material. The decolouration of the algal material is most probably due to solar radiation effects (bleaching) on the strong pigmentation of the coralline algae. Thus, the desiccation of a few centimetres of the upper part of the coralline algae belt produces a white fringe (of the corresponding width) that contrasts sharply with the reddish or pink encrustment of living algae immediately below.

The conspicuous white belt of dead coralline algae that can be formed immediately after an uplift episode, appears in the few days following the seismic event, and may be visible for weeks, or a few months. We used this bio-indicator to quantify uplift motions related to the 30 July, 1995 Antofagasta earthquake. Moreover, we address some of the problems in reconstructing the amplitude of the vertical motions.

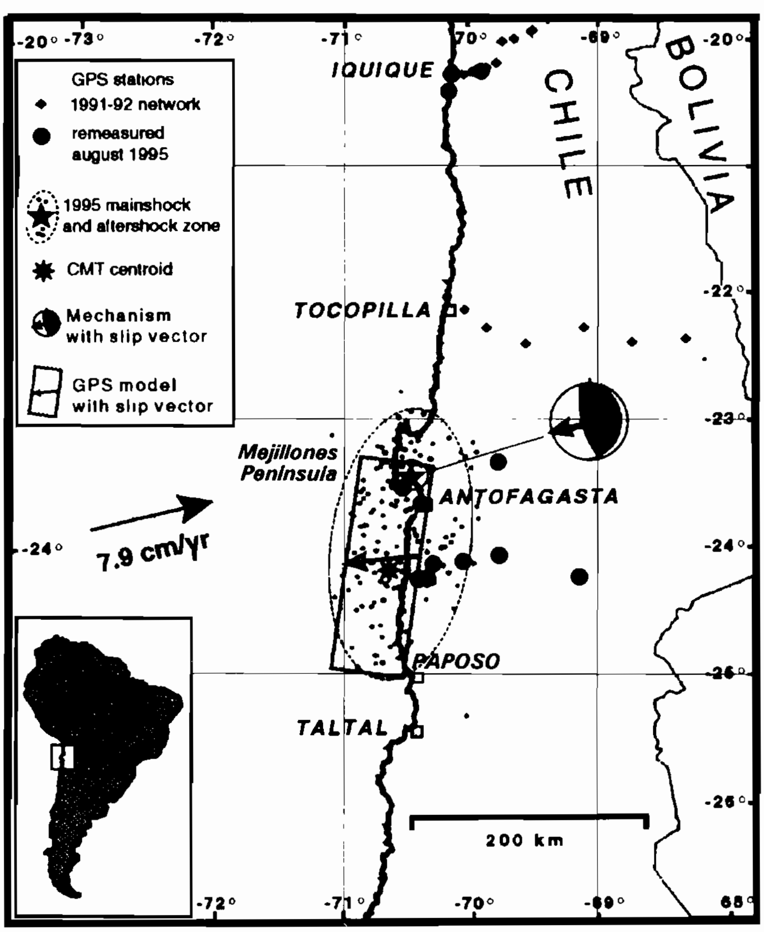

FIG. 2. The 30 July, 1995 Antofagasta earthquake: extension of the rupture, focal mechanism and distribution map of the aftershocks, simplified from Ruegg *et al.* (1996). The rectangle represents the best uniform slip model satisfying observed deformation field based on GPS measurements (see Fig. 3).

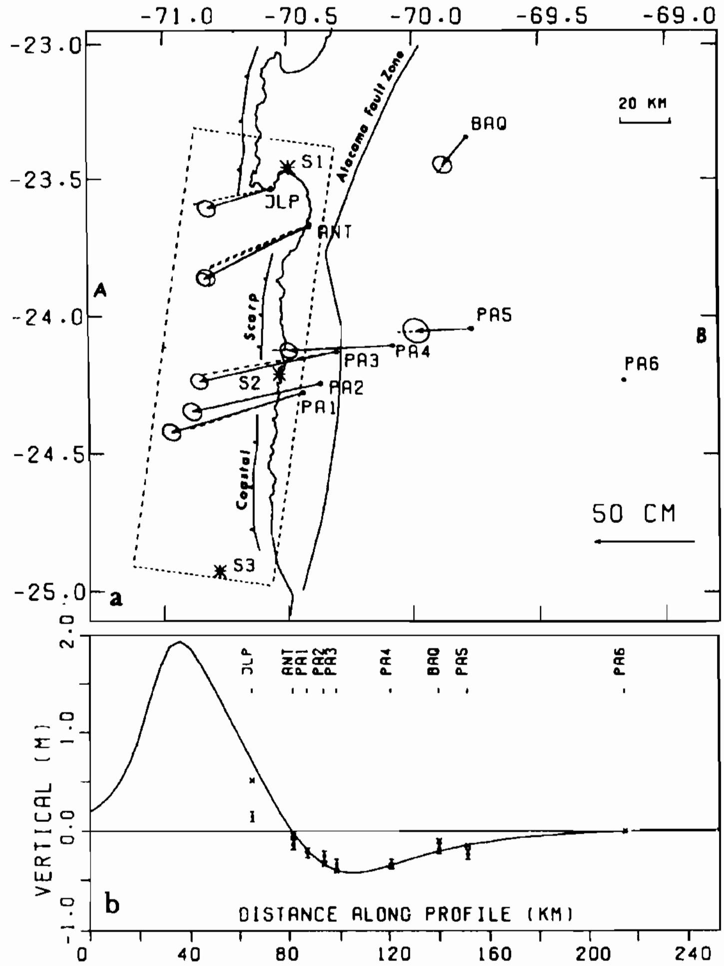

FIG. 3. Uniform slip model of deformation of the 1995 Antofagasta earthquake, calculated from GPS measurements, from Ruegg *et al.* (1996). The model suggests that the town of Antofagasta was precisely, and fortunately, located in the nodal area which separates the coseismically uplifted western area from the subsident inland region. This interpretation was assessed by the coralline algae record of deformation of the coastal area.

