Co-seismic deformation of an estuarine terrace, Constitución, Central Chile

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ABSTRACT

In the terrace T_e, of Constitución, many fractures and associated deformations of its platform appeared in the street pavements after the earthquake of 02.27.2010. On this basis, this work deals with the co-seismic deformation in this terrace, observed by means of survey of fractures and associated superficial deformations. The principal undulated and irregular surface of the terrace shows no difference between the profiles surveyed before and after the 2010 seism, with exception of those that represent a minor part in the northward sector. In exchange, the flagstones or slabs of pavement show brittle micro-deformations or pop up like array structures associated to micro fractures produced during the seism. There is great dissimilarity of size order between principal irregularities of the terrace surface (undulations) and micro-deformations. The principal irregularities of the terrace T_e indicate that its undulated form is inherited and older than the seism of 02.27.2010. Only a minor part represents a 2010 co-seismic deformation with gentle warping of the inherited undulation during the seism. In exchange, the flagstone dislocations or brittle deformations shown as pop-ups like array are co-seismic microforms. They appear only as small tectonic deformations in the epidermis of the inherited undulated surface. Their apparent random distribution is possibly the result of a complex interaction between the seismic waves and the inherited topography, producing strain structures.

Keywords: Estuarine terrace, co-seismic deformation, pavement flagstone, pop-up, strain co-seismic structures.

Deformación co-sísmica de una terraza estuarial, Constitución, Chile Central

RESUMEN

En la terraza T_e de Constitución aparecieron muchas fracturas y deformaciones de su plataforma asociadas en los pavimentos después del terremoto de 27.02.2010. Sobre esta base, este trabajo trata de las deformaciones co-sísmicas en esta terraza, observadas mediante levantamiento de fracturas y deformaciones superficiales asociadas. La superficie principal de la terraza, ondulada e irregular, no muestra diferencia entre los perfiles levantados antes y después del sismo de 2010, con excepción de los que representan una menor parte en el sector noroeste. En cambio, las losas de pavimento muestran micro-deformaciones por quebradura o estructuras tipo *pop-up* asociadas a micro fracturas producidas durante el sismo. Hay gran desigualdad de orden de tamaño entre irregularidades u ondulaciones principales de la superficie de terraza y micro deformaciones. Las irregularidades principales de T_e indican que su forma ondulada es heredada y más antigua que el sismo de 27.02.2010. Solamente una menor parte representa deformación co-sísmica de la ondulación heredada. Por lo tanto, la superficie principal de la terraza fue sólo levemente alabeada durante el sismo. En cambio, las dislocaciones de losas por quebradura, tipo *pop-ups,* son micro formas co-sísmicas. Ellas aparecen sólo como pequeñas deformaciones tectónicas en la epidermis de la superficie ondulada heredada. Su distribución, aparentemente al azar, puede resultar de una interacción compleja entre las ondas sísmicas y la topografía heredada, produciendo estructuras de esfuerzo.

Palabras clave: Terraza estuarial, deformación co-sísmica, losa de pavimento, *pop-up*, estructuras de esfuerzo co-sísmico.

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INTRODUCTION

Different cases of Late Quaternary tectonic deformation controlled by folding emerge in the world (for ex. M_CINELLY & KELSEY 1990). In the coast, BERRYMAN (1993) found tectonic co-seismic deformation in Holocene terraces formed in estuarine sequences that record the relative change of sea level during part of the postglacial transgression. Jointly, persistent behavior of long-term uplift and subsidence above a megathrust rupture patch has been also deduced (BRIGGS *et al.* 2008). A continental analysis indicated the tectonic segmentation of the MIS 1 terrace in South America (ARAYA-VERGARA 2007). Complementary surveys of regional scenarios show recent coastal tectonic deformations (RAMÍREZ-HERRERA e*t al.* 2010). In an example of estuarine environment, KELSEY *et al.* (2011) chronicled the expansion and contraction of an estuary and the resulting pattern of sedimentation during a sequence of uplift, coseismic subsidence and new uplift.

After observations by ARAYA-VERGARA (1981 and 2003), an estuarine terrace named T_e, formed generally by fine sediments, is thought to be formed during the Holocene, starting from the corresponding correlation among different sites in Central Chile. With regard to the seismic location of this landform, DARWIN (1851) related his experiences about the giant earthquake of 1835, predecessor of the great 2010 earthquake. The zone of the corresponding plate boundary stayed stuck since 1835 until 2010, showing a "seismic gap" or "Darwin gap" in honor of Darwin. LORITO *et al.* (2011) and MELNICK *et al.* (2012) discussed its seismological connotations, in order to appoint the role of the great 1835 and 2010 earthquakes in the tectonic behavior of the regional continental margin. The result of this discussion indicates that Constitución (Chile) is in this seismic zone. VARGAS *et al.* (2011) observed land-level coastal changes produced by the M_w8.8 2010 earthquake in this region, in the rupture seismic gap considered as the maximal along-strike extent of it. In the same region, KELSON *et al.* (2012) observed that co-seismic tectonic deformation associated to the Mw8.8 2010 produced coastal uplift southward from Constitución and subsidence northward from this same site. Nevertheless, even if the regional and local effect of tectonics are discussed (LANDIS 2004; LANDIS et al 2004; KELSEY 2011) in this zone, the case of Constitución coastal uplift or subsidence is unreported in the revised works. In spite of the lack of direct report, the deformation models indicate some situations of no level change or "hinge lines" in the region (LORITO *et al.* 2011 and KELSON *et al.* 2012). This suggests that Constitución is in the principal "hinge line" (Fig. 1).

