Investig. Geogr. - Santiago, Chile, 43: 17-34

Submarine failures in the bottom of the Aysén fjord, Northern Patagonia, Chile

José F. Araya Vergara[1] jaraya@uchilefau.cl

ABSTRACT

The present work deals with the relationship between the dislocated sedimentary structures of fjord sub-bottom and the possible sequence of failures in the Aysén Fjordland. The longitudinal profile of the fjord was obtained by means of a 3.5 kHz sub-bottom profiler record, obtained on board of the Vidal Gormaz research vessel. The observations were principally carried out in the ponding esplanade located in the zone of seismic cluster below the fjord. Here, the deformations of the visible sub-bottom affect all the thickness of sediments. There are different styles of deformation of sediments, with greater breakup in the older than in most recent layers. Its ^{14}C and ^{210}Pb age extends since the Termination I (Last Glaciation) until the Upper Holocene. Between 1922 and 1995 the earthquake of 1927 happened, giving an inter-seismic period of 80 years until 2007. This earthquake affected with smaller deformation up to the most recent layers judging by its ^{210}Pb age. A sub-bottom record post 2007 earthquake indicates disruptions of the tectonic structures recorded in1995. Therefore: a) the sub-superficial layers of ages between the Holocene and the Termination I can have been deformed also by earthquakes previous to 1927; b) these processes must be recurrent, sleeping, with renewed unbalances; c) its type of frequency must be episodic, oscillating between low (100 to 1000 years) and middle (0 to 100 years); d) its way of activity is by rupture; and e) the known frequency is between *ancient-historical* and *recent historical* (1 to 200 years BP or more).

Key words: Fjord, ponding esplanade, submarine failure, frequency, Aysén Fjord.

Procesos submarinos de ruptura en el fondo del fiordo Aysén, Norpatagonia, Chile

RESUMEN

Se estudia la relación entre estructuras sedimentarias dislocadas de sub-fondo y procesos de ruptura en el fiordo Aysén. El perfil longitudinal de éste fue obtenido mediante registros de un perfilador de subfondo a 3.5 kHz obtenidos a bordo del buque de investigación Vidal Gormaz. Las observaciones fueron hechas principalmente en la explanada de represamiento localizada en la zona de enjambre sísmico del fiordo. Aquí, las deformaciones del sub-fondo visible afectan todo el espesor de sedimentos. Hay diferentes estilos de deformación de sedimentos, con mayor ruptura en las capas más antiguas que en las más recientes. Su edad C^{14} y Pb^{210} se extiende desde la Terminación I (Última Glaciación) hasta el Holoceno Superior. Entre 1922 y 1995 sucedió el sismo de 1927, dando un período inter-sísmico de 80 años hasta 2007. Este sismo afectó con menor deformación a las capas más recientes según su edad Pb^{210} . Un registro post sismo 2007 indica rupturas en las estructuras tectónicas registradas en 1995. Por lo tanto: a) las capas sub-superficiales de edades entre el Holoceno y la Terminación I pueden haber sido deformadas también por sismos anteriores a 1927; b) estos procesos deben ser recurrentes, durmientes, con desbalances renovados; c) su tipo de frecuencia debe ser episódico, oscilando entre bajo (100 a 1000 años) y medio (0 a 100 años); d) su tipo de actividad es por ruptura; y e) la frecuencia conocida está entre *histórica antigua* e *histórica reciente* (1 a 200 años AP o más).

Palabras clave: Fiordo, explanada de represamiento, ruptura submarina, frecuencia, Fiordo Aysén.

Recibido el 27 de abril de 2011, aceptado el 22 de noviembre de 2011

---

[1] Departamento de Geografía, Facultad de Arquitectura y Urbanismo, Universidad de Chile. Portugal 084, Santiago, R.M. Chile.

INTRODUCTION

The first longitudinal profile of Aisén Fjord was obtained after the cruise Cimar Fjords 1 (ARAYA-VERGARA 1997). This profile shows troughs separated by sills. The sub-bottom of troughs is composed by laminated multi-beds sediments, which indicate a ponded structure. Because of this, the corresponding submarine forms were called *ponding esplanades* (Fig. 1). The genetic problem of the North Patagonian fjord bottoms was discussed by ARAYA-VERGARA (1998), starting from the study of the genetic relationships between morainal banks and ponding esplanades, including also the influence of mass movements. Distal dislocations in laminated facies of the inner trough (Fig. 1) were succinctly shown in ARAYA-VERGARA (2008a). The deformations are located next to the sill, which separates the inner and outer troughs of the fjord. They correspond successively to folds and features of mass movements recorded at 1995 in the area of the 2007 seismic crisis (ARAYA-VERGARA 2008b). Some landforms of submarine slope mass removals were shown by VIEIRA (2001) in the distal part of the fjord, and for the sector next to the sill between the inner and outer troughs (VIEIRA 2002). After the seismic crisis of January-April 2007, an analysis of this sill located in the area of seismic swarm (LARA 2008) indicated that this form is a volcano, inactive at present. Recent observations with echo-records of a 3,5 kHz acoustic profiler, suggest that the sill can be interpreted as a monogenic volcano controlled by faults (VARGAS *et al*. 2009). Searching the effects of the 2007 seismic crisis, these authors found that the sediments are also deformed by inverse and dextral faults, interpreted as the result of transpressive tectonics. Starting from the seismological, tectonic and volcanological analysis, LEGRAND *et al*. (2010) interpret this co-existence of tectonic and volcanic phenomena as retroactive links between volcanic fluids and fractures.

The age of the superficial beds of these sediments was established by SALAMANCA & JARA (2003). In the station 79 of the Cimar Fjords 1 cruise on board of the Vidal Gormaz research vessel (Figs. 1 and 2), they detected an age of 73 years ^{210}Pb for the upper 13 cm of sediments. The distribution of decays of ^{210}Pb by min/gr (dpm/g) shown by SALAMANCA & JARA (2003) for a thickness of 55 cm of sediment, indicates an exponential diminution between 55 and 30 cm of sub bottom, where the values of decay are relatively low. This trend is broken toward the bottom at ~25 cm. Between 13 and 1 cm near the bottom, SALAMANCA & JARA (2003) pointed out the geochronology of sediments based in the distribution of decays of ^{210}Pb.

Previously, the ^{14}C dating of sediment cores obtained during the R/V Polar Duke cruise (LEVENTER *et al*. 1995) from some sites of the ponding esplanade of other Patagonian fjords, suggest that these sub-bottoms must have begun to form before the end of the Last Glaciation. The ages of the surface layers of this cores insinuate that the process also continued during the Holocene. Moreover, ^{210}Pb dating demonstrated that sedimentation in North Patagonian fjords has continued at least until the last century (ARAYA-VERGARA 2008a).

Additionally, the effects of seismic crisis have been reported for the area. GREVE (1964, in NARANJO *et al*. 2009) estimated the magnitude 1927 earthquake in 7.1, triggering failures consisting in rapid flows in the sub- aerial slopes of the fjord and subsequent tsunamis. Moreover, the effects of the seismic crisis of January - April 2007 on the mass movements in the fjord sub-aerial slopes, have been described (NARANJO *et al*. 2009; SEPULVEDA & SEREY 2009; SEPÚLVEDA *et al*. 2010). At the same time, the zone of seismic swarm, which crosses the Aysén Fjord next to a fault zone, and its activity, has been also indicated (SERVICIO SISMOLÓGICO 2007; BARRIENTOS *et al*. 2007; MORA *et al*. 2010; LEGRAND *et al*. 2010). Finally, ancient scars of failures coincident with the location of the 2007 mass movements were discovered by ARAYA-

VERGARA (2008b). This shows that these breakdowns are temporarily recurrent. Finally, the records of sub-bottom obtained bay VARGAS *et al*. (2009) in the area of the Central Sill (Fig. 1) point out structures triggered by the seism of 2007, whose features will be compared with those recorded at 1995 (ARAYA- VERGARA 1997).

