

Effects of rocky shore coseismic uplift and the 2010 Chilean mega-earthquake on intertidal biomarker species

Juan Carlos Castilla^{1,*}, Patricio H. Manríquez^{2,3}, Andrés Camaño⁴

¹Departamento de Ecología y Centro FONDAF de Ecología y Biodiversidad, Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile, Casilla 114-D, Santiago, Chile

²Instituto de Biología Marina 'Dr. Jürgen Winter' and ³Laboratorio Costero de Recursos Acuáticos de Calfuco, Facultad de Ciencias, Universidad Austral de Chile, Casilla 567, Valdivia, Chile

⁴Arauco, Avenida El Golf 150, Casilla 880, Santiago, Chile

ABSTRACT: The devastating earthquake (moment magnitude: 8.8 MW) that struck Chile on 27 February 2010 and the following tsunami waves produced widespread damage, coastal coseismic uplifts, and large-scale mortality of rocky intertidal and shallow subtidal organisms. The effects were particularly remarkable around the Gulf of Arauco, Santa María Island and the Bay of Concepción (~36 to 38° S). Measurements of rocky intertidal and shallow subtidal belt-forming (biomarker) species conducted a few weeks after the earthquake indicated coastal uplifts ranging from ~0.2 to 3.1 m, which are similar to uplifts estimated by FitzRoy (1839; *Voyages of the Adventure and Beagle*, Vol. II) and Darwin (1839; *Voyages of the Adventure and Beagle*, Vol. III) after the 1835 Chilean earthquake. In major uplifted sites, there was massive mortality of the main intertidal and shallow subtidal belt-forming species, such as lithothamnioid melobesioid coralline algae, brown kelps and mussels, and dramatic changes in the marine rocky intertidal ecosystem. We suggest that in the southeastern Pacific, drastic and rapid coastal deformations seriously impinge on rocky shore populations, communities and ecosystems and may have significance for management and conservation practices, as for example in connection with alterations of parental stocks and recruitment rates.

KEY WORDS: Drastic events · Coastal deformation · Intertidal biomarkers · Massive mortality

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INTRODUCTION

In the southeastern Pacific, the Nazca tectonic plate is being subducted beneath the South American plate and mega-earthquakes occur every ~10 yr (Madariaga et al. 2010). Chile is one of the regions in the world where large earthquakes (≥ 7 MW) and rapid coastal uplift/subsidence are frequent (Lomnitz 1970, Comte et al. 1986, Ruegg et al. 2009). On 27 February 2010 at 03:34 h, local time, an 8.8 MW mega-earthquake, the fifth largest instrumentally recorded, occurred off the south-central coast between Concepción and Constitución (~35 to 38° S). The epicenter was located ~110 to 120 km northeast of Concepción (36° 49' S, 73° 03' W)

at a depth of 6.2 km, and the rupture zone was ~500 to 600 km long (Fariás et al. 2010, Madariaga et al. 2010). The characteristics of this earthquake were similar in many respects to those of a Chilean earthquake in 1835 that was reported by FitzRoy (1839) and Darwin (1839, 1846). There were preliminary verbal reports of coastal uplifts along the rupture zone at mainland sites as well as on Santa María Island (37° 02' S, 73° 31' W) in the Gulf of Arauco (Fig. 1). In addition, the earthquake generated tsunami waves up to 10 m causing enormous destruction and devastation in coastal villages (Marín et al. 2010).

Santa María Island (35 km²) sits 75 km landward from the southern end of the Concepción oceanic seis-