Some important observations carried out on disturbed anthropogenic pavements on unconsolidated sediments indicate valuable markers for the Quaternary tectonics and paleoseismicity (SILVA *et al.* 2005; RODRÍGUEZ-PASCUA *et al.* 2011; MARCO 2008). On the other hand, in the coastal sector of Navidad, Central Chile, ARRIAGADA *et al.* (2011) found some co-seismic fractures along road sections associated with the Mw 8.8 Maule 2010 earthquake. These authors interpreted these features as result of normal displacements and extensional cracks. Nevertheless, these accidents do not appear related with flagstones, but with compact pavements and without reference to one determined geomorphological landform. In the case of the estuarine terrace (T_e) in Constitución, many fractures and associated deformations of its platform appeared in the pavements composed by flagstones after the earthquake of 27.02.2010. On this basis, this work deals with the co-seismic deformation of this terrace, starting from the survey of fractures and associated deformations.

MATERIALS AND METHODS

The elected material

The estuarine terrace of Constitución (Fig. 1) represents the lowest coastal terrace in Central Chile, denominated T_e (ARAYA-VERGARA 2003). The evident post-seismic fractures, observed in the pavements of the existing streets on its surface, suggest that its structure results of a type of co-seismic deformation (Fig. 2).

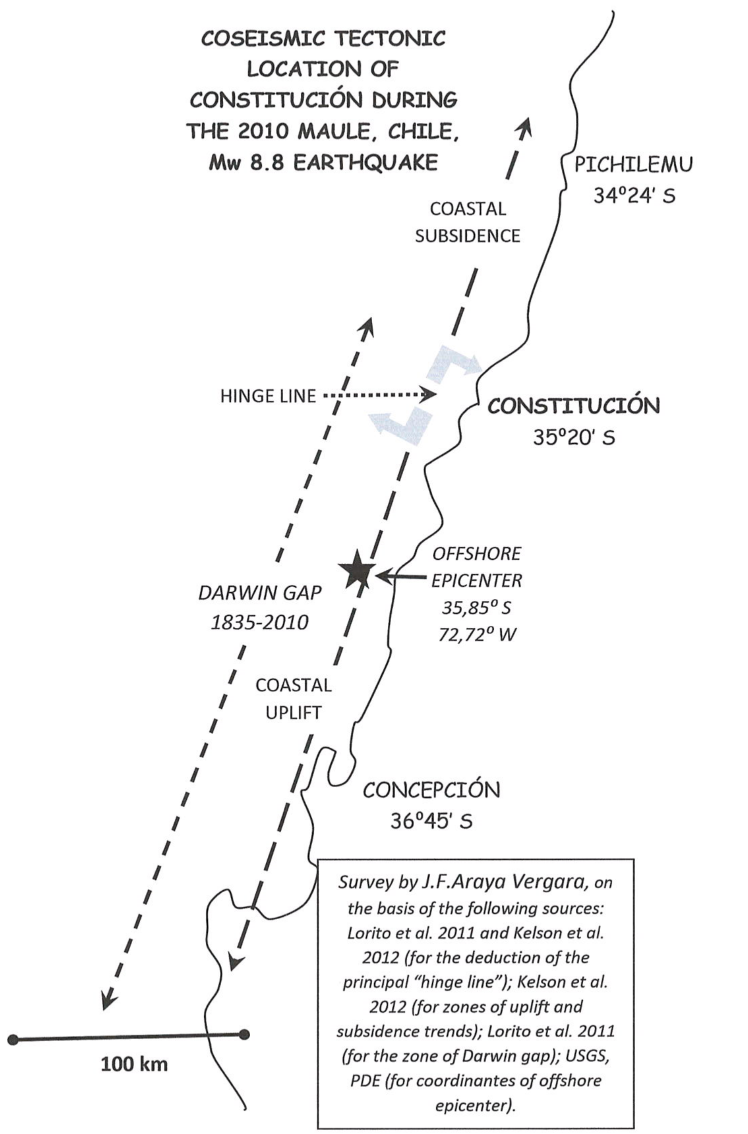

Fig. 1. Coseismic tectonic location of Constitución, Chile, during the 2010 Maule, Chile, Mw 8.8 earthquake.

Fig. 1. Localización tectónica cosísmica de Constitución, Chile, durante el sismo Mw 8.8 de 2010.

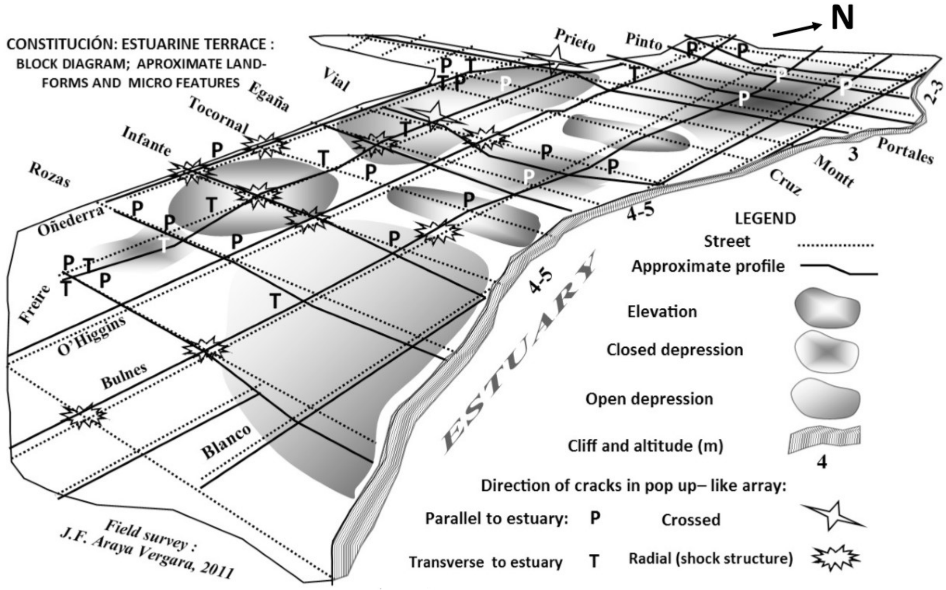

Fig. 2. T_e of Constitución: approximate sight of the principal undulate topography and micro deformations, represented by cracks.