In order to understand the processes derived from the related facts, the aim of the present work is the establishment of relationships between the dislocated sedimentary structures and the possible sequence of failures of fjord sub-bottom in the Aysén Fjordland.

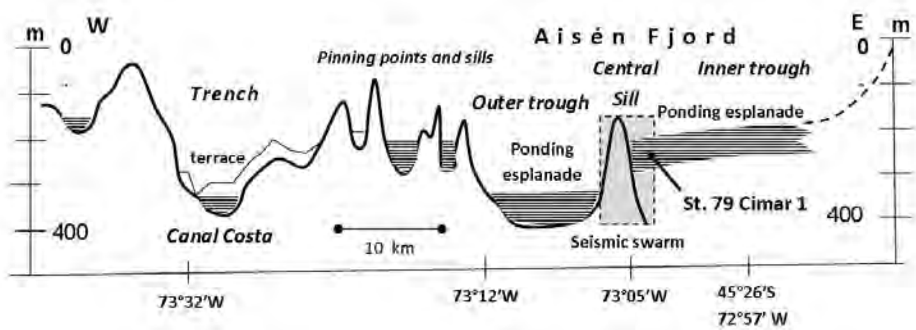

Fig. 1. Longitudinal profile of Aysén Fjord.

Fig. 1. Perfil longitudinal de Fiordo Aysén.

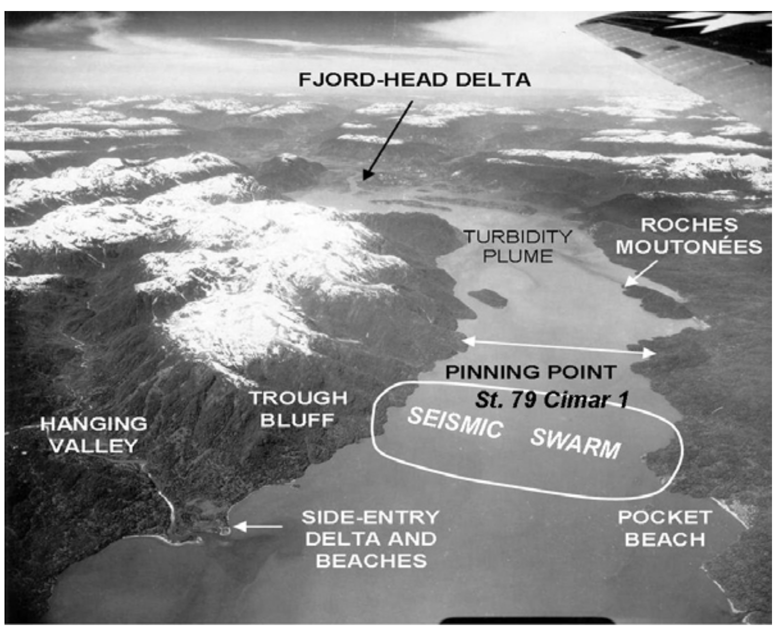

Fig. 2. 3D image of Aysén Fjord, with several fiordal features and the zone of seismic swarm (simplified, after Barrientos et al. 2007 and Servicio Sismológico 2007). Original photo: Aerial trimetrogon survey USAF.

Fig. 2. Imagen 3D de Fiordo Aysén, con varios rasgos fiordales y la zona de enjambre sísmico (simplificada, según Barrientos et al. 2007 y Servicio Sismológico 2007). Foto original: levantamiento aéreo trimetrogón USAF.

MATERIAL AND METHODS

As for the most part of the fiords of North-Patagonia, the trough bottoms of Aysén fjord sustain esplanades with sedimentary ponded structures, without morainal banks (ARAYA-VERGARA 1997 and 1998). The longitudinal profile of the Aysén fjord was obtained by means of high resolution 3.5 kHz sub-bottom profiler records, carried out on board of the Vidal Gormaz research vessel during 1995. Details of the analytical procedure used for interpretation of acoustic reflectors can be found in ARAYA-VERGARA (1997 and 1998). The dislocated structures pre 2007 earthquake found by ARAYA-VERGARA (1998 a and b) were compared with the record post 2007 earthquake obtained by VARGAS *et al*. (2009) in the zone of maximum deformation of the sediment layers (seismic swarm in Fig. 1). In order to improve the visualization of its sub-bottom structure and facilitate its comparison with the record obtained in 1995 during the Cimar Fjords 1 cruise, the vertical scale of the record published by VARGAS *et al* was exaggerated (x 6) in the present work.

In order to follow the chronological sequence of superficial sediments, the data compiled by SALAMANCA & JARA (2003) were reorganized, to obtain a compact distribution of the years of sedimentation as a function of the rate of accumulation, ^{210}Pb decay and depth.

The classification of echo types is based on the guidelines of DAMUTH (1980) and the scheme of PRATSON & LAINE (1989). The concepts of zonation of shallow-water gravity-flow deposits were taken from MYROW & HISCOTT (1991). For the search of relationships between slopes and bottom esplanades the experiences of THE GRAPE TEAM (1990) were useful. The model of MOUNTJOY *et al*. (2009) for submarine slow earthflow was used for the interpretation of complex structures. The classification of mass movements was made following the system of MULDER & COCHONAT (1996). For the analysis of sheet slides and rotational failures the types of features analyzed by BARNES & LEWIS (1991) were used.

RESULTS

The state before the March-April 2007 seismic crisis

Structure of the fjord bottom and sub-bottom

The long-profile of Aisén Fjord is composed by two principal troughs, the bottom of which is a ponding esplanade: the inner trough (Fig. 3) and the outer trough (Fig. 4), delimited by sills. The sill which separates the inner and the outer troughs will be called henceforth Central Sill; and the troughs, Inner Trough and Outer Trough respectively.

Inner Trough Its bottom and sub-bottom are composed by laminated multi-beds, the visible thickness of which is 30-50 m. Three zones can be distinguished in this trough from E to W: a) the non tectonic zone; it is the thickest, where the multi-beds show small or null deformation; b) the zone of tectonic resonance, where the multi-beds are gently dislocated; and c) the tectonic zone, delimited by the Central Sill, in which the beds are very displaced, showing flexures and folds of different curvature radius; its length is ~10 km.

Outer Trough Its bottom and sub-bottom (Fig. 4) are composed by badly structured laminated beds and diamicton, whose visible thickness varies from 30 m in the proximal zone to ~10 m in the distal one. Three zones are detectable in this trough from E to W: a) the mass removal zone, at the foot of the Central Sill, with structures of submarine mass removal; b) the proximal resonance zone, where there are gently dislocated laminated beds and diamicton; and c) the distal resonance zone, where the multi-beds are very gently deformed, overlaying a diamicton.

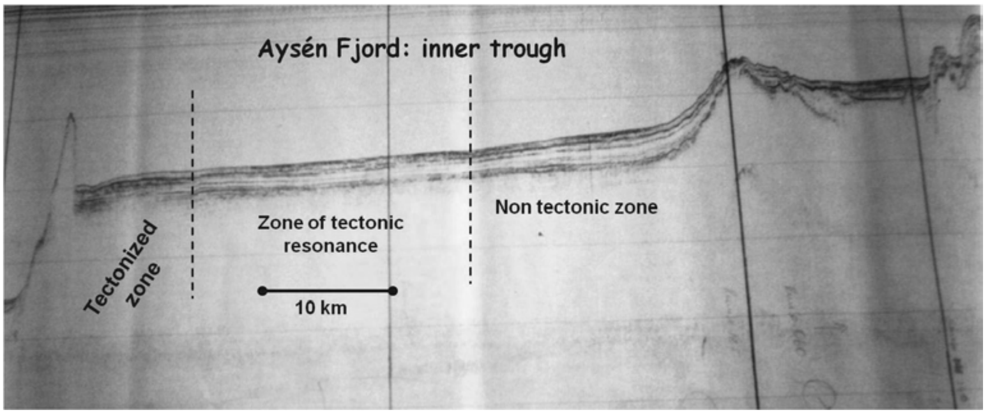

Fig. 3. Aysén Fjord: zones of the Inner Trough.