*Email: jcastilla@bio.puc.cl

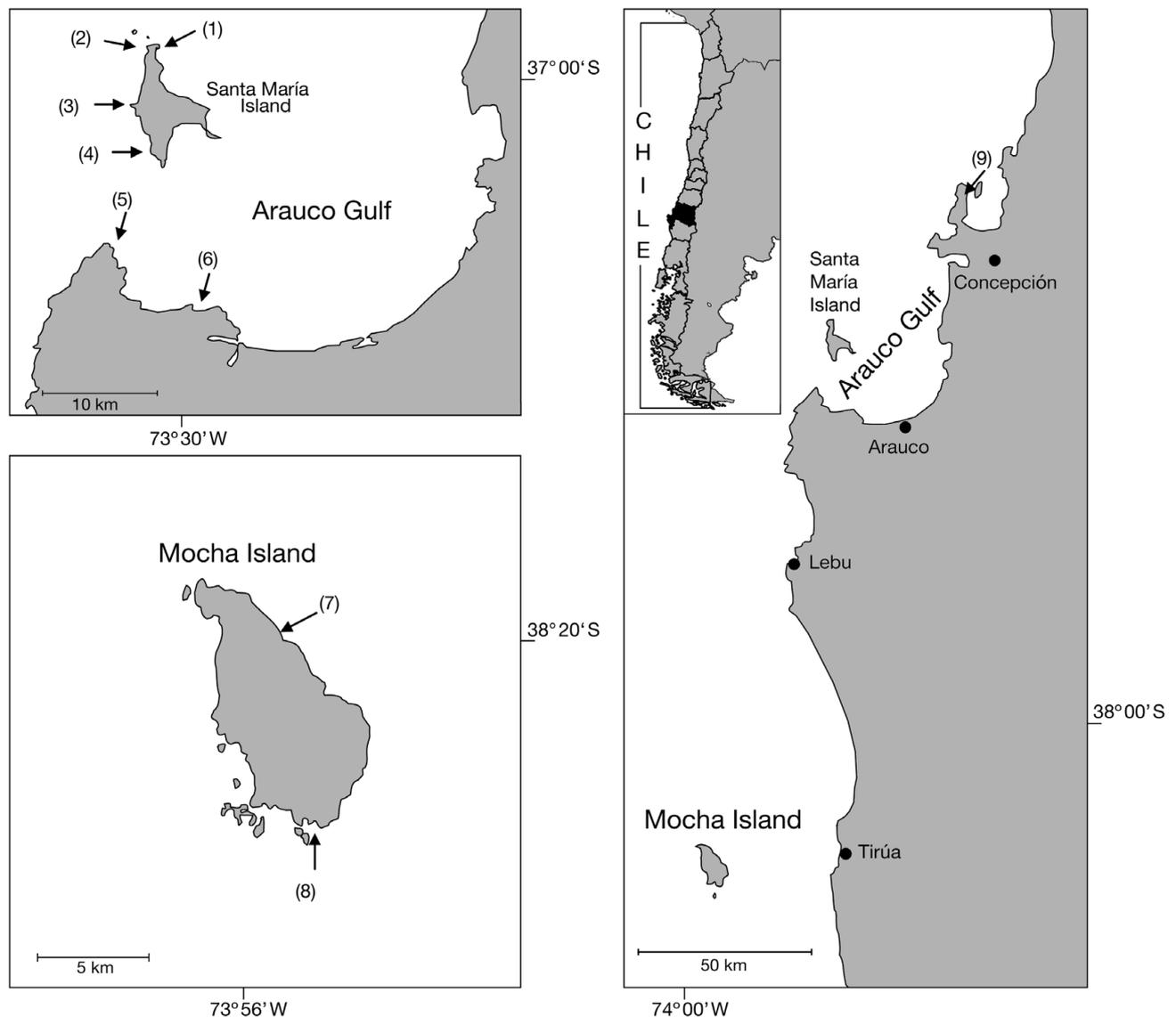


Fig. 1. Location of visited earthquake sites during 2010 (Garmin eTrex GPS). Santa María Island (18 to 21 March and 13 to 14 April): (1) La Ballenera ($36^{\circ}58'41''\text{S}$, $73^{\circ}31'30''\text{W}$), (2) Punta Gaviota ($36^{\circ}58'27''\text{S}$, $73^{\circ}32'06''\text{W}$), (3) Las Dolores ($37^{\circ}01'24''\text{S}$, $73^{\circ}33'07''\text{W}$), (4) Puerto La Chota ($37^{\circ}03'00''\text{S}$, $73^{\circ}05'25''\text{W}$). Gulf of Arauco (15 April): (5) Punta Lavapié ($37^{\circ}08'53''\text{S}$, $73^{\circ}34'53''\text{W}$), (6) Caleta Tubul ($37^{\circ}13'34''\text{S}$, $73^{\circ}26'7''\text{W}$). Mocha Island (24 to 25 April): (7) Muelle Viejo ($38^{\circ}20'20''\text{S}$, $73^{\circ}54'38''\text{W}$), (8) Punta Chales ($38^{\circ}24'58''\text{S}$, $73^{\circ}53'28''\text{W}$). Bay of Concepción (16 April): (9) Caleta Tumbes ($36^{\circ}38'11''\text{S}$, $73^{\circ}05'31''\text{W}$)

mic trench and is ~12 km above where the Nazca tectonic plate is being subducted beneath the South American plate. In fact, the island is the result of earthquake uplifts and deformations that have occurred since the late Pleistocene (Melnick et al. 2006). Major coseismic uplifts on Santa María Island and adjacent mainland sites have previously been reported, although not quantified (e.g. uplifts caused by an earthquake in 1751 (~8.5 MW; Lomnitz 1970, Comte et al. 1986). Santa María Island was also in the rupture zone of the ~8.2 MW mega-earthquake (Melnick et al.

2006) that occurred on 20 March 1835. HMS 'Beagle' visited the region in March, and FitzRoy and Darwin made observations based on the visible evidence of dead shellfish, water marks, surroundings and the verbal testimony of inhabitants. Darwin (1846) summarized FitzRoy's uplift reports: 2.4 m for the southern end, 2.7 m for the central part and 3 m for the northern end of the island. On the mainland, at Tubul (Fig. 1), there was an uplift of 1.8 m. Uplifts of 2.4 m for the Quiriquina Island ($36^{\circ}37'\text{S}$, $73^{\circ}03'\text{W}$) and 1.5 to 2.4 m for Talcahuano harbor ($36^{\circ}43'\text{S}$, $73^{\circ}07'\text{W}$) were also

reported. Darwin (1839, p. 414) vividly described the effects of the earthquake on rocky shores:

I do not wish to exclude the small starts which accompany earthquakes, as on the coast of Chile; and by such movement beds of shell might easily be uplifted, even in position exposed to heavy surf, without undergoing any attrition: for instance, in 1835, a rocky flat off the island of Santa Maria was at one blow up-heaved above high-water marks, and was left covered with gaping and putrefying mussel-shells, still attached to the bed on which they had lived.

The ~2 m coseismic uplift contour derived from these data has been interpreted as being parallel to the northeast-striking reverse fault system (Melnick et al. 2006). The rocky shore-level changes reported by FitzRoy (1839) and Darwin (1839, 1846) were determined using mostly the emerged upper limit of the dead belt of *Mytilus* as a pre-earthquake biomarker of the lower limit of the intertidal zone.

MATERIALS AND METHODS

Field visits. In order to evaluate biotic impacts and coseismic uplifts on rocky shore intertidal belts and communities following the mega-earthquake in February 2010, we visited 9 sites. These sites include most of those reported by FitzRoy (1839) and Darwin (1839, 1846), and full details are given in Fig. 1.

Biomarkers. Belts of intertidal sessile invertebrates and upper subtidal algae have been used as conservative biomarkers to evaluate the coseismic shore uplifts associated with earthquakes (National Academy of Sciences 1972, Bodin & Klinger 1986, Castilla 1988, Castilla & Oliva 1990, Carver et al. 1994, Ortlieb et al. 1996, Awata et al. 2008, Farías et al. 2010). As a first direct approach for measuring coseismic uplift, we used the vertical elevation of the white fringe zone formed by dead coralline lithothamnioid melobesoid algae (*Synarthrophyton* spp, *Lithophyllum* spp; I. Meneses pers. comm.) and of the dead holdfasts of the bull-kelp *Durvillaea antarctica* and the kelp *Macrocystis pyrifera*. The coralline algae lose pigment and appear white (bleached) after being exposed to solar radiation and elevated temperatures (Ortlieb et al. 1996, Ramírez-Herrera & Zamorano 2002, Farías et al. 2010). In Chile, the upper intertidal limits of pink-red-dish lithothamnioid algae, which is mainly a subtidal species, of the bull-kelp *D. antarctica* and of the kelp *M. pyrifera* occur around the Mean Low Water Neap (MLWN, Lewis 1964; also see Santelices & Ojeda 1984, Meneses 1993). Therefore, we measured the rise in the upper limit of lithothamnioids and of dead holdfasts of *M. pyrifera* and *D. antarctica* as pre-earthquake markers. On Santa María island and at mainland sites the lower limit of the intertidal belt-forming mussel