THE ANTOFAGASTA EARTHQUAKE

The M_s 7.3 Antofagasta earthquake which occurred on July 30, 1995 is the largest event of the last century in northern Chile. A local permanent seismological network (ORSTOM/EOPG-Strasbourg/Universidad de Chile) located the hypocentre at 23°26.7′S, 70°28.5′W and at a depth of 36 km below the Cerro Moreno airport of the city of Antofagasta (Fig. 2). According to the calculated moment magnitude (M_w 8.1) and the distribution of the aftershocks (Monfret *et al.*, 1995; Delouis *et al.*, in press), the rupture zone extended over an area of about 180 km by 70 km, from the northern half of Mejillones Peninsula (23°10′S) southward to Paposo (25°S; Ruegg *et al.*, 1996; Delouis *et al.*, in press). The earthquake ruptured an area located in the southernmost portion of an 800 km-long seismic gap. In the gap, two large earthquakes had occurred in 1868 and 1877, and produced heavy damage. Considering its large moment magnitude, the Antofagasta earthquake was surprisingly harmless, causing three deaths and little visible damage to the buildings of the city.

Surface deformation in the surroundings of Antofagasta and along the coast southward to Paposo was extremely reduced. In particular, no clear evidence for reactivation of faulting activity along the numerous recent fault scarps known in the area, including Mejillones Peninsula, the Atacama Fault Zone, and the coastal strip between El Cobre and Paposo was found (Ortlieb *et al.*, 1995a). The most conspicuous manifestations of co-seismic deformation were limited to gravity slides which occurred along the unstable coastal cliffs of the northern end of Antofagasta Bay, and some caving-in of loose ground (road embankment, in-fills in the quays of Antofagasta harbour). Near Blanco Encalada (24°20′S) some circular structures, with a diameter of several tens of metres, appeared in stabilised coastal dunes, and suggest some settling phenomena.

As the recurrence for strong earthquakes (M_w>8) in Northern Chile was evaluated to about 100 years (Comte and Pardo, 1991), and because the last major earthquake occurred in 1877, the whole area has been subjected, for the last few years, to a series of geological and geophysical studies to detect any possible precursor manifestation of a large earthquake. Thus, for instance, a geodetic (GPS) survey that encompasses the northern territory of Chile between 18° and 25°S and includes about 50 benchmarks, was initiated in 1991 and remeasured in 1992. Two weeks after the earthquake, the southernmost portion of the geodetic network, near Antofagasta, was remeasured. Between 1992 and August 1995, a relative westwards horizontal displacement of about 0.70 m and a subsidence of several decimetres of the pampa area (east of the Cordillera de la Costa range) were thus determined with respect to a reference benchmark located about 100 km east of the coastline (Ruegg *et al.*, 1996). The southern tip of Mejillones Peninsula, where only one benchmark was set, seemed to have been uplifted by an amount of at least 15 cm. Combined teleseismic (from very broad band digital records) and geodetic data were analysed and produced a deformation model reproduced in Fig. 3 (Ruegg *et al.*, 1996).

As only three geodetic stations had been previously (1992) set up in the Antofagasta coastal area (more were established after the 1995 earthquake), the vertical component of the modelled deformation was only weakly constrained (Fig. 2). Fortunately, the dead coralline algae belt provided independent quantitative data in a series of coastal localities that contributed to assess the solution proposed in Fig. 3 (Ruegg *et al.*, 1996). The presence, or lack, of a white fringe of coralline algae, and the variation in width of this feature, along the coast were used, for the first in Chile, to determine the extension of the uplifted area and the net amount of coseismic vertical motion (Ortlieb *et al.*, 1995a, b).

THE CORALLINE ALGAE RECORD OF THE COSEISMIC DEFORMATION IN THE ANTOFAGASTA AREA

The Study Area

During the survey for evidence of the coseismic, and/or post-seismic, ground deformation performed in the third week following the Antofagasta earthquake, we discovered at low tide a white fringe that had recently developed. We were rapidly convinced that the white belt was produced by local uplift motions, and not by some regional oceanographic phenomenon, like a particularly low tide, because there was a strong variation of the width of the belt along the Antofagasta embayment. The fact that along the coastline the belt width was progressively decreasing, or increasing, in some parts of the bay, and that it was practically nil in other parts, strongly suggested that irregular land/sea relative motions had recently occurred. The attribution of these motions to localised coastal uplift was the most logical interpretation. Interestingly, the gradients of increasing and decreasing values of the belt width along the coast varied from one area to the other within Antofagasta Bay and along the southern tip of Mejillones Peninsula. This pattern seemed to be compatible with tectonic motions related, in some cases, to block faulting and tilting.

The survey of the white belt that corresponded to the area of dead crustose coralline algae, located in the sublittoral fringe, needed to be performed precisely during the low tide maximum. Thus, the study and measurement of the dead algal belt was possible only during short spans every day. The total coastal area that was surveyed measured more than 250 km, between Mejillones (23°S) and Paposo (25°S; Fig. 2). A more detailed study concerned the area limited by Punta Coloso, at the southern extremity of the Antofagasta Bay, and Herradura de Mejillones Bay, on the northwestern coast of Mejillones Peninsula. Within this area, some coastal sectors which could not be reached by land were not visited. Most of the area studied with detail is rocky and thus was potentially interesting. Actually, it was confirmed that the coralline algae are well represented, albeit in varying abundance, all along the rocky coastlines, with only one major exception: within about 3 km north and south of the mining installation of El Cobre (24°15′S). Another stretch of the coast without coralline algae coatings is the northern Antofagasta Bay because the rocky shores are replaced there by sandy beaches. Finally, the area for which precise information was gathered covered a total of 70 km within the embayment and in the western coast of Mejillones Peninsula. Between El Cobre and Paposo, the survey of the coastline was negative (coralline algae were present but did not suffer any whitening) except for one single locality, on the southern side of Punta Tragagente (24°28′S). At that locality, a 10 cm wide belt of dead algae was measured along a very small sector (a few hundred metres long), while the maximum uplift recorded at about 1.5 km to the north and to the south of Punta Tragagente was less than 2 cm.