Fig. 3. Fiordo Aysén: zonas de la Artesa Interna.

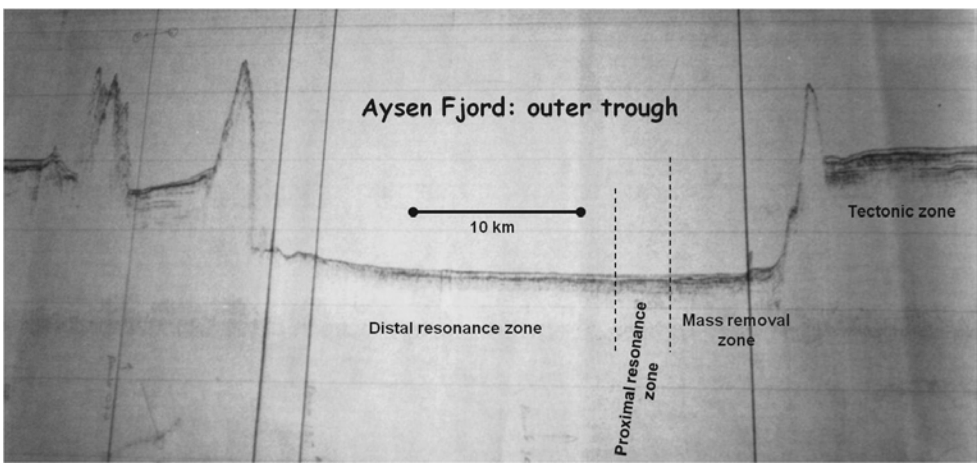

Fig. 4. Aysén Fjord: zones of the Outer Trough.

Fig. 4. Fiordo Aysén: zonas de la Artesa Externa.

Zones with maximum sub bottom deformation

As evidenced by the Figs. 5, 6 and 7, the zones of maximum deformation are the tectonic zone and the mass removal zone, adjacent to the Central Sill .

The tectonic zone of the Inner Trough (Figs. 5 and 6)

In a longitudinal extension of 10 to 15 km, the visible sedimentary thickness of this zone is ~ 40 m. The sub bottom profile shows two sections: A) The lower one presents generally indistinct echoes, which can be prolonged or semi prolonged. Their structure is wavy and very wavy, with some discontinuities. The dark reflectors are assumed to represent fine grained material. All together, the transparent parts of the irregular beds must represent coarser material. The very wavy structure of the dark units indicates the presence of folds with small curvature radius. The absence of underlying strong sub bottom reflectors indicating basement shows that these units are *cover folds*. B) The style of the upper section overlies an unit of transparent or coarse material, which fills the depressions corresponding to the synclines of the underlying very wavy dark bed that limits the lower section. This coarse material regularizes the irregular surface of the very folded sub bottom layers and generates a gently undulated bottom, represented by a dark, thick and distinct reflector. This feature indicates the late phase of fine sedimentation succeeding the coarse material. Overlying this unit, there is a thick transparent layer, overlain by a distinct, gently strong and relatively thin reflector, which represents a bed of fine sediments on the bottom surveyed at 1995. This bed is gently wavy, with big curvature radius, adapted to the paleo-topography indicated by the sweetly undulated underlying sub-bottom. Therefore, the style of folding of this section corresponds to *bottom folds*.

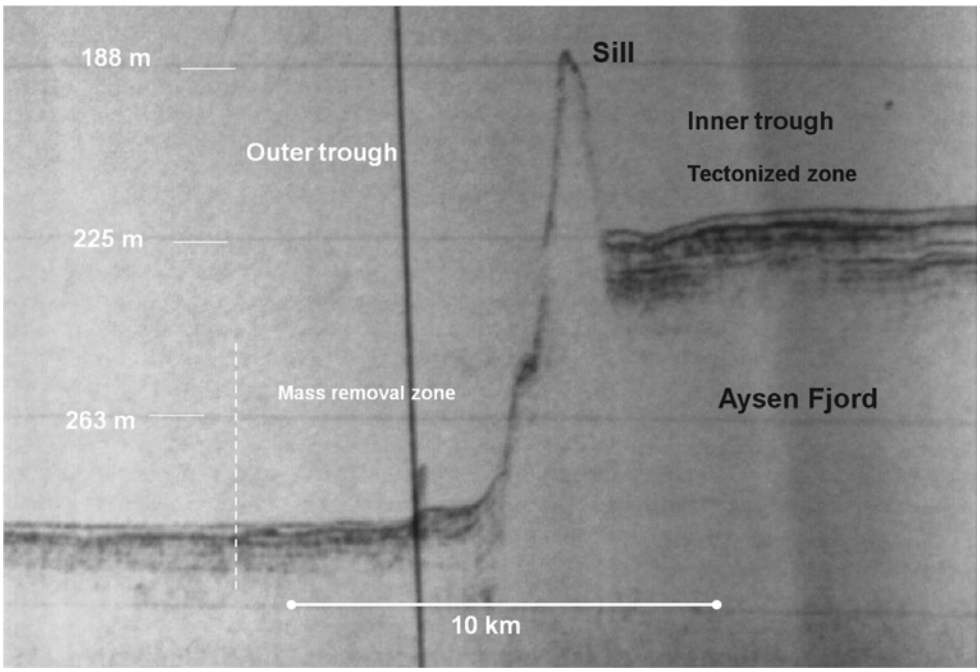

Fig. 5. Central Sill, tectonized zone of the Inner Trough and mass removal zone of the Outer Trough.

Fig. 5. Umbral Central, zona tectonizada de la Artesa Interna y zona de remoción en masa de la Artesa Externa.

