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The effect of subduction earthquakes on the coastal configuration of Northern Chile

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INTRODUCTION

The western border of Coastal Cordillera of northern Chile 18,5°S- 27,5°S, is characterized by the presence of a coastal cliff of 1 km height being the link with the sea. North Iquique (20°S), the cliff plunges directly to the sea and south Iquique, a coastal plain is developed at the base of the cliff with emerged Pliocene-Pleistocene marine platforms and terraces, isolating the cliff to sea wave abrasion (Fig. 1). The width of the coastal plain south Iquique is variable, with an average 1 km, the maximum at Mejillones Peninsula (23°S) and Caldera (27°S) with 10 km and former shore lines above its surface. These features indicates differential uplift rates. The age of the coastal cliff are constrained between upper Miocene and Lower Pliocene due to the Miocene continental rocks at the top of the cliff and the Pliocene marine rocks in the emerged platforms at the base of the cliff (Mortimer and Saric, 1975). Over these rocks, there are Pleistocene marine terraces in some places. Uplift rates are obtained in Michilla (22,7°S) 0,27 mm/yr for the upper Pleistocene; in Hornitos (23°S), 0,24 mm/yr for the upper Pleistocene; in Antofagasta (23,5°S) 0,06 mm/yr during the Pleistocene (Delouis et al, 1998); and Caldera (27°S) 0,34 mm/yr for the upper Pleistocene (Marquardt *et al* , 2004). Former processes that explained the coastal uplift of north Chile are the subduction erosion, the accretion of basal sediments and duplexing (von Henue and Ranero, 2003). The problem is that not evidence of uplift is located in all places at the base of the coastal cliff, and even do not explain the Pliocene subsidence of the shore area of north Chile (Mortimer and Saric, 1975). The subduction seismic cycle is a process that produced uplift and subsidence and in the present discussion, we try to establish a direct link between the vertical movements associated to the subduction seismic cycle and the field evidences of uplift or subsidence. We will consider emerged dated surfaces for upper Pleistocene-Holocene ages considering the earthquakes that they could experienced.