Measurement Methodology

The goal of the survey was to determine the amount of uplift indicated by the dead coralline algae a short time after the earthquake. No precise previous study had been dedicated to the position of the uppermost limit of the algae in distinct localities of the area. Thus, no absolute measurement, with respect to some reference datum (e.g. mean sea level) could be done, and that the approach was necessarily empirical. It was assumed that the difference in vertical height between the top of the living coralline algae encrustment and the top of the former upper limit (a few weeks before) of the encrustment, on the same transect, represented the amount of the coseismic uplift.

In many localities, the determination of the height, or width, of the white belt was straightforward and yielded a value which was relatively constant for hundreds of metres, or kilometres. Alternatively, in other stretches of the coastline, the values might increase (decrease), more or less continuously, laterally along the shoreline. But in some spots of the localities visited, the fringe exceeded 30% of the width measured in the close vicinity. These variations within a few metres, or a few tens of metres, along the coastline, were mostly due to the degree of exposure to strong waves, and to the effect of splash within the locality. They were commonly related to differences in the orientation of the coast and to variations in the microtopography of the area. These variations of belt width raised more important problems in terms of the accuracy of the evaluation of uplift amount than the precision of the measurements itself.

The width of the dead algae belt was measured with a tape disposed vertically. In most localities, the precision of the measurement was of the order of 1 cm (Fig. 4A and 4B). The cases in which the accuracy of the measurements posed some problems were those concerning the areas of smallest uplift (less than a few cm) and where the dead algal belt was thin and discontinuous. In a few cases (notably at Antofagasta, or immediately to the south of the town) the only evidence of uplift consisted in an alignment of small white patches. In these cases, the upper limit of the coralline algae was not well defined by an horizontal level, and ended upward by a series of isolated small patches, that eventually whitened after the earthquake.

To resolve the problems posed by differences within short distances of the width of the dead algae belt, we tried to establish a series of criteria, that would provide the most representative and accurate evaluation of the local uplift of the land.

One of these criteria was the parallelism of the upper and lower limits of the white belt of dead algae. The inclination of the lower and/or upper limits of the belt, with respect to the horizontal plane, indicated that wave motions were strong enough to displace upward the extension of the coralline algae belt, within the intertidal zone (Fig. 1). In these cases, the width of the white belt provided an amplified evaluation of the relative vertical motion. The parallelism of the white belt limits was normally observed in areas of agitated waters (for an optimal development of the algae) but with limited wave splash (at low tide). Such conditions were usually met in protected small re-entrants, or micro-coves, that remained linked with the open ocean even at the lowest tide level. An extreme opposite situation is that of vertical cliffs beaten by permanently strong waves (even on calm days), in which the upper limit of living coralline algae may be observed at up to 1 or 2 m above the mean low tide line (Fig. 5).

Another useful criteria for the representativity of the measurements was the coincidence between values determined on vertical microcliffs (Fig. 4A) and upon 'dormant' boulders commonly found in the infralittoral fringe (that had not been moved by the waves since the earthquake occurrence).

When, in a given locality, variation of the belt-width was large it appeared that the best estimate of uplift was near the lowest values obtained. The highest values corresponded to areas of relatively stronger waves, and thus were discarded The lowest measured values were sometimes due to the fact that some threshold separated the open ocean from the measured spot, in such a way that the measured belt width underestimated the amplitude of the reconstructed vertical motion. In every locality, it was necessary to locate the areas least affected by non-tectonic local effects that were susceptible to either amplify or diminish the evaluation of the coseismic uplift. This could not be determined on the basis of a mean value of several measurements of the height of the white belt, unless the measured values (within a few metres, or tens of metres of coastline) were differing by less than about 5%.

Results and Interpretation

The measured width of the dead coralline algal belt that was formed in a series of visited localities is indicated in Fig. 6. Two categories of measured values are distinguished: those satisfying the above mentioned quality criteria, and those which although of lower quality are the only evaluations possible of the amplitude of the belt. The latter category includes localities where the observations could not be completed satisfactorily due to difficulty of access, areas exposed to strong waves, measurements made before or after the low tide maximum, or those where the (former, and/or new) upper limit of the coralline algae zone was not neatly defined.

The survey of the distribution and width of the white fringe of coralline algae showed that the vertical motions caused by the 1995 Antofagasta earthquake were limited to an area between the northern Mejillones Peninsula and the southern extremity of the Bay of Antofagasta. The impossibility of accessing the coastline south of Punta Coloso left some doubts regarding the extension toward the south of the uplifted area. A coastal road could be used between Caleta El Cobre (24 10′S) and Paposo (25°S). At Caleta El Cobre, copper mining activities seem to have eliminated the coralline algae in the infralittoral zone, so that no record was possible. But at a few kilometres south of Caleta El Cobre, when the crustose algae are present in the infralittoral fringe, no white belt was observed. It is concluded that the area was not uplifted coseismically. The same situation (living coralline algae without white fringe) was observed southward, all along the coast, with the exception of one locality, Punta Tragagente, where a belt measuring up to 10 cm was observed. This area might have experienced a localised tectonic motion, unlike the coast to the north and south. At Paposo, coralline algae are common but no indication of desiccation of the upper limit of the algal crust was noticed.

Near Punta Coloso, a relatively 'steep' gradient of uplift motions was documented. In a short distance, the dead algal belt increased from less than 5 cm to about 25 cm (El Lenguado). It could not be determined whether the indicated deformation reflected a local tectonic effect linked, for instance, to a triggered slip on a small fault. Alternatively, it may reflect the fact that the coastline is locally trending ENE–WSW, instead of roughly N–S like further north, along the city of Antofagasta, and that the ENE–WSW direction would be that of the steeper gradient of the deformation pattern in that area.

Along the eastern shore of Antofagasta Bay, the coralline algae are as abundant in the infralittoral fringe than elsewhere, but no continuous, well-defined, white belt of desiccated algae was observed. Only a rather discontinuous narrow fringe or isolated small patches of white dead algae were visible along the shoreline, between the mouth of Quebrada El Way and La Chimba. These data suggest that the uplift motions in the area were less than 5 cm, and locally less than 2 cm, along a 35 km long stretch of coastline.