Fig. 2. T_e of Constitución: vista aproximada de la topografía ondulada principal y micro deformaciones, representadas por grietas.

METHODOLOGICAL BACKGROUND

On the basis of a classification of earthquake environmental effects (EEE) established in the ES107 Intensity Scale (MICHETTI *et al.* 2007, in RODRÍGUEZ-PASCUA *et al.* 2011), have been studied earthquake archaeological effects (EAE), based on strain structures, due to primary or direct forcing produced by a major earthquake (SILVA *et al.* 2005; GINER-ROBLES *et al.* 2009; RODRÍGUEZ-PASCUA *et al.* 2011). Experience on folded and fractured pavements indicates that these structures are sensible under a strain field. They can be deformed either by brittle or ductile processes (ALTUMEL, 1998). Following the classification of seismic effects on pavements (SILVA *et al.* 2005; RODRÍGUEZ-PASCUA *et al.* 2011), there are two types of folded pavements: flagstone pavements and mortar pavements. The flagstone pavements show slabs separated by fractures. They present two categories: regular and irregular. In the regular one, the set of slabs has rectangular elements. In exchange, in the irregular flagstones, the slabs show bending and the deformed set lacks of rectangular elements, containing in the contrary multi-directional cracks. Both regular and irregular flagstone pavements present folds structures pop-ups. The expression pop-up is applied here to thrust or strike-slip movements between flagstones, named basement pop-up structures. A pop-up appears if a pair of oppositely moving slabs tend to move upward, because a conjugate thrust and back thrust interaction. In some cases, the opposite movement produces a type of tectonic wedge. On the other hand, in the mortar pavements there are no fractures in the slab, but only folds. For flagstones pavements separated by fractures, with regular fabric, the deformational elements are: orientation of the axis fold (flagstone orientation), dip direction and angle of flagstones, direction of both limbs of the fold, plunge of the axis fold, direction of the thrust (slip vector), length of shortening (*ey*) and its direction, parallel to the slip vector (RODRÍGUEZ-PASCUA *et al.* 2011).

Other type of structure in deformed pavements is the shock, consisting generally in triangular rupture in the corner-edge of the flagstones. This is due to horizontal movement produced by seismic waves, which trigger collision of flagstones and rupture of corner-edges. In regular pavements with perpendicular directions between slabs, the presence of shock structures results of the orientation of the flagstones with regard to the incoming seismic wave (STIROS 1996 in RODRÍGUEZ-PASCUA *et al.* 2011; MARCO 2008).

As result of these mechanisms, fractures in pavements of roads show three principal categories: a) Longitudinal: the cracks are parallel to the pavement's centerline of the road. b) Transverse: the cracks are perpendicular to the pavement centerline of the road (HU & XU 2001; training.ce.washington.edu 2009). c) With breaks without specified sense of deformation (SCHMIDT *et al.* 1995), which will be named *radial* in this work, because are result of convergence of two or more directional cracks, representing a *shock* structure.

Procedures

The field survey consisted on mapping of all the street pavement cracks, observed after the earthquake of 02. 27. 10, on the surface of the terrace Te. The crack directions were drawn on amplified image Google Earth (detailed scale ca. 1: 2500), using the classification proposed by HU & XU (2001) and SCHMIDT *et al.* (1995). Starting from the cracks, the segments of pavement were identified as flagstones or slabs. So, were observed the dip direction and angle of the opposed slabs, or otherwise, the lack of local declivity and the possible existence of pop ups structures. Some declivity angles close to cracks were measured with clinometer (Brunton type compass). At the same time, the general declivity of streets was estimated preliminarily and qualitatively by sight, but their profiles were surveyed by means of the profiler associated with Google Earth (Image 2014 Terra Metrics; Data NOAA; Images 2014 CNES/Astrium). They were surveyed lengthwise of the streets on the terrace surface. These profiles are reliable only for to show the form of the terrace surface, in terms of its irregularities (profit or loss of elevation), but not its absolute altitudes. In order to find the possible deformational effects of the 02.27.2010 earthquake, two set of profiles were compared: for 2009 and 2013 (before and after the seism). They were confronted with the location of cracks. In order to determine extension and general altitude of the terrace, the topographic base chart used was *Constitución: Carta de Inundación por Tsunami* (1: 10.000) of the Servicio Hidrográfico y Oceanográfico de la Armada, with contours every 5 m. The altitude of the terrace scarp in the estuarine border was established directly with tape and referred to the high tide level in the estuary, applying 6 measurements placed at the distance of ~ 200-300 m, starting from the seaward end and covering all the estuarine edge in front of the city (ca. 1.5 km).

RESULTS

General sight of the terrace T_e

As indicates the Table 1, this terrace is an approximately plane landform. Its general declivity between the inner limit and the scarp is hardly perceptible by sight. Altogether, it presents also scanty perceptible declivity down estuary next to the scarp. There are local deviations with regard to this general feature and in direction of the azimuths indicated in the table. The Fig. 2 represents an approximate sight of the principal undulate topography, showing the irregularities of the terrace surface and the distribution of the micro deformations represented by structures of pavement cracks.

Two order of declivity angle are detached in the terrace surface: a) General and scanty perceptible one, in which the streets with azimuths of ~335 show an indifferent declivity trend (Fig. 3); in exchange those with azimuth ~65°, point out a landform sloping toward the estuary (Fig, 4). b) Special and perceptible, represented by streets with azimuths of ~335 and 65°, which renders possible the description of the principal irregularities (Figs, 3 to 7).