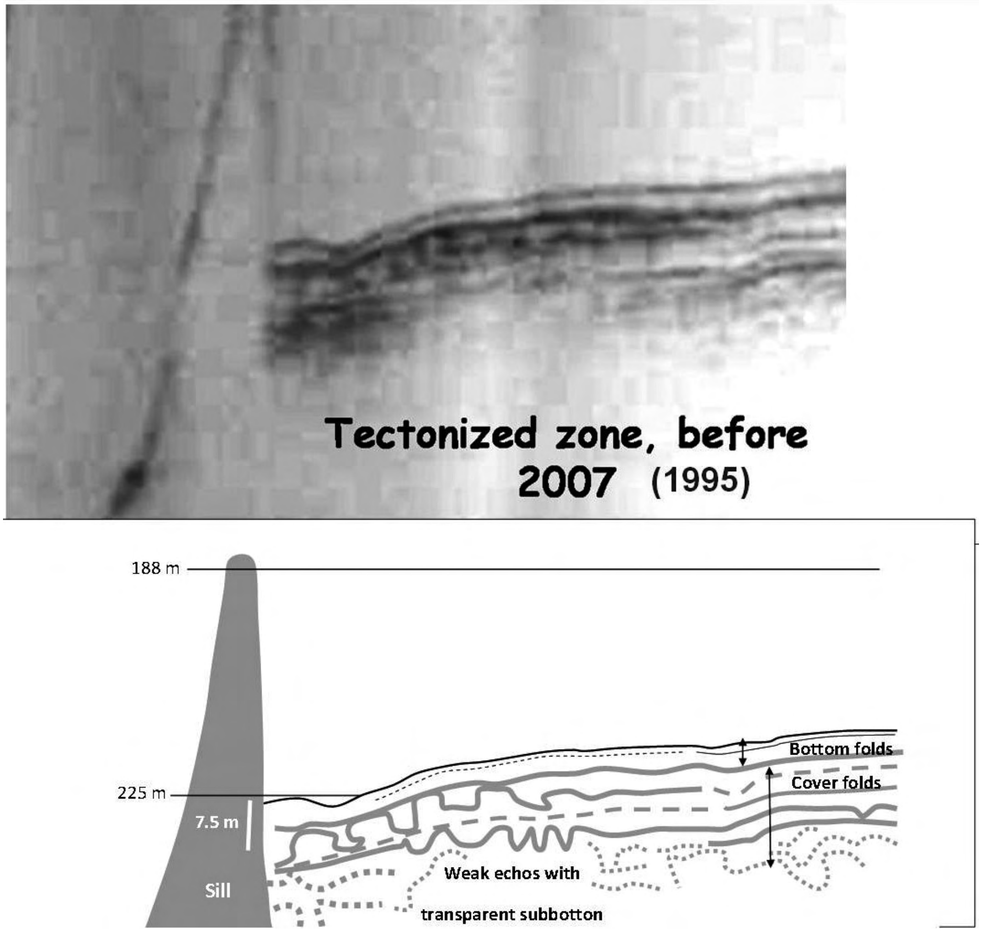

Fig. 6. Tectonized zone of the Inner Trough: acoustic structure before 2007 (1995).

Fig. 6. Zona tectonizada de la Artesa Interna: estructura acústica antes de 2007 (1995).

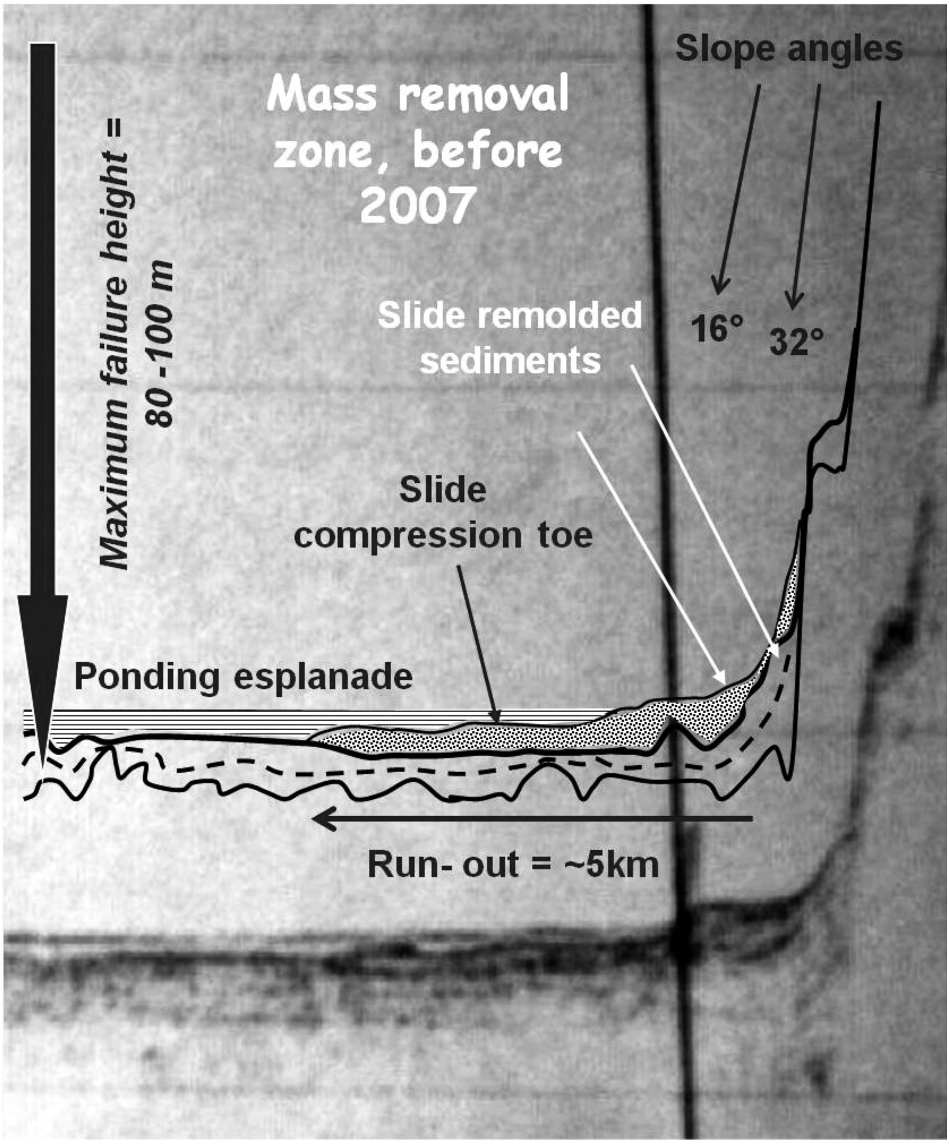

Fig. 7. Mass removal zone of the Outer Trough: acoustic estructure and interpretation before 2007 (1995).

Fig. 7. Zona de remoción en masa de la Artesa Externa: estructura acústica e interpretación antes de 2007 (1995).

The mass removal zone of the Outer Trough (Figs. 5 and 7)

At the western slope of the Central Sill irregular slope and bottom echoes appear, indicative of rugged floor morphology. In the slope, there is evidence of irregular, blocky, hyperbolic, steeply dipping echoes.

The upper part of this section of slope has the aspect of listric and synthetic slide plane, indicating the existence of a source zone. The middle part has structures which suggest the presence of slide remolded sediments or landslide debris in transit, generating the basal concavity and being the result of the transport zone. The lower part is observed from the basal concavity to the sub bottom of the trough, where complex echoes suggest the presence of slide compression toes. These features indicate that there were two pulses of failure. The ancient pulse is represented by a toe, whose body is evidenced by semi transparent indistinct echoes. A dark, relatively thick and generally distinct reflector indicates the existence of a drape of fine sediments. This compression toe overlies a rugged surface modeled on transparent or semi transparent materials, with some indistinct and semi prolonged reflectors. The proximal part of this unit has the form of plunge pool, or depression at the base of slope, followed downslope by a topographically positive rampart. The younger pulse is represented by a shorter toe, whose body appears as indistinct and semi prolonged echoes, evidenced by a complex mixture of dark and transparent features. It covers the plunge pool formed on the ancient pulse. A dark, relatively prolonged and distinct reflector indicates a drape that overlies these features. The run-out of the ancient toe is ~5 km; meanwhile, the corresponding to the younger toe is ~3 km. So, the compression toes are the result of the material deposition or removal zone at the fjord bottom.

Alltogether, the compression toe of the ancient pulse is overlain by horizontal beds or ponded structure of esplanade, which shows gently wavy deformation. Therefore, this deformation indicates resonances produced from the younger compression toe , after the formation of the horizontal laminated layers. That is to say, the material of the esplanade has been supplied from the ancient mass removal mechanism and subsequently compressed by the younger compression toe.

