Chapter

Current Geodynamics and Evolutionary Trends of a Headland Bay Beach System in the Semi-Arid Coast of Chile

María-Victoria Soto, Misael Cabello and Joselyn Arriagada-González

Abstract

The Chilean coast is controlled by the tectonics and structure, generating an irregular coastal landscape, with bays, marine terraces, sandy and gravel beaches, sand dune fields and Andean slopes, forming some mega cliffs that are attacked by waves. The Chilean coastline is shaped by headland bay beaches, with a dynamic coast modeled by south-western winds and south–north longshore current. We analyzed the case of the Coquimbo mega headland bay beach, which consists of four headland bay beaches. A methodological study was carried out on the morphometric parameters of the shoreline and the types of beaches dominated by waves along with geomorphological analysis of the coastal zone. We observed a mass transfer process from south to north. The northern sections of the bays are the places with the densest sand dune fields. This concentration of dunes occurs in each bay individually and in the mega bay as well. The sedimentary supply comes from Andean catchments to the shoreline and is transported and reworked by the longshore current to the northern area, where a huge sand field dune has developed, 120 km away from the mouth of Limarí River, the most southern catchment in the study area. In the mega bay, the current trend is a continuous sedimentary supply, despite the semi-arid conditions and the extreme drought that has affected the area since 2011. The study area is also a popular destination in Chile for beach tourism and is a place of interest for the mining industry.

Keywords: headland bay beaches, sand dunes, Andean catchments, sandy supplies

1. Introduction

The first approach to headland bay beaches, logarithmic bays and crenulated bays was realized by Halligan (1906 in Ref. [1]), [2–7], and recently by [8–11]. The concept of bays as units for analysis in coastline territories and the theories related to headland bay beaches are particularly important for the comprehension of the geodynamic processes of the Chilean coastline [12], due to the geographical position of the country in the subduction zones of the South-American and Nazca plates, involving a dynamic tectonic movement along the Chilean and western South-America coastal configuration.

In this context, and from a morpho-structural perspective, we were able to explain the configuration of irregular coastline associated to tectonics and structural controls in the study area [13–15]. We established the influence of relevant factors in the geometry of the Chilean coastline, what the morphometric conditions of the coastline are, the longshore current, the angle of waves incidence and the types of beaches dominated by waves. These variables were then used to create a morphologic model and a process-response system [16–20]. The impact on the headland bay beaches shows a systematic distribution of wave energy in the longshore current direction. The headland bay beaches are a complex system of mass transfer and form evolutions which are controlled by the structure, the tectonics and the lithology of the area [21, 22].

The study area is Coquimbo Bay, which is located between the mega headland Punta Lengua de Vaca and the sand dunes of Los Choros to the extreme north of the bay. This zone is a headland bay beach system (**Figure 1**). These systems have not been studied much in Chile, the few studies that have been carried out include [1, 17, 18, 21–25].

Figure 1 shows the general geographical context of the study area. The bays feature the river mouths of the Andean catchment which are the areas that supply mass to the littoral. In the high Andean catchment, some remnant glaciers still remain, with a glacial-snowy-pluvial system, which generates a permanent flow to the Limari and Elqui rivers, despite the intense drought that has been affecting the area since 2010–2011. The catchments (in green) are mainly coastal and subject to rainfall patterns, as well as the low Andean Coastal Range.

In the study area, the big headland of Punta Lengua de Vaca in the north, which is 7.5 km long, plays a role in protecting the bay from SW winds, which show a morpho-sedimentological expression as far away as the big sand dune field, 120 km further north. Between both limits of the Coquimbo mega bay, marine terraces, paleo dunes, beach ridges and sandy beaches are found.

It has been demonstrated that in Chile, sand dunes are concentrated in the northern area of bays, due to the effect of the headlands in wave refraction associated with the prevailing SW–NE winds and the longshore current from the river mouths to the bays [12, 17–19, 21, 23, 25–27].