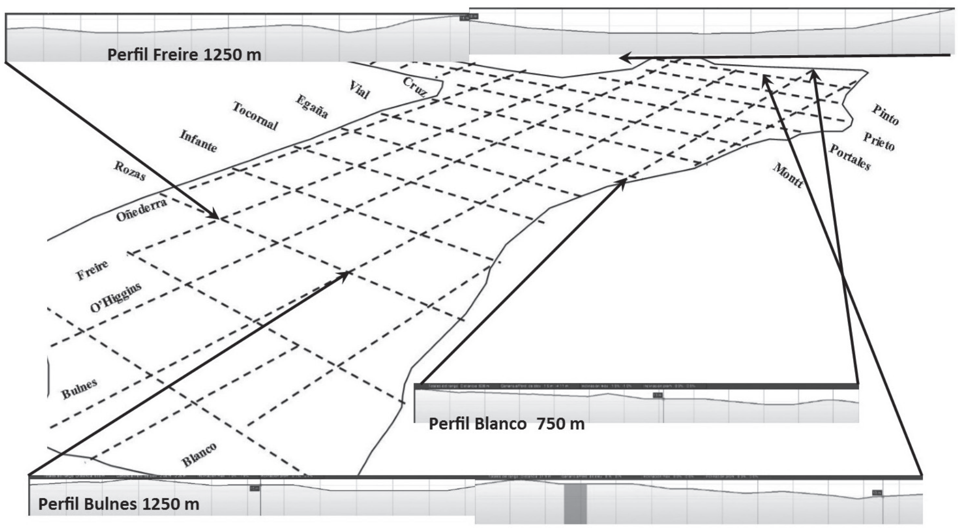

Fig. 3. Profiles of streets (azimuth 335°).

Fig. 3. Perfiles de calles (azimuth 335°).

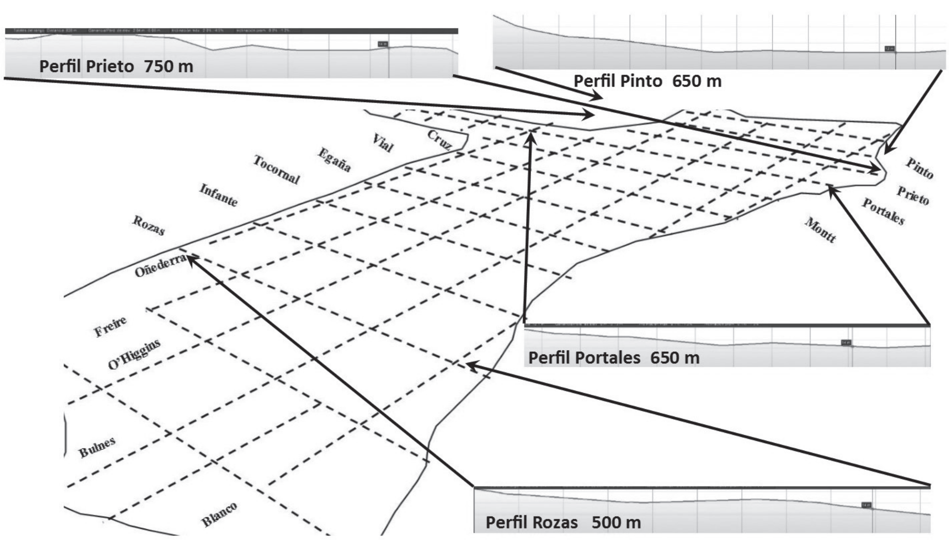

Fig. 4. Profiles of streets (Az 65°).

Fig. 4. Perfiles de calles (Az 65°).

Table 1. General morphometry of T_E

Tabla 1. Morfometría general de T_E

General elements	**Area (Km2)**	**Innermost contour (m)**	**Max. registered height (m)**	**Scarp in estuarine line (m), from N to S**
	~2.3	5	7	~3 toward de N – 4 or 5 toward the S
General declivities	**Streets of Az = 335°**	**Streets of Az = 65° (degrees)**	**Principal deviations Az = 335° (degrees)**	**Principal deviations Az = 65° (degrees)**
	Indifferent	Toward the estuary = 0.2 – 0.3	1.4 – 0.3 – 0.2	0.6 – 0.4 – 1.4
Degree of undulation	**Streets Az = 335°, wave length (m)**	**Streets AZ = 65°, wave length (m)**	**Δ height summit – depression (m)**	**Slopes θ °**
	416 – 166	250 – 217	1 – 2	0.7 – 0.3

The undulated and irregular surface

Principal irregularities (pre and post seismic impact)

The surveyed profiles of streets indicate topographical differences among them, showing local irregularities of the terrace surface. The differences of elevation among segments of each street are of some decimeters to one or two meters. Generally, the profiles for 2009 and 2013 (before and after the 2010) seism show no morphological difference (Examples in the Fig. 5). Consequently, in the detail, the principal surface of the terrace is gently irregular, but generally unchanged by the 2010 earthquake.

Deformational features. The principal surface (Figs. 4 and 5; 6 and 7)

In the southward sector, the profile of O'Higgins Street is the same before and after the 2010 seism. However, in the northward sector the distribution of depressions and elevations before and after the seism is incongruent (Fig. 6). This type of change is observed also in the profile of Portales, perpendicular to O'Higgins Street and in the environs of its crossing, what indicate that the deformation affected a specific sector of the northern part of the terrace (Fig. 7). In O'Higgins Street, the zone of change covers ~300 m (between Portales and Pinto streets). The deformation consists in a widening and regularization of the pre-existent bottom in a local depression. The differences of elevation between 2009 and 2013 are commonly decimetrical. The similar deformation observed in the profile of Portales street, near the limit of the deformed zone, indicates a little subsidence trend, but in Prieto Street – northward of Portales – there is no seismic deformation (Fig. 7).