Geochronology of the recent sediments

Starting from the dating of SALAMANCA & JARA (2003) for the station 79 of Cimar 1 close to the western border of the Inner Trough (Fig. 1), a detailed study carried out in the present work for the period of 73 years between 1922 and 1995, indicates a strong breaking of equilibrium in the distribution of dpm/g of ^{210}Pb next to the bottom. Overlaying a sub-bottom depth of 13 cm, during 1922 were deposited ~4 cm of sediments, descending the rate of sedimentation (Fig. 8). Between 1922 and 1933 began a relatively long period of increasing decay up to 1977 (lapse of 44 years), during which the rate of sedimentation continued its fall, adding a thickness of 3-4 cm of sediment. Since 1977 until 1995 clear decreasing of the decay of ^{210}Pb is evidenced, associated to an increasing of the sedimentation rate (Figs. 8 and 9), aggregating a thickness of 4 cm of sediment.

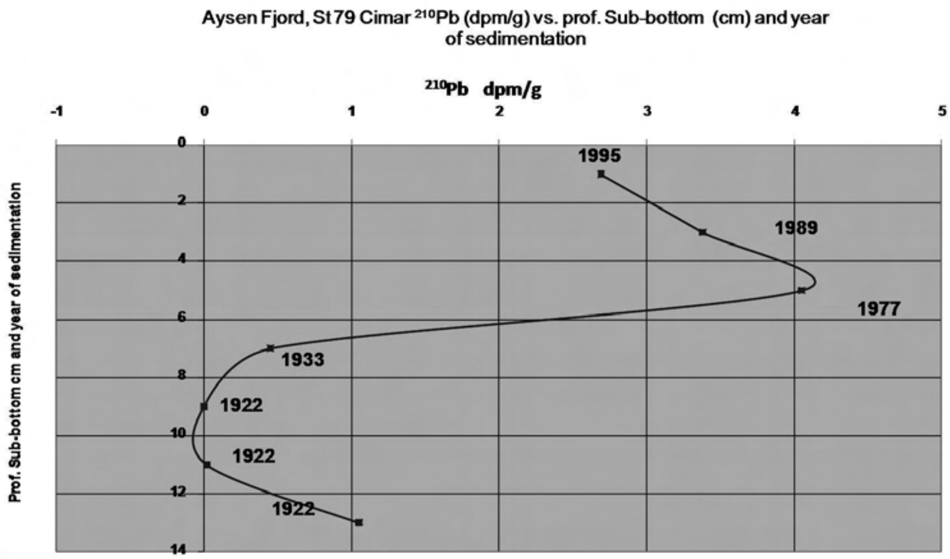

Fig. 8. St. 79 of Cimar 1-Fjords: extinction of 210Pb, sub-botton depth and year of sedimentation of the superficial layers.

Fig. 8. Estación 79 de Cimar 1-Fiordos: extinción de Pb210, profundidad de sub-fondo y año de sedimentación de las capas superficiales.

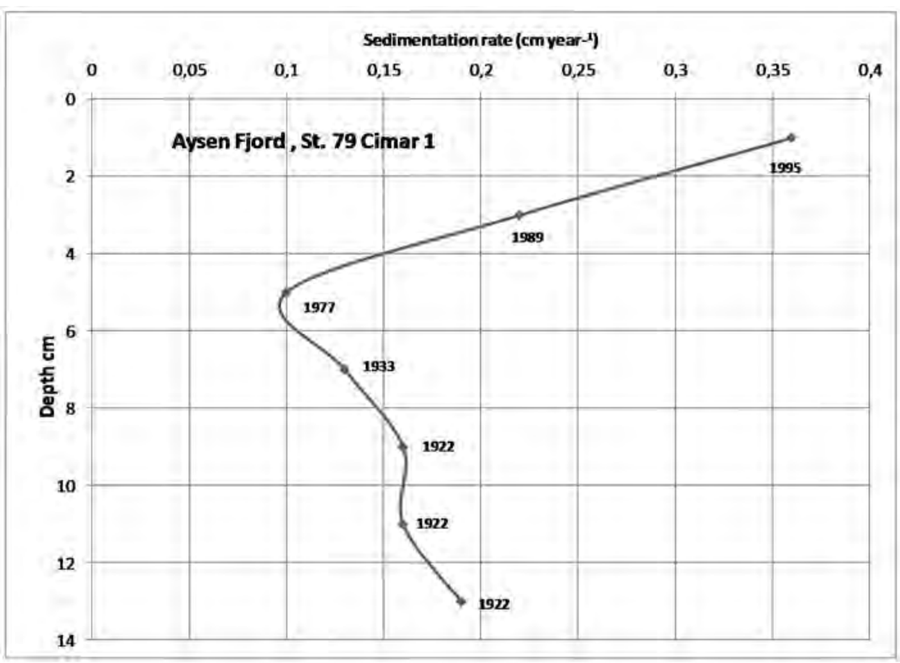

Fig. 9. St. 79 of Cimar 1-Fjords: Sedimentation rate vs. sub-bottom depth of the superficial layers.

Fig. 9. Estación 79 de Cimar 1-Fiordos: Tasa de sedimentación vs. Profundidad de sub-fondo de las capas superficiales.

During the 73 years of sedimentation reported for the St. 79, the site was affected by the earthquake of 1927. That is to say, when the seism operated, the thickness of the dated sediments was ~ 4-8 cm smaller. Therefore, and speculatively, the complementary thickness of sediment reached at 1995 could be deposited since 1927.

The impact of the March-April 2007 seismic crisis

The Central Sill and its environs

Contrasting the records obtained in 1995 with those of VARGAS *et al*. (2009) (Fig. 10), the following comments can be made:

- The Central Sill separates the esplanades of the Inner and Outer troughs, whose depth difference is 75 – 134 m (keeping in mind both records). This depth dissimilarity indicates that this sill is older than the filling of the troughs, even though the difference of bottom depth could be of tectonic origin.
- In the 1995 record, no part of the Central Sill overlies the multi-beds of the esplanade in the Inner Trough. Contrarily, in the post 2007 earthquake record, flanks of reflectors in form of hyperbolae tend to overlie these multi-beds.
- The sedimentary structure of multi-beds next to the Central Sill is different between the two records. The folded structure of the upper layers observed inside the Inner Trough in the 1995 record is not noticeable in the post 2007 earthquake record. In this case, parallel multi-beds tilt from the sill toward the esplanades, both in the direction of the Inner and the Outer troughs. On the other hand, the mass movement features observed in the 1995 record of the Outer Trough are not identified in the 2007 scene. Here, the multi-beds which tilt toward the esplanade are in direct lateral contact with the flank of the sill.