At the north-westernmost end of Antofagasta Bay, at La Rinconada, an irregular belt and aligned white patches

FIG. 4. Typical aspects of the white, dead fringe of coralline algae after the 1995 Antofagasta earthquake in a series of localities. (A) Conspicuous fringe of dead coralline algae, at Punta Jorge (southern tip of Mejillones Peninsula). At that relatively protected locality, the width of the white fringe measured 31 cm. (B) Close up of the limit between the white fringe of dead algae and the unaltered pink encrustment of the same algae, on a 'dormant' boulder. Note that the precision of the measurement may be better than 1 cm. (C) Small pond in the lower intertidal zone which is permanently submerged and where the coralline algae remained alive (pink colour), while the surroundings are coated with white dead algae (hammer for scale at left in the foreground). (D) Example of the white fringe on the western side of Mejillones Peninsula, close to Caleta Bandurria del Sur. Measured width was 28 cm. (E) The white fringe at El Lenguado, near the southern end of Antofagasta Bay. Note the coincidence between the top of the white fringe and the base of the colonies of *Pyura praeputialis* (ascidians). It is expected that, unless the coast registers a subsequent subsidence, the ascidians will colonise the area abandoned by the coralline algae. (F) About 10 weeks after the earthquake, the (formerly white) fringe of dead crustose algae get covered with green algae: observe evolution with respect to photo 4E. Monitoring the position of the upper limit of the living coralline algae encrustment should provide information regarding the evolution of the vertical motions (including an eventual compensatory subsidence).

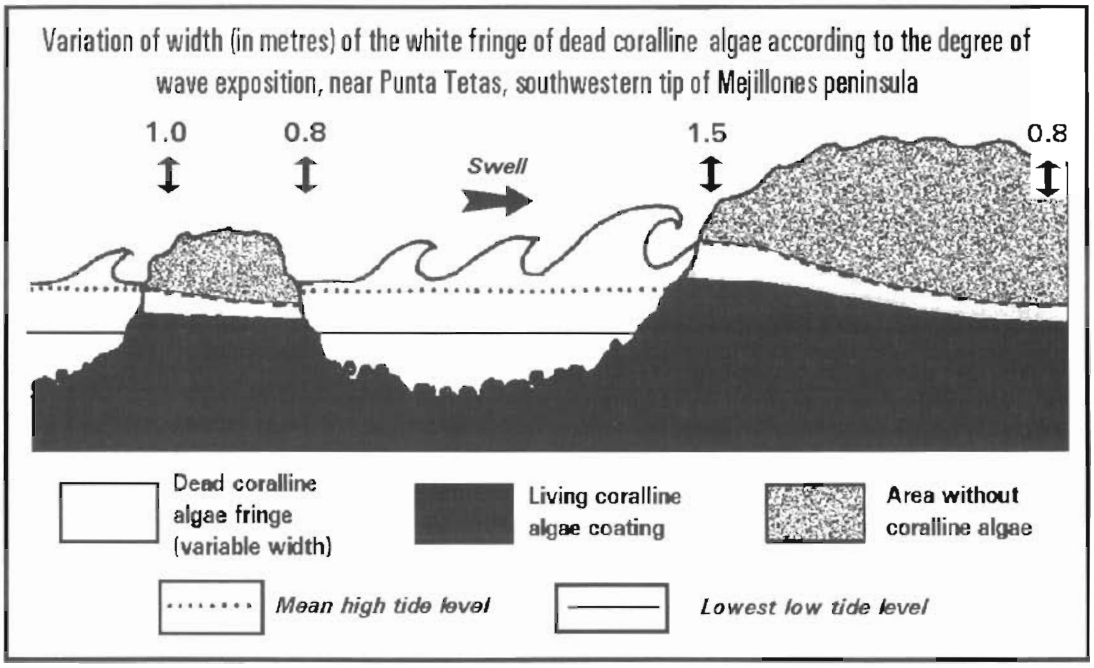

FIG. 5. Sketch of the vertical zonation of the dead and living coralline algae at the south-westernmost end of Mejillones Peninsula (near Punta Tetas), in the locality where wave activity is very strong. Note the variation in height of the upper limit of the crustose algae coating which may even reach the mean high tide level. In this locality (see also Figs 6 and 7A) was measured in the protected part of the coastline, not the 1.0 or 1.5 m values observed in the more exposed areas.

of desiccated coralline algae appeared in the infralittoral fringe. At most, the width of the irregular white belt measured between 5 and 8 cm. In that locality the uplift motion was probably less than 5 cm. Southward from La Rinconada, several localities were visited and showed increasing values of a much better defined belt. At Playa Los Metales, the village of Juan Lopez, and Punta Jorge (the southernmost point of Mejillones Peninsula, Fig. 6), the belt measured, respectively, 20, 25 and 31 cm (Fig. 4A). The reconstructed deformation pattern along this NNE–SSW oriented coastal stretch clearly indicates an increasing differential uplift toward the southern tip of Mejillones Peninsula. This coastal stretch is partly controlled by a major, left-lateral normal, fault that has been active during the Quaternary (Okada, 1971; Armijo and Thiele, 1990; Ortlieb *et al.*, 1995b, 1996a, b), but no indication of any triggered slip was observed, neither along the coast nor inland, to the north of La Rinconada. Furthermore, the vertical distribution of the Middle and Late Pleistocene marine terraces of the area indicates that, at least on the long term, greater uplift of the western faulted block occurred north of La Rinconada, and that the southern tip of the peninsula had been uplifted less. We conclude that the recorded deformation of the northwestern shores of Antofagasta Bay was not caused by slip on the La Rinconada fault, but, rather, is due entirely to coseismic slip of the main thrust plain.