SUBDUCTION EARTHQUAKE CYCLE AND EVIDENCES OF COASTAL UPLIFT

The subduction seismic cycle consists in four phases of deformation (Thatcher & Rundle, 1979): preseismic, coseismic, post seismic and interseismic, during a complete cycle the total movements are quasi elastic. To simplify the analysis, we will consider only the two phases more important: interseismic and coseismic. During the interseismic phase both plates are locked, so deformation energy is cumulating producing a flexure of the forearc zone on the overriding plate. The interseismic deformation in north Chile can be showed by GPS studies (Klotz et al, 1999, Chlieh et al, 2004) indicating that the forearc zone is moving arcward in the direction of convergence decreasing the values from coast to arc. During the coseismic phase, both plates are decoupling and the flexure of the overriding plate extends towards the trench in the same direction of convergence but opposite sense. This extension can be observed in GPS surveys during the 1995 Antofagasta earthquake of northern Chile and 2001 (Klotz *et al*, 1999) and for the Arequipa earthquake of southernmost Peru (Ruegg *et al* 2001). In this process a zone of coseismic uplift is located close to the trench and subsidence arcward. It is observed that during a complete cycle, more of the coseismic movements are recovering during the interseismic phase, but not all, so the coseismic phase is dominant during a complete seismic cycle in most subduction zones of the circumpacific (Thatcher & Rundle, 1979). With these features of seismic cycle, we will consider two aspects to relate this with the upper Pleistocene-Holocene field evidences of uplift and subsidence: (1) The normal trench shore distance between the coseismic uplift and subsidence: if the uplifted zones coincides with coseismic uplift and (2) Interseismic recovery: if the theoretical cumulative coseismic uplift experienced by dated uplifted surfaces is bigger than real one. To do this, the algoritm of Okada (1995) is used to model a subduction earthquake with the seismotectonic features of northern Chile. It consist in a Wadatti-Benioff dip plane of 22° and seismic coupling between 10-50 km depth (Delouis et al, 1998). With these data, the curve of vertical coseismic movements is generated and the distance of transition between the trenchward uplift and arcward subsidence is measured. This distance is measured in north Chile from trench axis and will be compared with the shorelines that lies in the uplift areas and if this shorelines has field evidence of uplift like uplifted marine terraces or emerged platforms (Fig.1), for the contrary the shores that lies in the subsidence zone will be compared if they coincides with the active coastal cliff. It was checked that the transition zone between uplift and subsidence depends of seismic coupling width and dip of Wadatti-Benioff zone and not of slip or rake of the sliding along the Wadatti-Benioff plane, it only has effects in the vertical amplitudes. To compare the cumulative coseismic uplift and the real one (interseismic recovery), it is requested the vertical coseismic amplitudes of the characteristic earthquake and the time of recurrence of an area with several dated uplifted surfaces. The uplift of the shoreline in a given area is obtained from the curve of vertical coseismic movements obtained by the Okada (1995) algorithm considering the characteristic earthquake measuring the trench-shore distance and the vertical coseismic movement corresponding at that distance. The age of the emerged surfaces as marine terraces are known, so they are divided by the recurrence time of the earthquakes, so the amount of earthquakes experienced by these surfaces from their emerging time is obtained. Then it is multiplied the number of earthquakes obtained by the uplift obtained in the curve of coseismic movements. It is assumed to simplify the analysis uniform slip and recurrence time of the earthquakes and the eustatic variations of sea level is neglected. The chosen area in north Chile to compute the interseismic recovery is Caldera, 27°S (Fig. 1) because there are many dated uplifted terraces and the seismotectonics of this area is known. The dated uplifted marine terraces in Caldera and Bahia Inglesa (2 km south Caldera) are obtained from Vita-Finzi and Mahn (1994) and Marquardt et al (2004), Table 1. The dip of the Wadatti Benioff is 22° and the seismic coupling ranges between 10-50Km (Comte et al, 2002). The last characteristic earthquake that struck that area occurred in 1922. Some geometric parameters of this earthquake are obtained with teleseismic analysis by Beck et al (1988) the fault plane N20°E/20°SE. The Mw magnitude of this earthquake is assumed bigger than 8.0 because it produced a strong tsunami with runoff over 9 m in the coasts of north Chile (Beck *et al* 1988). From such features, 8 m of slip for the 1922 earthquake is considered. The recurrence time for this earthquake, was obtained by Belmonte and Comte (1997) being 126 years. The geometry of the fault plane considered is N8°E/22°E, the strike was assumed parallel to the trench and the dip considering the geometry of the subduction zone at that area 22°. It is generalized for all north Chile. The results are shown in Fig.2.

From Fig. 2, the normal trench distance of transition between coseismic uplift and subsidence is 105 km. So it is traced from trench (Fig 1). It can realize that south Iquique, the trench and shoreline are almost parallel but north Iquique, the trench-shore distance increases because the trench change it strike from N8°E approximately to N40°E and the shoreline remains in NS strike. So it lies in the teoric coseismic subsidence. It was reported that the 1868 and 1877 earthquakes of northernmost Chile, produced subsidence in the shore between Arica and Iquique (Kausel, 1986). So it agrees well with this results and north Iquique, begin the area of active cliff without evidences of uplift (emerged marine terraces or platforms). South Iquique, the most shoreline lies in the area of coseismic uplift. The Mejillones peninsula and Caldera area are the most westward shorelines and has the biggest uplift rates of northern Chile with paleo shorelines in their surface. So it is a clear relation between the areas of teoric coseismic uplift and subsidence and the evidences on field and that the uplift is bigger in westward shorelines in the areas of bigger coseismic uplift. About the interseismic recovery in the Caldera area, the results are shown in Table 1 and are consistent in all marine terraces with values between 95,4 - 97,5%. If cumulative earthquakes took place, the height of the oldest 410 ka terrace should be over 4 km, so it is located below 0,2 km. These results agrees well with the quasi elastic behaviour of seismic cycle and the remanent uplift is interpreted due to the coseismic uplift not recovered in the interseismic phase during the subduction earthquake cycle. The similar values of interseismic recovery obtained in surfaces of different ages and heights, suggests the uniform repetition of similar earthquakes in time. If we change the slip of the fault assuming 0,3m of coastal uplift, the interseismic recovery values are in the order of 85% and if it is assumed 2,3m, the values are in the order of 98%. If the isostatic sea levels (Pillans *et al*, 1998) for the ages of the terraces are included in the heights of the terraces, the values of interseismic values do not vary very much. The important interseismic recovery and the coincidence between the areas of coseismic uplift and coastal plain at the base of the coastal cliff with emerged marine terraces and platforms and coseismic subsidence with the active cliff north 20°S, indicates that the seismic cycle of subduction earthquakes is an important factor controlling the uplift and subsidence in the shore of north Chile rather than local tectonics.