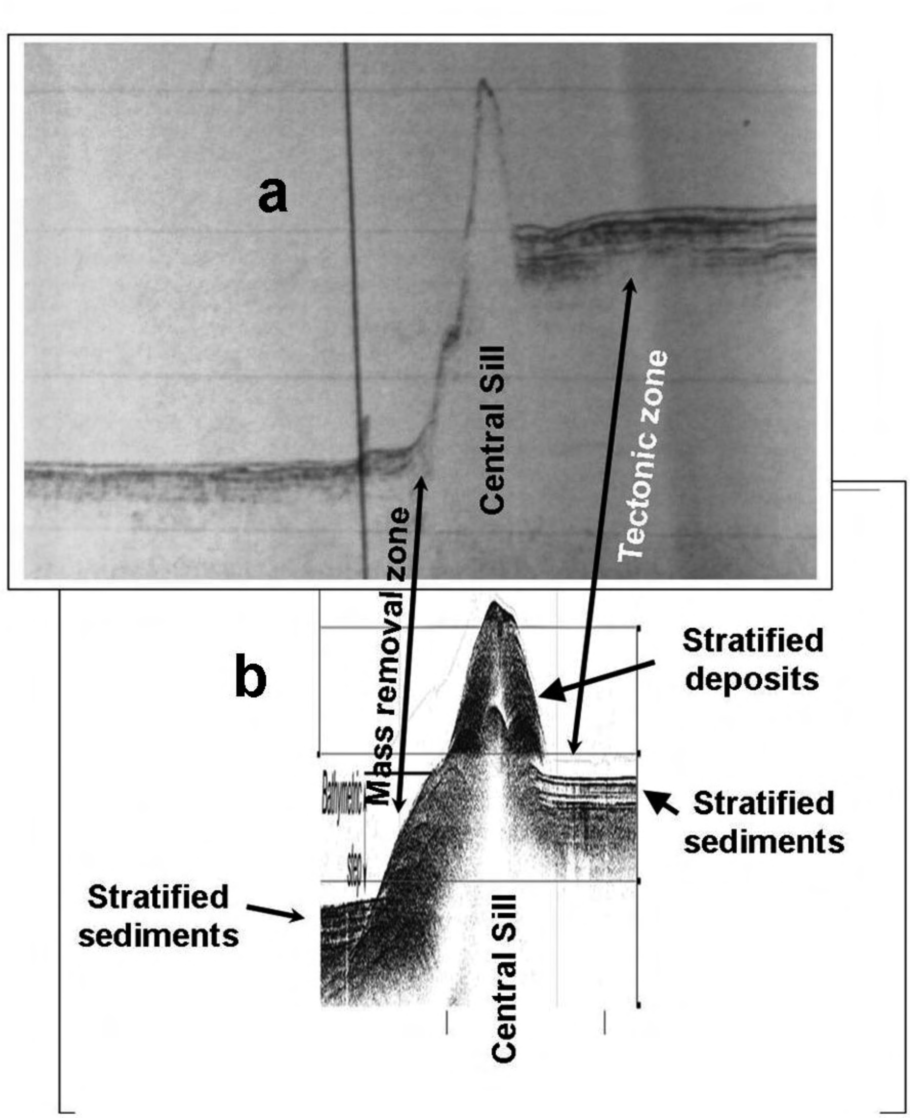

Fig. 10. Sedimentary estructure and landforms of the Central Sill, tectonized zone and mass removal zone: a) before 2007 (1995), after Araya-Vergara (this work); b) after the seism of 2007, in Vargas et al. (2009), vertical scale modified.

Fig. 10. Estructura sedimentaria y formas del terreno del Umbral Central, zona tectonizada y zona de remoción en masa: a) antes de 2007 (1995), según Araya-Vergara (este trabajo); b) después del sismo de 2007, en Vargas et al. (2009), escala vertical modificada.

DISCUSSION

Features of submarine seismic impact: basis for a theory

The experience in co-seismic submarine morphogenetic operations indicates three principal types of alteration in pre-existing sedimentary structures of bottoms: a) deformations or disruptions by direct seismic wave forcing, b) dislocations by compression under impact or load of slope removals and c) plunge pools produced by localized impact of mass removal falls. From the point of view of the comparative morphogenesis, the following experiences illustrate each mechanism:

a) The dislocations in laminated layers of the Inner Trough were succinctly shown in ARAYA-VERGARA (2008a) and, because its location in the seismic swarm zone, they can be interpreted as an example of direct seismic wave forcing. b) As cases of compression under impact or load of slope removals, several examples appear in Messier Channel (Central Patagonia), where proximal and central bending are associated to compact slide blocks, slide remolded sediments and slide compression toes (ARAYA-VERGARA 1999). Alltogether, in Saguenay Fjord (Canada) the seafloor was compressed under the impact and load of slope removals during the 1963 earthquake (SYVISKI & SCHAFER 1996). c) Additionally, some impacts may be deduced by means of observation of plunge pools. AARSETH *et al*. (1989) associate this expression to submarine slides in glaciomarine sediments. LEE *et al*. (2002) discuss two models for the creation of these forms: by hydraulic jumps and by impacts of submarine sediment-laden density flows. Their observations, as implication for facies model, allow also to predict the location of plunge pools in submarine prograding -slope sequences. Jointly, an analysis of BOURGET *et al*. (2010) indicates that pools could be related both to hydraulic jumps and impact of sediment-laden density flows. In agreement with observations of SEXTON *et al*. (1992) these features are characteristic of seismic architecture in seascapes of fjords.

Tectonic deformation vs. superficial decay of ^{210}Pb and sedimentation rate

Coeval to the earthquake of 1927, an increase of the sedimentation rate in the fjord near the Central Sill because of sub-aerial slope failures was possible. But these rates fell in the lapse 1922-1977, meanwhile the decay of ^{210}Pb ascended (Figs. 8 and 9). Therefore, it is difficult to attribute the superficial irregularities in the distribution of these variables to a greater sediment load triggered by slope failures. The deformations of sediment beds have different styles (Fig. 6). The underlying beds are more deformed than the superficial ones in a thickness at least of 50 m. Consequently, different co-seismic tectonic forcings produced bottom folds in contrast with the sub-superficial cover folds.

The possible age of the deformed layers

Taking into account the age of the recent dated sediments (13 last cm at 1995), the base of its thickness was deposited in 1922. Therefore, the underlying deformed material will be named pre 1922. Its hypothetical age can be exposed only by means of regional extra or interpolation.

As evidenced by the regional datings (LEVENTER *et al*. 1995; KILIAN *et al*. 2003), the ages for an upper thickness of > 8.23 m of laminated multi-beds in the fjords of the Patagonian Fjordland are approximately at the limit between the Last Glaciation and the Holocene (ca. 10-15 ka). If the visible thickness of the tectonically deformed layers in Aysen Fjord is ~50 m at the zone of the seismic swarm, it is possible that its age elapses at least since the upper Last Glaciation (Termination I) until the Holocene. A proxy for this epoch could be the result of the coring in the Jacaf

Fjord (44°20.00'S-72°58.15'W). For a sub-bottom depth of 180 cm, the age model indicated that the core spans the last 1800 ^{14}C cal years (REBOLLEDO *et al*. 2008; SEPÚLVEDA *et al*. 2009). That is to say - and considering speculatively the case of Jacaf Fjord - the 2

superficial meters of sediments in Aysen Fjord were probably deposited during the Upper Holocene or Sub-Atlantic.

If the sedimentary filling of the Inner Trough was formed since the Last Glaciation and its bottom is higher than that of the Outer Trough, the Central Sill age must be greater than that of the trough filling . Then, accepting that this sill may represent a volcano (LARA 2008; VARGAS *et al*. 2009), its age must be not only Holocene but also Pleistocene. However, it is likely that its slopes have provided materials both to the esplanade of the Inner Trough and the mass removal zone of the Outer Trough.

The impact of the March-April 2007 seismic crisis

The experiences of LEE *et al*. (2006) show that a same rupture can trigger a variety of simultaneous failure types, as evidenced by several sub-bottom profiles and multi-beam scenes. Therefore, in the case of the Aysén Fjord, it is possible that the seismic impact must be dealt altogether with volcanic processes, starting from the observations of LARA (2008) and VARGAS *et al*. (2009).

In this context, if the Central Sill is older than the multi-beds of the esplanade, it is plausible that some material supplied by the slopes of this form during the seismic crisis of 2007 overlay the multi-layers of the esplanade. All together, if the disruptions of multi-beds observed for 1995 are not visible after 2007 and only parallel beds appear dipping toward the esplanade, this feature can be a result of mass removals during the seismic crisis, but not necessarily a product of volcanic activity. Nevertheless, the discrepancy observed between the records of 1995 and after 2007 can be due to its difference of resolution.

CONCLUSIONS

In agreement with the displayed analysis, the following hypothesis can be exposed:

- Considering that: a) the deformations of the visible sub-bottom affect all the thickness of sediments in the zone of seismic cluster; b) its possible age extends since the Termination I (Last Glaciation) until the Upper Holocene (Sub- Atlantic); c) between 1922 and 1995 happened the earthquake of 1927, giving a inter-seismic period of 80 years until 2007; d) there are different styles of deformation of sediments, with greater breakup in the older than in most recent layers; and e) the 1927 earthquake affected with smaller deformation to the most recent layers judging by its age 210Pb.