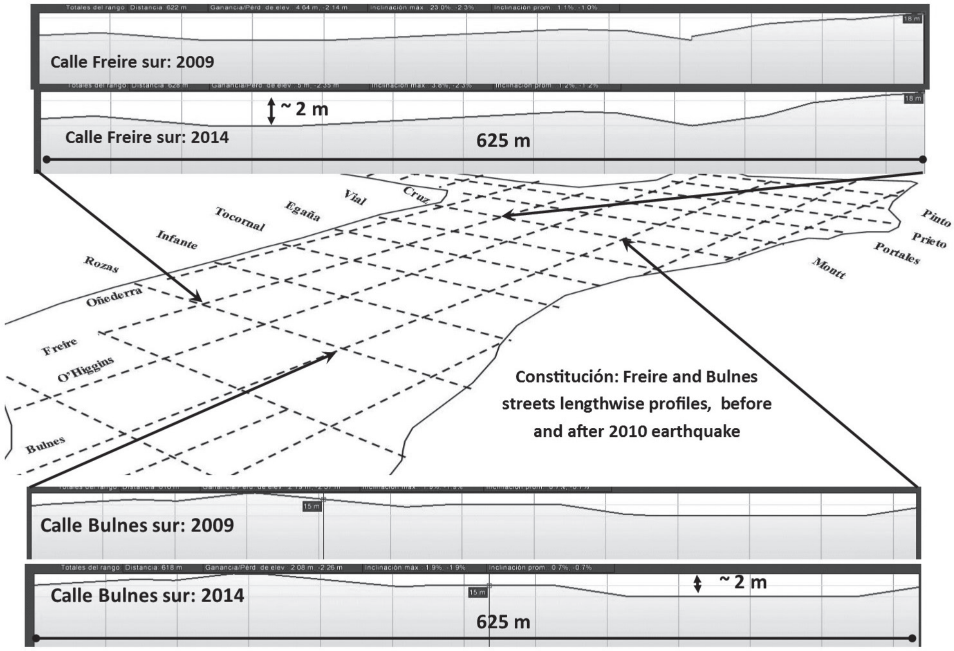

Fig. 5. Examples of street profiles (Az 335°) unchanged by the 2010 seism.

Fig. 5. Ejemplos de perfiles de calle (Az 335°) no cambiados por el sismo de 2010.

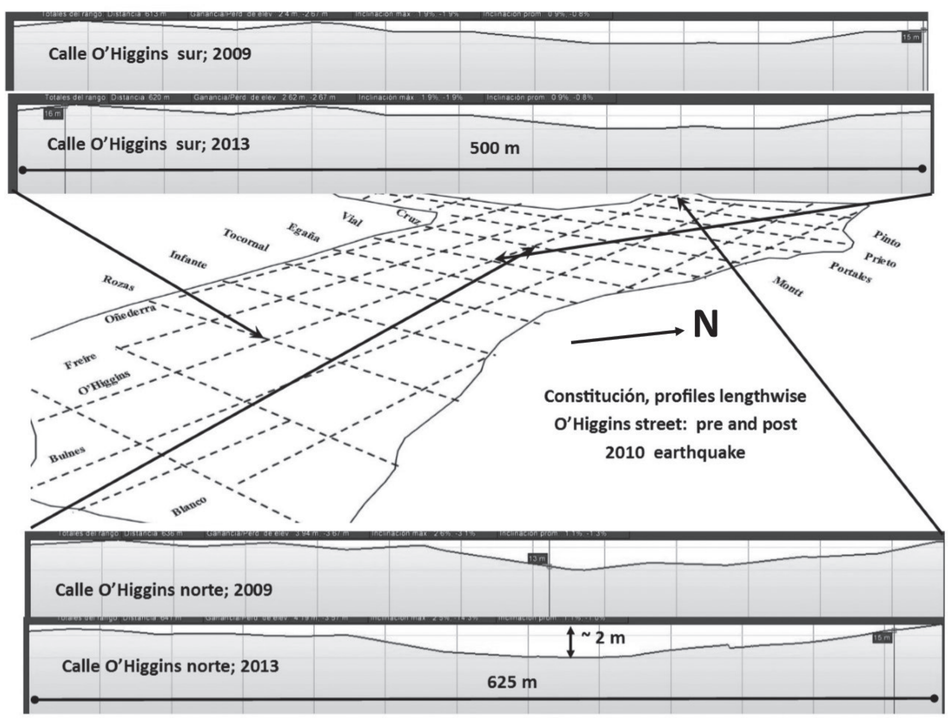

Fig. 6. Profiles of O'Higgins Street, indicating change in the northern part during the 2010 seism.

Fig. 6. Perfiles de calle O'Higgins, indicando cambio en la parte norte durante el sismo de 2010.

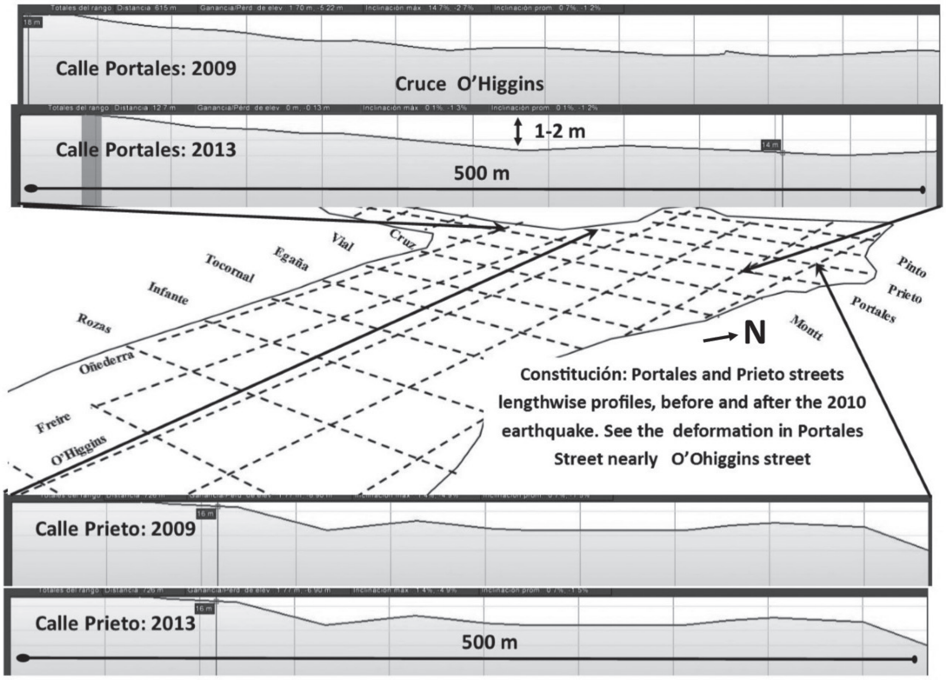

Fig. 7. Profiles of Portales Street, indicating change in the environs of O'Higgins Street during the 2010 seism. Prieto Street as reference.