The southern extremity of Mejillones Peninsula, between Punta Jorge and Punta Tetas, is of difficult access, and could be visited only briefly in the weeks

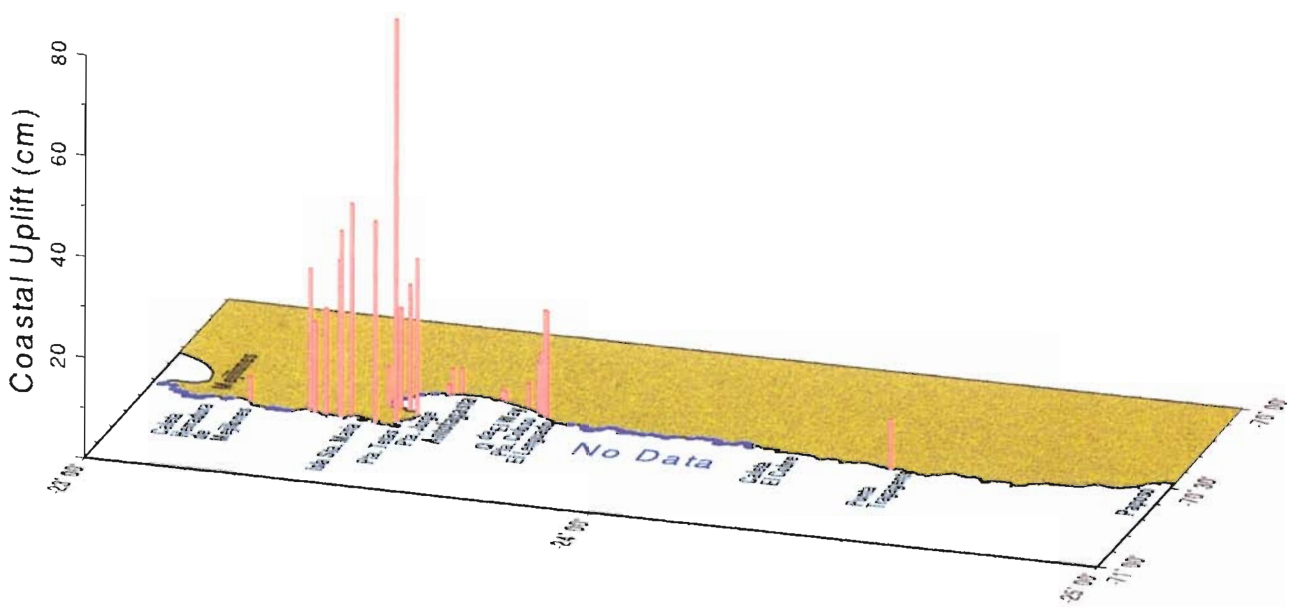

FIG. 6. Reconstruction of the coseismic uplift motion associated with the July 30, 1995 Antofagasta earthquake as recorded in the intertidal zone, between 23° and 25°S, through the width of the dead coralline algae fringe. Regions without data are indicated in blue. Maximum uplift was recorded at the south-easternmost extremity of Mejillones Peninsula.

following the 1995 earthquake. To the northwest of Punta Tetas, a wide fringe of dead algae was observed, and a rough evaluation of about 40 cm was made (from the distance). Only in the last week of December 1995, was it possible to make more thorough observations in the area, specifically in the northern part of the large bay to the east of Punta Tetas. Remnants of the white fringe produced by the 30 July, 1995 earthquake were still visible, and measured 80 cm (Fig. 7). This *in situ* measurement is 50–100% higher than the preliminary data previously reported (Ortlieb *et al.*, 1995a, b). The location of the bay at the southwestern tip of the peninsula, and its orientation toward the south, enhance its exposure to high waves and thus explains the vertical zonation of the intertidal area is greatly expanded upward (Fig. 5). The infralittoral fringe and coralline algae encrustment there, are wider than in the rest of the Antofagasta area. These considerations cast some doubt upon the precision of the estimated amplitude of the uplift indicated by the (formerly) white fringe of dead algae. However, the 80 cm value may not be exaggerated, for it is supported by the observation of former belts of dead ascidian *P. praeputialis* now located 1 m above the top of the infralittoral fringe (i.e. the top of the encrusted living coralline algae; Fig 7A). This is the only locality where the ascidians did not survive the consequences of the coseismic uplift, probably because there was substantially larger uplift in that area. It must be mentioned that during the December 1995 survey, another, much more recent, white belt of dead algae was present in the infralittoral fringe (Fig. 7). That newly formed white belt, which measured some 10–12 cm, is tentatively assigned to a small uplift episode that would have occurred shortly(?) before the third week of December. At the end of December, no other locality showed any newly developed white fringe, so that it is inferred that no regional oceanographic phenomenon was involved in the process. However, as the permanent siesmological network did not register any significant event in November or December (T. Montfret, *pers. commun.*, 1996), the formation of the new small white fringe in the Punta Tetas area cannot be correlated to any precise aftershock, and is perhaps the slow response of movement on a local independent block.

In western Mejillones Peninsula, well exposed to oceanic swell, the infralittoral fringe is often covered with large kelp (*L. nigrescens*) but coralline algae are also present. The southern half of this coastal stretch manifested a practically continuous belt of dead coralline algae, with a width varying between 20 and 45 cm. From Caleta Bandurrias del Sur (23°20′S) northward, there is no access to the coast (high, heavily beaten, seacliffs which cannot be reached easily by sea or from inland), until the Bay of Herradura de Mejillones. In the last locality, on the western side of the bay, the only evidence of a recent vertical motion were discontinuous remnants of a narrow light pink (not quite white) fringe of about 5 cm width. We suggest that the bay was located at the northern limit of the coseismically deformed region. Near Mejillones (El Rincon), and further to the north (Chacaya, Hornitos), no evidence of uplifted coralline algae were found.

Figure 6 synthesises the distribution of uplift estimated from the dead coralline algae belt. We emphasise that the plotted values do not simply correspond to the measured width of the white belt in all the localities, but are restricted to the data that may best represent the vertical changes. In many localities wider bands of dead crustose algae were observed but they corresponded to areas struck by the waves that could not provide useful data (Fig. 5).