- Therefore, it is deduced that the sub-superficial layers of ages between the Holocene and Termination I can have been deformed by earthquakes previous to 1927.

- In spite of the knowledge of only two historical earthquakes, the location of the seismic swarm in a known seismo-tectonic zone (see introduction) allows to hypothesize some frequency categories of rupture, as evidenced by the dislocated sedimentary structures. In agreement with the categories of time dimensions proposed by FLAGEOLLET (1996): a) these processes must be recurrent, sleeping in activity state, with renewed unbalances; b) its type of frequency must be episodic (irregular evolution), oscillating between low frequency (100 to 1000 years) and middle frequency (0 to 100 years); c) its way of activity is by rupture; and d) the known frequency is between *ancient-historical* and *recent historical* (1 to 200 years or more).

- In addition to recounted experiences on sub bottom structures of Patagonian fjords (ARAYA-VERGARA 2008a), unpublished observations carried out by the author in some of them indicate sedimentary disruptions (i.e. in Eyre Fjord). The study of its distribution can show the field of influence either seismic or other in these environments.

It is probable that some of the interpretation given can be improved with better sub-bottom records and more complete geo-chronological dating.

In order to obtain a regional experience in fiordal bottom disruptions, more tectonic, seismological and geomorphologic analysis must be made in Patagonian fjords and channels.

ACKNOWLEDGMENTS

This study was supported by the Cimar 1- Fiordos program (CONA). The survey of subbotton was possible thanks to the good work of the technical staff on board of the AGOR Vidal Gornaz research vessel. The corresponding acoustic records were well preserved for analysis, thank to the Executive Secretary staff of the Comité Oceanográfico Nacional. The author thanks to Prof. Francisco Hervé (University of Chile) for the useful comments of the manuscript, anyhow other anonymous referees.

REFERENCES

AARSETH, I., I. LØNNE & O. GISKEØDEGAARD, 1989. Submarine slides in glaciomarine sediments in some Western Norwegian fjords. Mar. Geol., 88: 1-21.

ARAYA-VERGARA, J.F., 1997. Perfiles geomorfológicos de los fiordos y depresión longitudinal de Norpatagonia. Cienc. Tecnol. Mar, 20: 3-22.

ARAYA-VERGARA, J.F., 1998. El problema genético de los fondos de fiordo Norpatagónicos. Invest. Mar., Valparaíso, 26: 71-81.

ARAYA-VERGARA, J.F., 1999. Secuencia de formas deposicionales submarinas en la fractura del Canal Messier, Patagonia Central. Invest. Mar., Valparaíso, 27: 39-52.

ARAYA-VERGARA, J.F., 2008a. The submarine geomorphology of the Chilean Patagonian fjords and piedmonts. In: Silva, N. & S. Palma (Eds.), Progress in the oceanographic knowledge of Chilean interior waters from Puerto Montt to Cape Horn. Comité Oceanográfico Nacional – Pontificia Universidad Católica de Valparaíso, pp. 25-27.

ARAYA-VERGARA, J.F., 2008b. Rasgos morfogenéticos co-sísmicos en el Fiordo Aysén. En: Comité Oceanográfico Nacional-Chile (Ed.): Crucero Cimar 13 Fiordos. Informes preliminares. CONA, Valparaíso, pp. 171-176.

BARNES, Ph.M. & K.B. LEWIS, 1991. Sheet slides and rotational failures on a convergent margin: the Kidnappers Slide, New Zealand. Sedimentology, 38: 205-221.

BARRIENTOS, S., K. BATAILLE, C. ARANDA, D. LEGRAND, J.C. BÁEZ, H. AGURTO, A. PAVEZ, J. GENRICH, C. VIGNY & F. BONDOUX, 2007. Complex sequence of earthquake in Fjordland, Southern Chile. In: Proceedings, Geosur 2007, Santiago de Chile, p. 21.

BOURGET, J., S. ZARAGOSI, N. ELLOUZ-ZIMMERMANN, N. MOUCHOT, T. GARLAN, J.J. SCHNEIDER, V. LANFUMEY & S.

LALLEMANT, 2010. Turbidite system architecture and sedimentary processes along topographically complex slopes: the Makran convergent margin. Sedimentology, doi: 10.1111/j.1365-3091.2010.01168.x

DAMUTH, J.E., 1980. Use of high-frequency (3.5 kHz) echograms in the study of near-bottom sedimentation processes in the deep-sea; a review. Mar. Geol., 38: 51-75.

FLAGEOLLET, J.C., 1996. The time dimension in the study of mass movements. Geomorphology, 15: 185-190.

KILIAN, R.,M. FESK-MARTIN, C., SCHNEIDER, H. BIESTER, G. CASASSA, M. ARÉVALO, G.WENDT & J. BEHRMANN, 2003. Late glacial ice retreat in the southernmost Andes: sedimentological an palynological implications. In: 10° Congreso Geológico Chileno, Versión Digital, Universidad de Concepción, Departamento de Ciencias de la Tierra, Concepción, 5 pp.

LARA, L. 2008. Holocene submarine volcanoes in the Aysén fjord, Patagonian Andes (44°S: relations with the Liquiñe-Ofqui Fault Zone. 7° International Symposium on Andean Geodynamics, Extended Abstract, Nice, pp. 285-288.

LEE, S.E., P.J., TALLING, G.G.J. ERNST & A.J. HOGG, 2002. Occurrence and origin of submarine plunge pools at the base of the US continental slope. Mar. Geol., 185: 363-377.

LEE, H., H. RYAN, R.E. KAYEN, P.J. HAEUSSLER, P. DARTNELL & M.A. HAMPTON, 2006. Varieties of submarine failure morphologies of seismically-induces landslides in Alaska fjords. Norwegian J. of Geol., 86: 221-230.

LEGRAND, D., S. BARRIENTOS, K.BATAILLE, J. CEMBRANO & A. PAVEZ, 2010. The fluid-driven tectonic swarm of Aysen Fjord, Chile (2007) associated with two earthquakes (Mw=6.1 and Mw=6.2) within the Liquiñe-Ofqui Fault Zone. Continent. Shelf Res., doi:10.1016/j.csr.2010.05.008

LEVENTER, A., J. STRAVERS, S. ISHMAN & L. KRISSEK, 1995. Holocene sedimentation rates on the southern Chilean continental margin. Antarct. J. U.S., 30(5): 13-16.

MORA, C., D. COMTE, R. RUSSO, A. GALLEGO & V. MACANO, 2010. Aysén seismic swarm (January 2007) in southern Chile: analysis using Joint Hypocenter Determination. J. Seismol., DOI 10.1007/s10950-010-9190-y. Springer Sci. 2010. Published online.

MOUNTJOY, J.J., J. M$_C$KEAN, P.M. BARNES & J.R. PETTINGA, 2009. Terrestrial-style slow-moving earthflow kinematics in a submarine landslide complex. Mar. Geol., 267: 114-127.

MULDER, Th. & P. COCHONAT, 1996. Classification of offshore mass movements. J. Sedim. Res., 66(1): 43-57.

MYROW, P.M. & R.N. HISCOTT, 1991. Shallow-water gravity-flow deposits, Chapel Island Formation, Southern Newfounland, Canada. Sedimentology, 38: 935-959.

NARANJO, J.A., M. ARENAS, J. CLAVERO & O. MUÑOZ, 2009. Mass movement-induced tsunamis: main effects during the Patagonian Fiorland seismic crisis in Aisén (45°25'S), Chile. Andean Geol., 36(1): 137-145.