Perumytilus purpuratus was also located around the MLWN (see Fig. 2a for post-earthquake measures). Therefore, as an indication of tidal height for uplift measures of the 4 belt-forming biomarkers, we refer to MLWN that in 2009 was 0.23 m, relative to zero datum. Uplift measurements of the biomarkers on Santa María and at the mainland sites were done *in situ* using a 1 m scale placed vertically at the water level at low and high tide and by projecting this level horizontally back to the rock face, where the pre-earthquake belt-forming biomarkers were located. When elevations were >1 m, a 5-m tape measure (1 cm accuracy) was used to measure the vertical change. Date and hour of low and high tide measurements were noted and tide levels were corrected using interpolations as reported by the Hydrographic and Oceanographic Service of the Chilean Navy.

RESULTS

Regardless of the intertidal biomarker used, the mean uplift on Santa María Island ranged between 2.1 and 3.1 m for the northern end, 2.1 and 2.4 m for the center and 2.4 m for the southern end of the island. On the mainland, elevations reached 1.9 m at Punta Lavapié. Punta Lavapié is close to Caleta Tubul, a site where FitzRoy and Darwin made observations, but we could not use Tubul because the site was covered by a landslide. At Caleta Tumbes and Mocha Island, we detected only minor uplifts of ~0.2 to 0.3 m, where only the peaks of some subtidal rocks were raised above MLWN (Table 1). Since the maximum tidal range in the study area is ~2 m (Tablas de marea de la costa de Chile 2010), most of the uplifted areas were moved above the upper tide limit. Further evidence of the uplift was the presence of wide areas with infralittoral specimens of the kelps *Macrocystis pyrifera* and *Durvillaea antarctica* and the mid-low intertidal belt of the mussel *Perumytilus purpuratus* that was dry and completely exposed to air during low and high tides (Fig. 2 a,b). At 5 of the 9 sites visited, dramatic uplifts occurred, and we recorded 100% mortality for all belt-forming intertidal and shallow subtidal organisms (Table 2). The exceptions to these catastrophic biotic events were Caleta Tumbes and Mocha Island, where we detected relatively minor uplifts and where intertidal and shallow subtidal communities appeared normal without extensive evidence of invertebrate or algae mortality; however, a few boulders were carried higher into the intertidal by the tsunami.

In addition, at the uplifted sites we recorded catastrophic mortalities of several intertidal rocky shore and shallow subtidal edible/commercial species, regularly gathered during low tides by hundreds of artisan



Fig. 2. Photographic record of coseismic uplift and the massive stranding of marine invertebrates at the northern end of Santa María Island after the February 2010 earthquake-tsunami. (a) Intertidal uplifted rocks showing belt of the mussel *Perumytilus purpuratus*; (b) low intertidal-infralittoral rocks with specimens of the brown kelp *Macrocystis pyrifera* and bull-kelp *Durvillaea antarctica*; (c) stranded giant jumbo squid *Dosidicus gigas*; (d) specimens of crab *Taliepus* spp. Photographs taken at (a,b) Las Gaviotas and (c,d) La Ballenera, northwest and northeast of Santa María Island, respectively (all photographs taken on 13 April 2010). (a,b) Whitish coloration represents dead lithothamnioids after being exposed to air due to uplift. Scale bar: (a–c) 2 m long with white and red sections of 0.1 m each and (d) 3 cm