Dislocation theory offers useful models to explain surface deformation. Uniform slip faults embedded in an elastic halfspace, such as that proposed by Ruegg *et al.* (1995), or variable slip models, being preliminary examined, can reproduce the observed vertical changes (as well as horizontal GPS data) fairly well. Because we are mainly concerned with the coastal changes, and not on the modelling aspects of the data, we shall only briefly discuss the fault characteristics. Figure 8 shows the expected elevation change due to a fault that extends nearly 150 km long (north–south) by 80 km wide with maximum fault displacement of about 7 m (offshore Caleta El Cobre), where the largest moment release has been detected by teleseismic waveform modelling (Ruegg *et al.*, 1995). The dip of the fault is 19°E, corresponding to the dip of the Wadati-Benioff zone, defined by the aftershocks located by the local network (Monfret *et al.*, 1995). Slip direction on the fault is assumed to be the same as the convergence direction between the Nazca and South American plates.

The maximum vertical displacement (1.8 m) occurring offshore, Caleta El Cobre, is responsible for the small tsunami observed along the coast. (1.6 m of upward movement recorded by the mareograph located in the port of Antofagasta.) Along the coast, the model predicts almost no uplift except in the southern portion of Mejillones Peninsula, reaching more than half a meter of uplift in its southwestern end. The total moment of this model reaches 2 x 10^{21} Nm, equivalent to a magnitude M_w 8.2, one tenth higher than previous estimates from long period seismic waves and geodetic observations (Ruegg *et al.*, 1995), and almost 1° higher than the magnitude estimated with surface waves at shorter periods. This discrepancy is reflecting large fault displacements with low frequencies or, in other words, a significant behavior as a slow earthquake.

CONCLUSIONS

Common pink-coloured coralline algae cover the infralittoral fringe and the infralittoral zone along the rocky shorelines of northern Chile, and of Antofagasta area in particular. The upper limit of extension of these algae may be defined as the line below which no drying-up occurs ever, even during the lowest tides. Desiccation and exposure to natural UV radiation, produce immediately the death and subsequent whitening of these algae.

The 30 July, 1995 the Antofagasta earthquake was accompanied by coastal uplift motions that could be

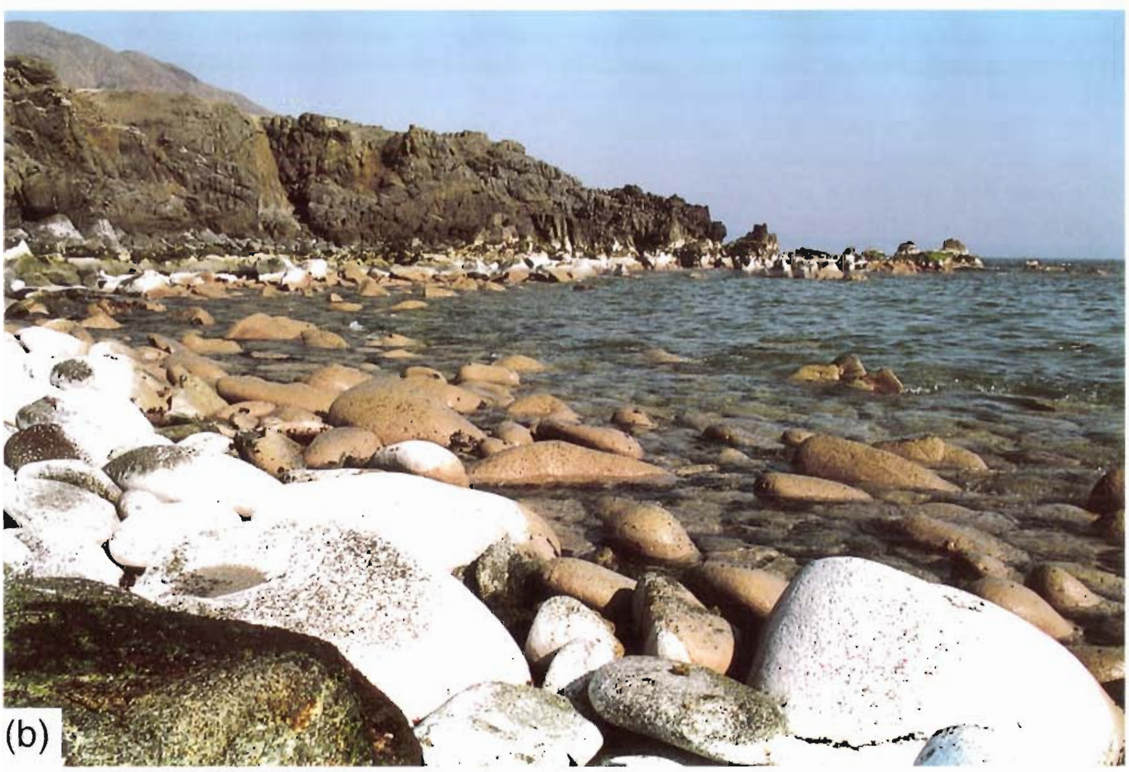

FIG. 7. Near the southwesternmost extremity of the Mejillones Peninsula, was observed the highest width of the dead algal fringe (80 cm) produced by the 30 July earthquake, and also evidence for a second small (10 cm) local uplift motion that occurred before mid(?) December 1995. (A) Remnants of the post-July 1995 fringe of dead algae are visible from the base of the 1 m scale up to 20 cm below the top of scale. The top of the former upper limit of the crustose algae coating is figured by a 20 cm high fringe of ascidians (*Pyura praeputialis*), like in Fig. 4E and 4F. Below the scale, a conspicuous, more recently formed white fringe of 10–12 cm width was observed at the end of December 1995. This secondary feature depicts a new uplift episode of minor amplitude. (B) 2 km SW from the locality of 7A, in south-westernmost Mejillones Peninsula, boulders in the infralittoral fringe (photograph taken at low tide) also registered the secondary 10 cm uplift in December 1995.