PRATSON, L.F. & E.P. LAINE, 1989. The relative importance of gravity-induced versus current-controlled sedimentation during the Quaternary along the Mideast U.S. outer continental nargin revealed by 3.5 kHz echo character. Mar. Geol., 89: 87-126.

REBOLLEDO, L., J. SEPÚLVEDA, C.B. LANGE, S. PANTOJA, S. BERTRAND, K. HUGHEN & D. FIGUEROA, 2008. Late Holocene marine productivity changes in Northern Patagonia-Chile inferred from a multi-proxy analysis of Jacaf channel sediments. Estuar. Coast. Shelf Sci., 80: 314-322.

SALAMANCA, M.A. & B. JARA, 2003. Distribución y acumulación de plomo (Pb y ^{210}Pb) en sedimentos de los fiordos de la XI Región, Chile. Cienc.Tecnol.Mar, 26(2): 61-71.

SEPÚLVEDA, J., S. PANTOJA, K.A. HUGHEN, S. BERTRAND, D. FIGUEROA, T. LEÓN, N.J. DRENZEK & C. LANGE, 2009. Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jacaf Fjord, 44°S). Quat. Res., 72: 400-409.

SEPÚLVEDA, S.A. & A. SEREY, 2009. Tsunamigenic, earthquake-triggered rock failures during the april 21, 2007 Aysen earthquake (45,5°S). Andean Geol., 36: 131-136.

SEPÚLVEDA, S.A., A. SEREY, M. LARA, A. PAVEZ & S. REBOLLEDO, 2010. Landslides induced by the April 2007 Aysén Fjord earthquake, Chilean Patagonia. Landslides, DOI 10,1007/s10346-010-0203-2. Springer Verlag 2010. Published online.

SERVICIO SISMOLÓGICO, 2007. Informe del Servicio Sismológico sobre actividades realizadas entre 2-8 Marzo 2007. Servicio Sismológico Universidad de Chile. http://www.sismologia.cl/ultimo_evento/Segundo Informe_Aysén.pdf.

SEXTON, D.J., J.A. DOWDESWELL, A. SOLHEIM & A. ELVERHØI, 1992. Seismic architecture and sedimentation in northwest Spitsbergen fjords. Mar. Geol., 103: 53-68.

SYVISKY, J.P.M. & Ch.T. SCHAFER, 1996. Evidence for an earthquake-triggered basin collapse in Saguenay Fjord, Canada. Sedim. Geol., 104: 127-153.

THE GRAPE TEAM, 1990. Preliminary results of seismic reflection investigations and associated geophysical study in the area of the Antarctic Peninsula. Antarctic Sci., 2(3): 223-234.

VARGAS, G., S. REBOLLEDO, S. SEPÚLVEDA, R. THIELE, B. TOWNLEY, C. PADILLA, R. ROULD & M. HERRERA, 2009. La ruptura sísmica submarina de Abril de 2007 y tectónica activa en la Falla Liquiñe-Ofqui, Aysén, Chile. En: Congreso Geológico Chileno, Resúmenes expandidos, Santiago, S9_089, 4 pp.

VIEIRA, R., 2001. Morfogénesis y dinámica de las vertientes submarinas en la costa de fiordos de Norpatagonia-Chile. Invest. Geogr. Chile, 35: 101-124.

VIEIRA, R., 2002. Morfogénesis y dinámica de las vertientes submarinas en la costa de fiordos de Norpatagonia, Chile. Tesis para optar al grado de Magister en Geografía. Universidad de Chile, Facultad de Arquitectura y Urbanismo, Escuela de Postgrado. Santiago, 103 pp., inédito.

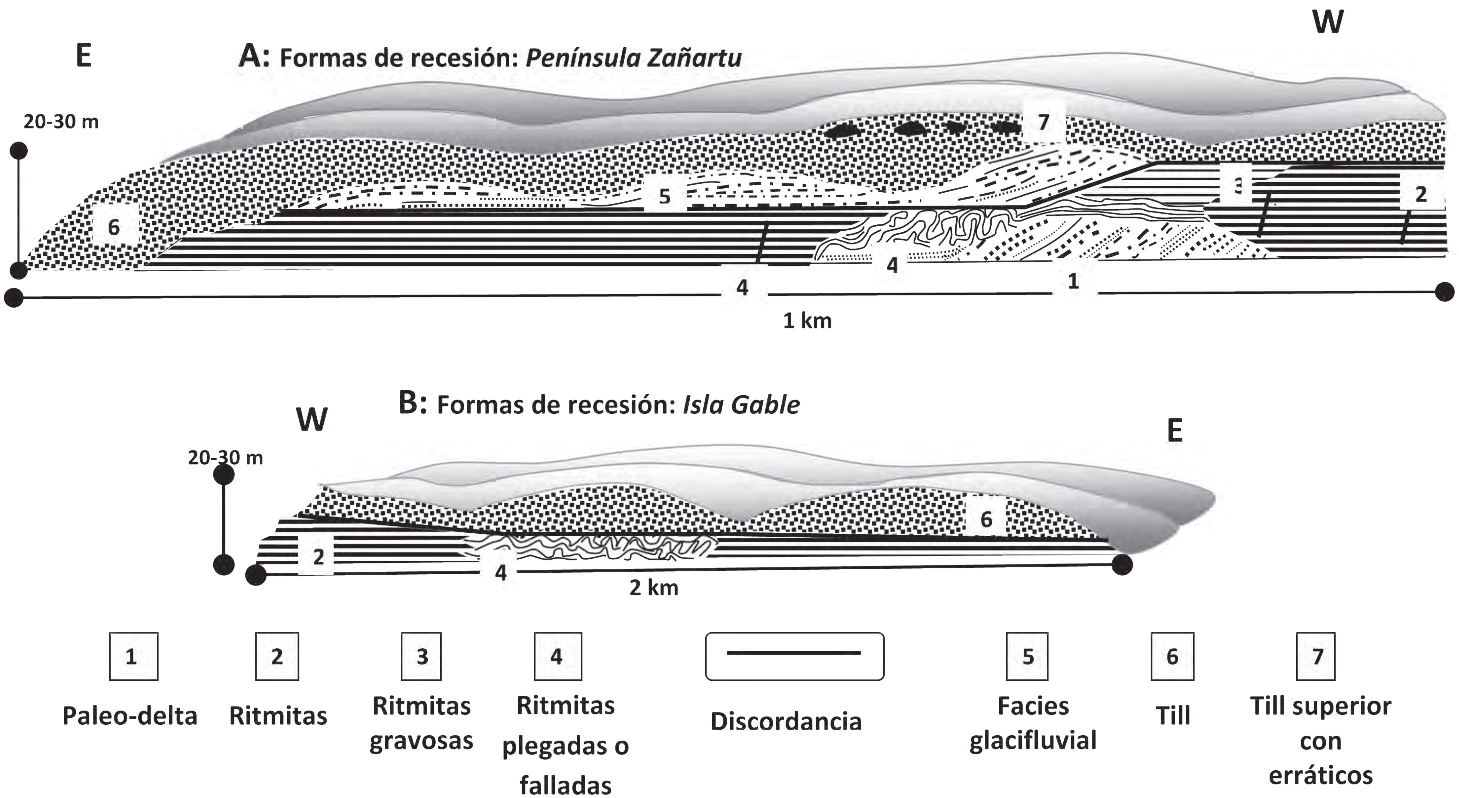

Imagen de Investigaciones GEOGRÁFICAS Convergencia de elementos del dominio paraglacial en perfiles del páleo-fiordo Canal Beagle. Levantamiento: J.F. Araya Vergara. jaraya@uchilefau.cl