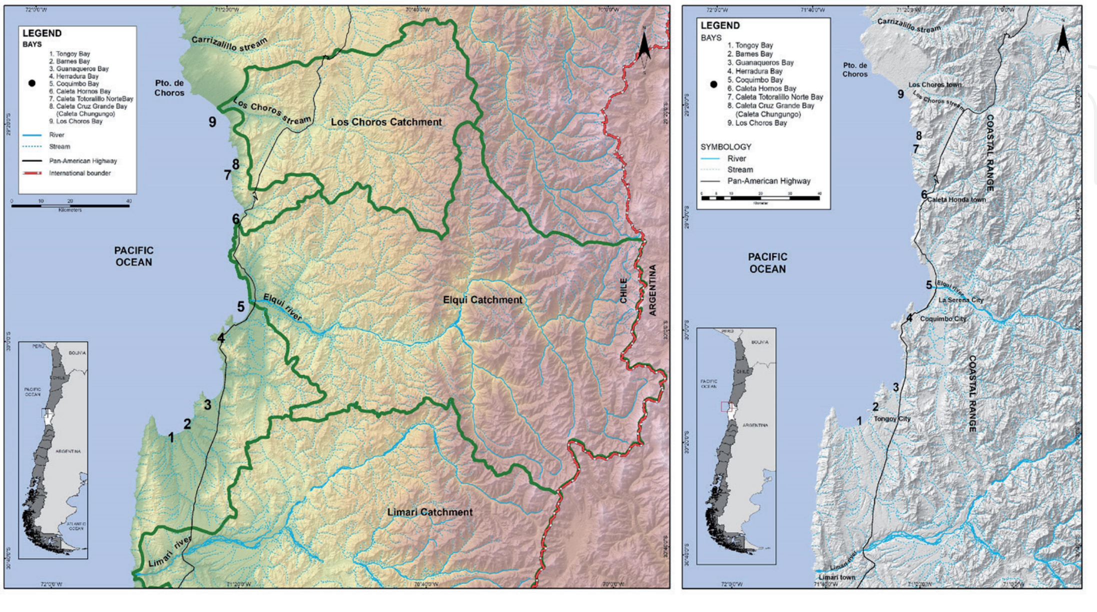

Figure 1.
Geographical context of bays and catchment in the Coquimbo mega bay, Chile. Details of the research environment: Headland bay beach system from Punta Lengua de Vaca headland to Los Choros sandy beach with huge sand dune fields.

2. General geomorphology of Coquimbo mega bay

The geomorphological map of the area of study (**Figure 2**) shows the different groups of identified forms, associated with its location on the western side of the coastal range. The geomorphological map has been created by utilizing existing information [28–34] and fieldwork data.

The hillslopes of the Coastal Range have been formed by intrusive and volcanic rocks and are in direct contact with the coast. These bays have marine terraces, Pleistocene and Holocene sand dunes, beaches and platforms of active abrasion, reefs, cliffs and small bays of rocks or gravel. These characteristics are very important in the northern area of the mega bay where Cabello [35] identified up to three levels of marine abrasion platforms. These sectors are mostly uninhabited but they are subject to a great deal of economic and environmental interest such as mining extraction activities, protected natural areas such as marine parks and artisanal fishing creeks used by indigenous people (Changos people). These different uses of the land and the sea are not compatible with each other; hence, the area is subject to latent environmental conflicts.