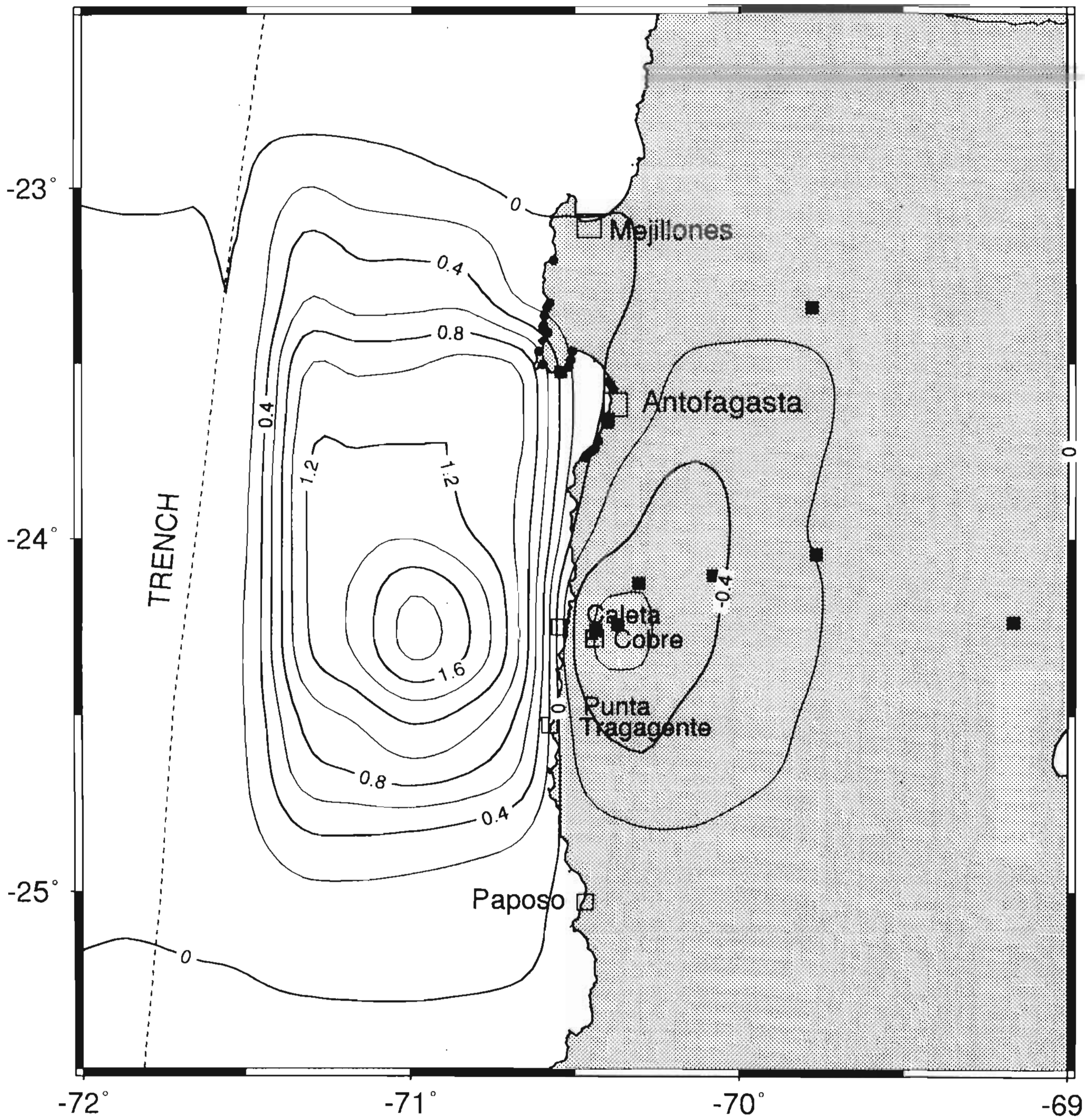

FIG. 8. Expected elevation change (contours in m) associated with the July 30, 1995 Antofagasta earthquake. These values are based on a variable fault slip model derived from the study of the coralline algae fringe and geodetic (GPS) observations. The nil elevation change runs parallel to the coast south of Antofagasta. The deformation is limited to the area between Mejillones and Paposo.

recorded by these algae. A white belt formed by the rapid death of the algae appeared at low tide in the study area, and was visible during the following weeks and months. This belt of varying width along Antofagasta Bay and around Mejillones Peninsula was assumed to depict the area of the infralittoral fringe that had been uplifted. Through a cautious study of a series of localities, it was shown that this was true in relatively protected areas, but that in the more exposed coastal stretches some particular requisites were necessary to determine the amplitude of the coseismic uplift.

Providing that in every locality, the most representative value of the belt width was selected (and not the mean, or the largest or smallest measured value), the dead coralline algae fringe effectively provided the best available evaluation of the positive vertical motion suffered by the coastal area during the Antofagasta earthquake.

Through a monitoring of the vertical position of the base of the dead algal belt (i.e. the upper limit of the presently living coralline algae) in a number of studied localities, we expect to determine in the future whether some areas will subside or, on the contrary, be more uplifted. In some localities, like the area of Punta Coloso, marine terrace data strongly suggest that no significant long term vertical uplift motion occurred in the course of the last 125,000 years (Ortlieb *et al.*, 1993, 1995b), so that it would be possible that some compensatory subsidence happened after the 1995 earthquake. Though, one year after the Antofagasta earthquake, no subsequent vertical motion, in either direction, was registered in the Coloso area (Fig. 4E and 4F). In another locality, at the southern tip of Mejillones Peninsula, a 10 cm secondary uplift that probably occurred in early December 1995 that was observed, but could not be related to any single seismic event. Finally in the case that no further vertical motions occur, the periodic photographic control set up in some localities should be useful to study the biological colonisation and reorganisation of the sublittoral zone, immediately above the new infralittoral fringe.

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REFERENCES

Adey, W.H. (1986). Coralline algae as indicator of sea-level. *In*: Van de Plassche (ed.), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*, pp. 229–280. GeoBooks, Norwich.