Table 1. Mean \pm SD rocky intertidal uplift (m) associated with the Chilean earthquake of 27 February 2010. Upper or lower limits of dead specimen of kelp (holdfast), lithothamnioid coralline algae and mussels were used as pre-earthquake biomarkers for intertidal uplift at 8 sites where measurements were done. Height measurements ($n = 20 \text{ site}^{-1}$) of the limits of belt-forming species were taken *in situ* over haphazardly selected areas and then referred to Mean Low Water Neap (MLWN) tides. (-): absence of data

	Santa María Island				Mocha Island		Mainland	
	La Ballenera	Punta Gaviota	Las Dolores	Puerto la Chota	Muelle Viejo	Punta Chales	Punta Lavapié	Caleta Tumbes
Upper limit of dead lithothamnioids	2.9 \pm 0.2	3.0 \pm 0.2	-	2.2 \pm 0.1	0.2 \pm 0.1	0.3 \pm 0.2	1.6 \pm 0.1	0.2 \pm 0.1 ^a
Upper limit of dead <i>Durvillaea antarctica</i>	-	3.0 \pm 0.2	2.1 \pm 0.1	-	-	-	-	-
Upper limit of dead <i>Macrocystis pyrifera</i>	2.7 \pm 0.2	2.9 \pm 0.2	1.9 \pm 0.1	-	-	-	-	-
Lower limit of dead <i>Perumytilus purpuratus</i>	2.8 \pm 0.1	3.1 \pm 0.2	2.2 \pm 0.1	-	-	-	1.9 \pm 0.2	0.4 \pm 0.3

^aChanges at Caleta Tumbes observed on 6 isolated intertidal rocks

Table 2. Mortality, density and size parameters of intertidal belt-forming (A) macroalgae and (B) encrusting algae and the mussel *Perumytilus purpuratus* on Santa María Island (Las Gaviotas) and adjacent mainland rocky intertidal platforms following the Chilean earthquake of 27 February 2010. *Macrocystis pyrifera*: low intertidal and shallow subtidal; *Lessonia nigrescens*: low intertidal; *Durvillaea antarctica*: low intertidal and shallow subtidal; Lithothamnioids and *Corallina* spp.: mainly subtidal; *P. purpuratus*: mid-intertidal. SMI: Santa María Island, MPL: Mainland Punta Lavapié, MCT: Mainland Caleta Tumbes. Quadrats: number of haphazardly placed quadrats of 1 m² used to assess the density and cover of belt-forming species. Where applicable, values are mean \pm SD. (-): absence of data. 100 specimens were used in each case to measure holdfast diameter and mussel size

A	Site	Quadrats (n)	Mortality (%)	Density (ind. m ⁻²)	Max. holdfast diameter (cm)
<i>Macrocystis pyrifera</i>	SMI	24	100	12.3 \pm 7.9	14.31 \pm 3.2
<i>Lessonia nigrescens</i>	SMI	25	100	5.0 \pm 1.9	14.87 \pm 6.9
<i>Durvillaea antarctica</i>	SMI	25	100	10.8 \pm 4.9	25.40 \pm 5.9
B	Site	Quadrats (n)	Mortality (%)	Rock cover (%)	Mean length (cm)
Lithothamnioids and <i>Corallina</i> spp.	SMI	25	100	90.2 \pm 10.8	–
	MPL	20	100	90.5 \pm 9.9	–
	MCT	–	100	–	–
<i>Perumytilus purpuratus</i>	SMI	25	100	84.8 \pm 17.4	2.5 \pm 0.6
	MPL	20	100	86.1 \pm 11.9	2.3 \pm 0.3
	MCT	20	100	91.0 \pm 8.4	2.3 \pm 0.4

fishers. These species included *Concholepas concholepas* (muricid gastropod, locally known as loco), *Fissurella* spp (keyhole limpets, locally known as chapas or lapas), *Pyura chilensis* (tunicates, locally known as piures), the Rhodomeniales *Sarcothalia* sp. (known as luga) and the Ceramiales *Chondracanthus* sp. (known as chicoria de mar). Furthermore, thousand of specimens of the giant jumbo squid *Dosidicus gigas*, crabs, sea urchins, chitons and snails, among other invertebrates, were stranded along the western and eastern coast of Santa María Island by the tsunami (Fig. 2c,d). According to locals, strandings on the northern tip and western coast of the island do not occur with any frequency on the island.