Fig. 7. Perfiles de calle Portales, indicando cambio en las inmediaciones de calle O'Higgins durante el sismo de 2010. Calle Prieto como referencia.

Micro deformations

The Table 2 indicates examples of characteristically observed structures, consistent in deformations of pavement flagstones, expressed in different types of pop-ups or pop up-like arrays, where faults separate distorted slabs. The corresponding features suggest that they result of thrust or strike-slip movements between flagstones, named basement pop-up type structures. Between a pair of moving slabs, the observed pop-ups or pop up-like arrays appear where at least one flagstone tends to move upward and its surface dips showing itself as a reverse slope with respect to the fault. Generally, little faults separate flagstones. The Figure 2 shows the distribution of cracks orientation. There are different styles of micro tectonics for flagstones separated by unidirectional cracks or faults: dipping slab vs. normal slab, two or more dipping slabs vs. normal slab and two or more dipping slabs. There are also bidirectional sets conforming crossed structures and multidirectional sets shaping radial structures or shocks.

The Figure 8 and 9 show the principal cases of micro deformations analyzed in the field. All these styles indicate that they resulted of brittle deformation in flagstone pavement. Consequently, they are regular strain structures.

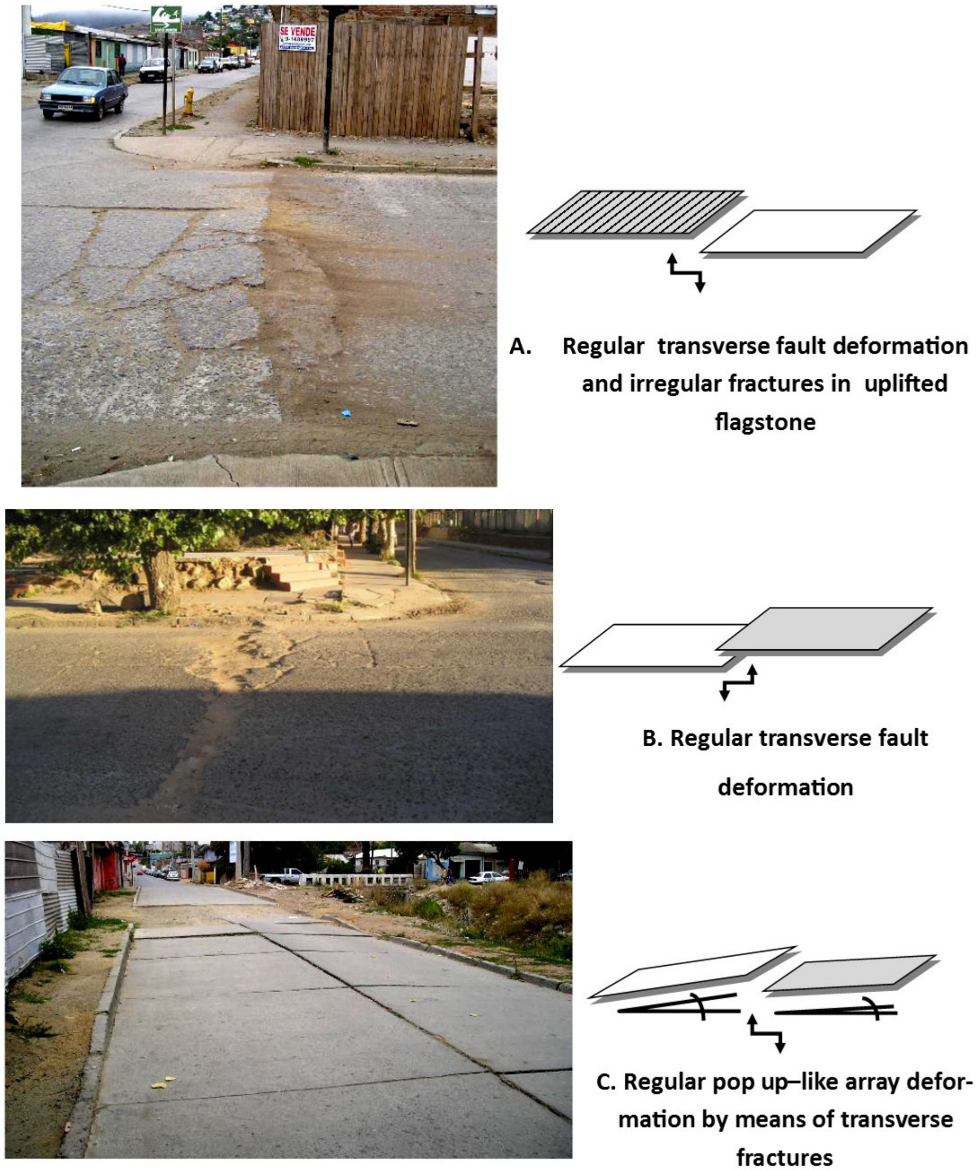

Fig. 8. T_e surface: examples of regular and simple pop up-like arrays.

Fig. 8. Superficie de T_e: ejemplos de estructuras tipo pop-up regulares y simples.