Adey, W H and Johansen, H W (1972). Morphology of Corallinaceae with special reference to *Clathromorphum*, *Mesophyllum* and *Neopolyporolithon*, gen. nov. (Rhodophyceae Cryptonemiales). *Phycologia*, **13**, 329–344.

Adey, W.H. and Vassar, M. (1975). Colonization, succession and growth rates of tropical crustose coralline algae (Rhodophyta, Cryptonemiales). *Phycologia*, **14,** 55–69.

Armijo, R. and Thiele, R. (1990). Active faulting in northern Chile: ramp stacking and lateral decoupling along a subduction plate boundary? *Earth and Planetary Science Letters*, **98**, 40–61

Bodin, P. and Klinger, T. (1986). Coastal uplift and mortality of intertidal organisms caused by the September 1985 Mexico earthquakes. *Science*, **233,** 1071–1073.

Castilla, J.C. (1988). Earthquake-caused coastal uplift and its effects on rocky intertidal kelp communities. *Science*, **242,** 440–443.

Castilla, J.C. and Oliva, D. (1990). Ecological consequences of coseismic uplift on the intertidal kelp belts of *Lessonia nigrescens* in central Chile. *Estuarine, Coastal and Shelf Science*, **31**, 45–56.

Darwin, C. (1846). *Geological Observations on South America*. Smith, Elder & Co.

Delouis, B., Monfret, T., Dorbath, L., Pardo, M., Rivera, L., Comte, D., Haessler, H., Caminade, J.P., Ponce, L., Kausel, E. and Cisternas, A. (*in press*). Forecasting the end of a gap: the large Antofagasta (Northern Chile) earthquake of July 30, 1995 and tectonic implications. *Bulletin of the Seismological Society of America*.

Guiler, E.R. (1959). Intertidal belt-forming species on the rocky coasts of Northern Chile. *Papers and Proceedings of the Royal Society of Tasmania*, **93,** 33–57.

Gutierrez, J.E. and Lay, J.E. (1965). Observaciones biológicas en la población de *Pyura chilensis* Molina. 1782, en Antofagasta (Urochordata Ascidiacea, Pyuridae). *Estudios Oceanológicos (Chile)*, **1**, 1–32.

Johansen, H.W. (1971). Effects of elevation changes in benthic algae in Prince Willian Sound. *In*: *The Great Alaska Earthquake of 1964*, pp. 35–68. National Academy of Sciences, Washington, D.C.

Lebednik, P.A. (1973). Ecological effects of intertidal uplifting from nuclear testing. *Marine Biology*, **20,** 197–207.

Littler, M.M. (1972). The crustose Corallinaceae. *Oceanography and Marine Biology*, **10,** 103–120.

Meneses, I. (1986). Estado actual del conocimiento de las algas coralináceas crustosas. *Gayana Botánica (Chile)*, **43,** 19–46.

Monfret, T., Dorbath, L., Caminade, J.P., Pardo, M., Comte, D., Ponce, L., Cisternas, A., Delouis, B. and Rivera, L. (1995). The July 30, 1995 Antofagasta earthquake: an 'hypocritical' seismic event. American Geophysical Union Fall Meet. (San Francisco, 1995), Suppl. *Eos*, **76,**(46), F427 (abstr.).

Okada, A. (1971). On the neotectonics of the Atacama fault zone region. Preliminary notes on late Cenozoic faulting and geomorphic development of the coast range of northern Chile. *Bulletin of the Department of Geography Kyoto University*, **3,** 47–65.

Ortlieb, L., Ghaleb, B., Hillaire-Marcel, Cl. and Pichet, P. (1993). Deformación de la línea de costa del último interglacial en la región de Antofagasta, Norte de Chile. *International Workshop on The Quaternary of Chile (Santiago, 1993)*, abstr. vol., p.25.

Ortlieb, L., Barrientos, S., Lavenu, A. and Monfret, T. (1995a). Coseismic uplift motions near Antofagasta, N Chile, related to the July 30, 1995, Ms 7.3 event: First field evidence from the intertidal area. American Geophysical Union, Fall Meeting (San Francisco, 1995), Suppl. *Eos*, **76**, F375–F376 (abstr.).

Ortlieb, L., Goy, J.L., Zazo, C., Hillaire-Marcel, Cl. and Vargas, G. (1995b). *Late Quaternary Coastal Changes in Northern Chile*. Guidebook for a fieldtrip, II annual meeting of the International Geological Correlation Program, Project 367 (Antofagasta, 19–28 Nov. 1995), ORSTOM, Antofagasta, Chile. 175 pp.

Ortlieb, L., Goy, J.L., Zazo, C., Hillaire-Marcel, C., Ghaleb, B., Guzmán, N. and Thiele, R. (1996). Quaternary morphostratigraphy and vertical deformation in Mejillones Peninsula, Northern Chile. *3rd International Symposium on Andean Geodynamics. (St. Malo, Sept. 1996)*, 4 pp. (*in press*).

Ortlieb, L., Díaz, A. and Guzman, N. (1996). A warm interglacial episode during isotope stage 11 in Northern Chile. *Quaternary Science Reviews*, **15,** (*this issue*).

Plafker, G. (1964). Tectonic deformation associated with the 1964 Alaskan earthquake. *Science*, **148**, 1675pp.

Raffaelli, D. (1979). The grazer-algae interaction in the intertidal zone of New Zealand rocky shores. *Journal of Experimental Marine Biology and Ecology*, **38,** 81–100.

Ruegg, J.C., Campos, J., Armijo, R., Barrientos, S., Briole, P., Thiele, R., Arancibia, M., Cañuta, J., Duquesnoy, T., Chang, M., Lazo, D., Lyon-Caen, H., Ortlieb, L., Rossignol, J.C. and Serrurier, L. (1966). The Mw=8.1 Antofagasta (North Chile) earthquake of July 30,1995: First results from teleseismic and geodetic data. *Geophysical Research Letters*, **23**, 917–920.

Stephenson, T.A. and Stephenson, A. (1972). *Life Between Tide Marks on Rocky Shores*. Freeman, W.H. and Company, San Francisco.