DISCUSSION

Ranges of uplifts based on intertidal vertical elevation of bleached lithothamnioid algae recently reported (Fariás et al. 2010) for localities included in our study agree well with our measurements. Further, this study was the first quantification of coseismic uplifted massive mortalities of intertidal and shallow subtidal invertebrate and bioengineer species, such as the mussel *Perumytilus purpuratus* and the algae *Macrocystis pyrifera* and *Lessonia nigrescens*. These species offer shelter for hundreds of invertebrates within their beds or holdfasts (Cancino & Santelices 1984, Prado & Castilla 2006).

On the southeastern Pacific coast, coseismic deformations (Lomnitz 1970, Comte et al. 1986, Beck et al. 1998, Melnick et al. 2006, Ruegg et al. 2009, Madariaga et al. 2010, Fariás et al. 2010) affect shallow infralittoral and intertidal communities. This causes large, sudden and

rapid mortalities, the disruption of zonation patterns, the alteration of local biogeography and species composition, the enhancement of local and widespread patchiness and produces temporal changes in marine coastal ecosystems (for Chile: Castilla 1988, Castilla & Oliva 1990, Ortlieb et al. 1996, present study). Also, in the southeastern Pacific, other sudden/cyclical drastic events, such as elevation of the oxygen minimum zone and ENSO, cause rapid mortality of the adult and early stages of pelagic species (Barber & Chávez 1983, Bakun & Broad 2003, Chávez et al. 2003), shallow subtidal shellfish species (Castilla & Camus 1992) and intertidal rocky and sandy-beach communities (Tomicic 1985, Soto 1985, Arntz et al. 1987, 1988).

The ecological role of natural sudden and/or predictable disruption and catastrophes on natural marine populations and communities has been repeatedly addressed. For instance, Harris et al. (1984) experimentally demonstrated that for kelp forests, after a major natural disturbance, refuge facilitation (rather than inhibition or neutral effects) substantially contributed to the regeneration processes. Dayton & Tegner (1984) reported that combined major disturbances regimes (strong winter storms and summer ENSO effects) may have long-lasting structural effects on *Macrocystis pyrifera* communities. Paine (1979) experimentally demonstrated that local population persistence of the sea palm *Postelsia palmaeformis* required predictable annual disturbance regimes of moderate intensity, while infrequent, large-scale catastrophes may contribute little to sea palm population persistence. In the same vein, Castilla (1988) monitored substantial changes in the intertidal–shallow subtidal vertical distribution of the competitively dominant kelp *Lessonia nigrescens* due to sudden rocky shore uplifts

caused by an earthquake in 1985, along more than 150 km of the coast of central Chile. Ecologically negative consequences on mid-intertidal zonation in the area lasted for several years, encompassing several generations of the species involved (barnacles, mussels and kelps) and impinging on the resilience of the intertidal ecosystems (Castilla & Oliva 1990).

Sudden or predicted drastic impacts effecting marine populations and communities have been regarded as natural erratic or cyclical unmitigated disasters (Castilla 1988). Large-catastrophic events translating into dramatic and rapid coastal biological disasters, such as that described here, may affect, for example, selection in impacted areas by disrupting gene flow from unaffected areas. Moreover, the recovery and resilience of marine populations or communities under scenarios with drastic and rapid catastrophes should be more challenging for species with direct development than for species with dispersive larval stages, because successful production of local offspring relies mainly on the survival of local parents. This highlights the value of the southeastern Pacific for studying the evolution of life history traits. Furthermore, understanding how marine populations, communities and ecosystems recover (van Nes & Scheffer 2007) and deal with highly disrupted environmental conditions (Castilla & Camus 1992) may have significance for management and conservation practices, as for example in connection with alterations of parental stocks and recruitment rates.

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