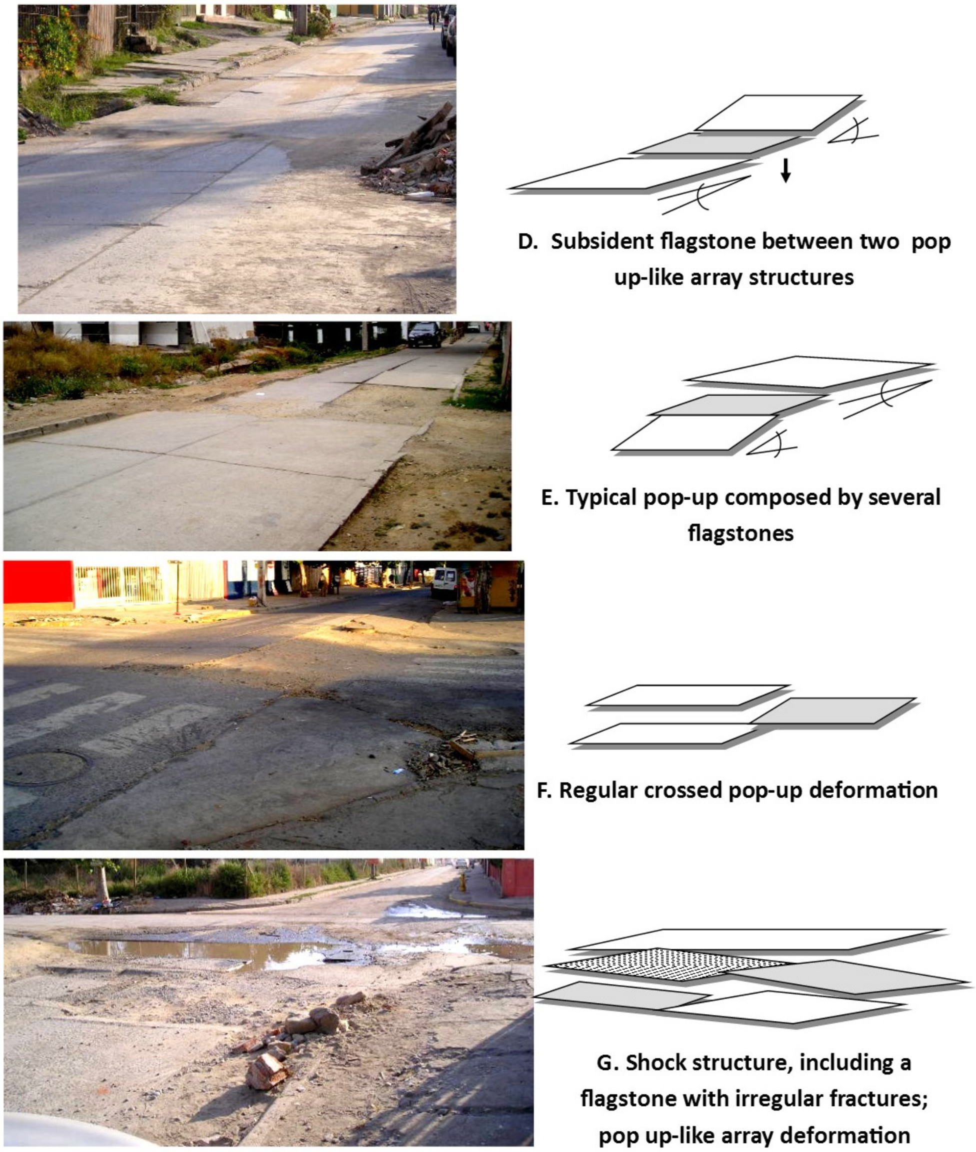

Fig. 9. T_e surface: examples of composite or complex pop up-like arrays.

Fig. 9. Superficie de T_e: ejemplos de estructuras tipo pop-up compuestas o complejas.

Size orders: principal irregularities vs. micro-deformations

The street profiles (Figs. 3 to 7) indicate that the common apparent wavelength of the principal irregularities fluctuate between 200 and 400 m. Their difference of elevation is only metrical or decimetrical. In exchange, the brittle micro-deformations measured in the field are metrical in their extension and centimetrical in their height difference of slabs (Table 2). Consequently, there is a great dissimilarity of size order between principal irregularities and micro-deformations. Altogether, the Figure 2 and 10 indicate that the different types of pop-up and the specific elements of the principal undulation have independent locational patterns. Inside the principal irregularities, deformed flagstones appear indistinctly in summits and depression bottoms (whose declivity angles fluctuate between 0.2 and 1.4°, see Table 1). In exchange, the dip angle of deformed flagstones is generally 2-5° (Table 2).

Table 2. Examples of brittle deformations in flagstone pavements in streets of Constitución.

Tabla 2. Ejemplos de deformaciones quebradizas en calles de Constitución.

Corner between streets (see Fig. 3)	**Street between two crossed streets (see Fig. 3)**	**Direction of cracks**	**Style: crack, dip angle, slab, zimuth** Inner border of terrace ⟷ direction Scarp estuary
O'Higgins – Rozas		Longitudinal (parallel to estuary)	~10 cm 2-5°; 45-60°.
Freire – Rozas		Longitudinal (parallel to estuary)	2-5°; 225-240° ~10 cm
	Rozas between Freire and Oñederra	Transverse (parallel to estuary)	2-5°; 225° ~10 cm 7-8 m
	Oñederra between Rosas and Infante	Longitudinal and transverse	1-2°; 225°-240°
Oñederra – Infante		Longitudinal (parallel to estuary)	2-5°; 225° ~10 cm 4 m
Oñederra – Tocornal		Crossed and radial	~10 cm 2-5°; 45-60° Frequent dip