CONCLUSION

The subduction seismic cycle plays a major role that controls the uplift or subsidence of the shoreline in north Chile and the geometric factor that controls it is the normal trench-arc distance between coseismic uplift and subsidence. If the trench-shore distance is lesser than the transition one; it is espected uplift and emerged marine platforms, if not, subsidence and the submergence and erosion of the former relief like the coastal cliff of northern Chile, that continues receding north 20°S.

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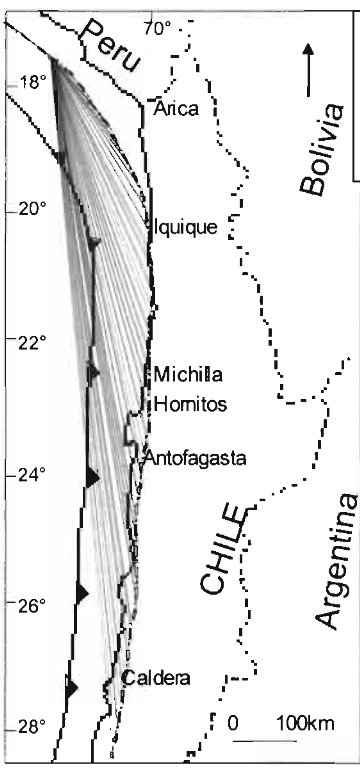

Fig. 1 Location map. Segmented line: transition between coseismic uplift (left) and subsidence (right).

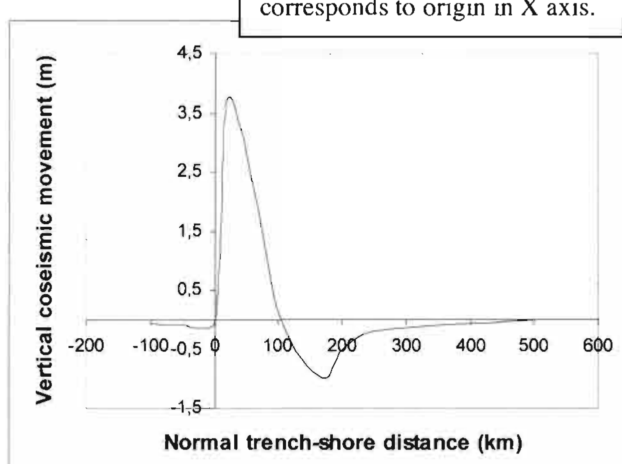

Fig.2. Coseismic vertical movements for the 1922 Atacama earthquake using the 1995 Okada algorithm. Trench corresponds to origin in X axis.

Table 1 Interseismic recovery for 7 terraces in Caldera area. Height and age from Vita-Finzi and Mahn, (1994) and Marquardt et al, 2004).

Location	age (ka)	height (m)	Number of earthquakes	Total coumulative coseismic uplift (m)	Interseismic recovery (%)
B. Inglesa**	430	139	3413	4436,9	96,9
B. Inglesa*	210	78	1667	2167,1	96,4
B. Inglesa*	100	31	794	1032,2	97,0
B. Inglesa*	29,2	7,5	231	300,3	97,5
Caldera**	430	162	3413	4436,9	96,3
Caldera*	210	67	1667	2167,1	96,9
Caldera*	34,4	16,5	273	354,9	95,4