DISCUSSION

If the deformation model of the central coast (LORITO *et al.* 2011 and KELSON *et al.* 2012) suggests that the terrace of Constitución is settled in a zone of no level change or "hinge line" in the region affected by the seism of 02.27.2010, the terrace T_e was not importantly uplifted nor subsided during this impact. The field observations agree with this deduction. The undulated surface (principal irregularities) of the terrace is not result of the 2010 rupture, with exception of one small sector in the northern part of the terrace, as evidenced by the topographic profiles. The field observation in this sector do not indicate influence of the 2010 co-seismic tsunami in its change, which suggests only a tectonic origin. In exchange, the preexistent irregular surface of the nearly entire terrace seems a differentially settled ground and not necessarily a co-seismic feature. Observations of a similar case in the Dead Sea fault zone indicated intuitively the influence of inherited factors on co-seismic features (MARCO 2008). In the case of Constitución, the morphogenetic role of the undulated surface can be compared with the model of HOPKINS (1838) exposed by DARWIN (1851) about the deformational response of a cover overlaying an undulated terrain. It indicates that, starting from its summits, the cover disjoints into slabs. Therefore, the dip of the slabs imitates the slopes of the undulated terrain. The resulting features are equivalent of pop-ups in the summit zone. Nevertheless, the types of geomorphological placing shown by the micro-deformations in Constitución, expressed as pop-ups in flagstones, disagree with this model, because these features appear in different element of the inherited topography (not necessarily the summits).

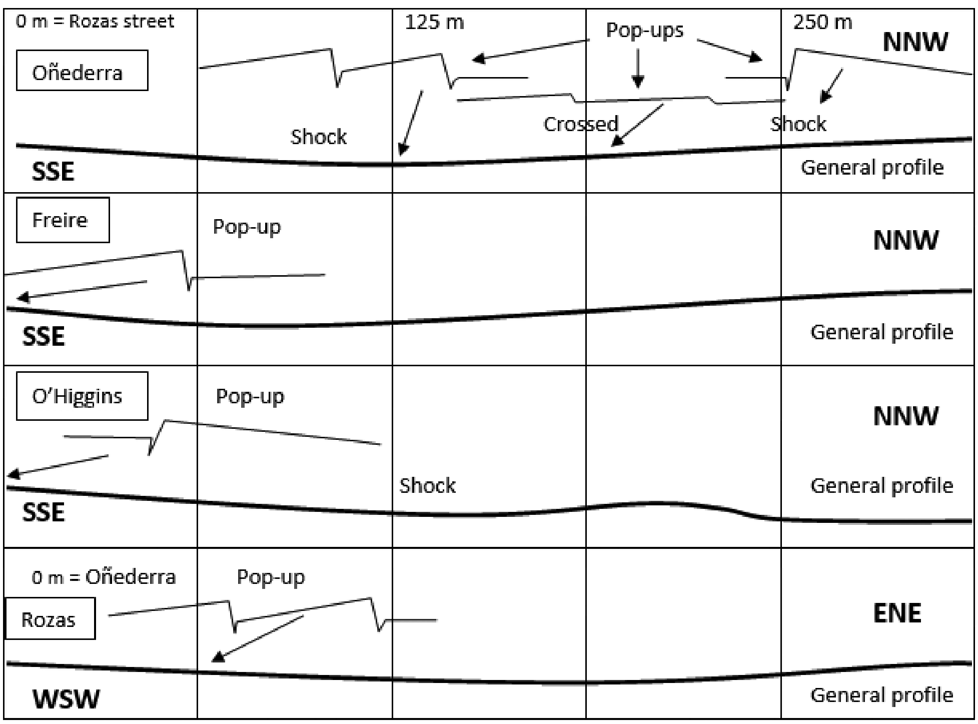

Fig. 10. Examples of deformed flagstones expressed as pop up-like arrays and their placing in the general form of the respective street pavement profile.

Fig. 10. Ejemplo de losas expresadas como estructuras tipo pop-up y su emplazamiento en la forma general del perfil del pavimento de calle respectivo.

According to the classification of seismic effects on pavements (SILVA *et al.* 2005; RODRÍGUEZ-PASCUA *et al.* 2011), the observed flagstone pavements in micro-deformations can be both regular and irregular and their principal deformational elements can be used in order to explain the distribution of the corresponding structures. However, this distribution is apparently random and, consequently, its analysis very difficult. Nevertheless, an approximate way of analysis is possible, describing the frequency of pop-up types. In the regular flagstone pavements, the set of slabs has rectangular elements, indicated by the cracks and fault direction, due to its regular fabric. Of 41 observed pop-ups, 49 % of the cracks or faults is parallel to the estuarine coastline and 24 % is transverse to this line. In the parallel case, the dip angle of flagstones can be both toward the estuarine scarp and toward the inner border of terrace. For the cases of irregular flagstone pavements, only 5% are crossed structures and 22 % are shock deformations with multidirectional cracks. There is no clear field evidence of mortar pavements expressed only as folds, but some of fault tectonics in anticlinal structures are possible in the pavement. Therefore, its likely existence suggests only the orientation of fold elements (limbs, plunge, *ey* or length of shortening). On the other hand, the distribution of shocks is apparently random. They seem due to horizontal movement produced by seismic waves, which trigger collision of flagstones and rupture of corner-edges in regular pavements with perpendicular direction between slabs (STIROS 1996 in RODRÍGUEZ-PASCUA *et al.* 2011; MARCO 2008).

CONCLUSIONS

In order to evaluate the degree of deformation of the terrace T_e as consequence of the 02.27.2010 seism, it is necessary to take into account the differences between the principal undulation and the distortions of minor features. The seism produced only a gently and well localized warping of the terrace. In exchange, the flagstone dislocations shown as pop-ups are co-seismic microforms or small deformations on the inherited undulated surface. In other words, they are epidermal landforms on the summits, slopes and bottom of a pre-existent surface. This apparent random distribution can be the result of a complex interaction between seismic waves and inherited topography. As general conclusion, the co-seismic deformation of an estuarine terrace ought to be studied comparing landforms of different size order in its surface.

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