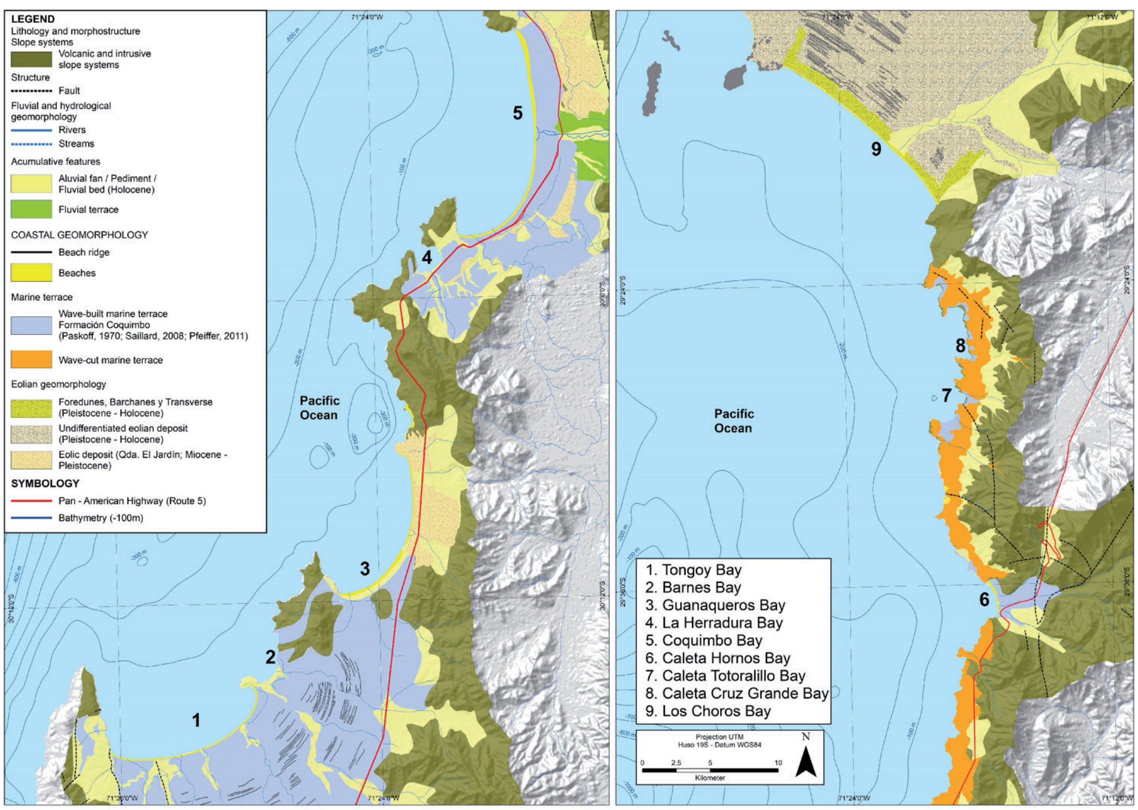

Figure 2.
Geomorphological map of the study area.

3. Littoral zone

The analysis of the littoral zone was achieved by using the classification of wave-dominated beaches by Wright & Short in Ref. [36], complemented with the morphometry of the shoreline by [1, 22].

The mid and southern zones of the area feature bays and sandy beaches. Tongoy bay (N°1 in **Figure 2**) in the southern part of the Coquimbo mega bay has been formed by the effect of the great headland named Punta Lengua de Vaca, which is 7.5 km long. Tongoy is a Reflective beach with low energy, with breaking waves smaller than one-meter-height; this Reflective pattern was observed during the 2007–2019 period. The structural influence in the bay can be quantified through the values of the coastal area morphometrics, with a 67° asymmetry angle and a 95° refraction angle (**Figures 3** and **4**).

The neighboring bay, Guanaqueros (N° 3 in **Figure 2**) is a 17 km long sandy beach. The wave dominated-beach type varies between Reflective with low energy, in the south and Intermediate (Longshore Bar through Rhythmic Bar and Beach and Transverse Bar and Rip) in the north. It has an asymmetry angle of 357° in the northern part and 44° in the southern part. Due to the local headland presence, the refraction angle reaches 20° (**Figures 3** and **4**).

Coquimbo Bay has a wide coastline strip of approximately 15 kilometers of sandy beach. This bay is protected by a rocky point which forms Coquimbo's peninsula in the southern part and is an obstacle to the prevailing SW winds and their associated wave action. We observed a systematic distribution of the wave energy from south to north, similar to the theoretical model, which implies a Reflective-Intermediate-Dissipative beach in the southern, center and northern sectors of the bay. From the point of view of the relative position of the shoreline, Coquimbo Bay has an asymmetry angle of 353° and a refraction angle of the surge action of 26° (**Figures 3** and **4**).

The mid-northern area is a rocky coast hosting cliffs and mixed sand and gravel beaches. It has little bays sculpted into the Coastal Range. Morphometric values are variable with asymmetry angles of 6°, 58° and 330°, which illustrate the strong irregularity of this part of the coast.

The wave dominated beaches showed widely varied patterns and were identified as low energy Reflective, Intermediate Transverse Bar and Rip, and Low Tide Terrace (**Figures 3** and **4**). The systematic distribution pattern of wave dominated beaches, Reflective-Intermediate-Dissipative, is hard to verify except for in a few little bays with sandy or gravel beaches. This pattern was not identifiable for rocky beaches with abrasion platforms or reefs because of the alteration of the surge generated by these forms.

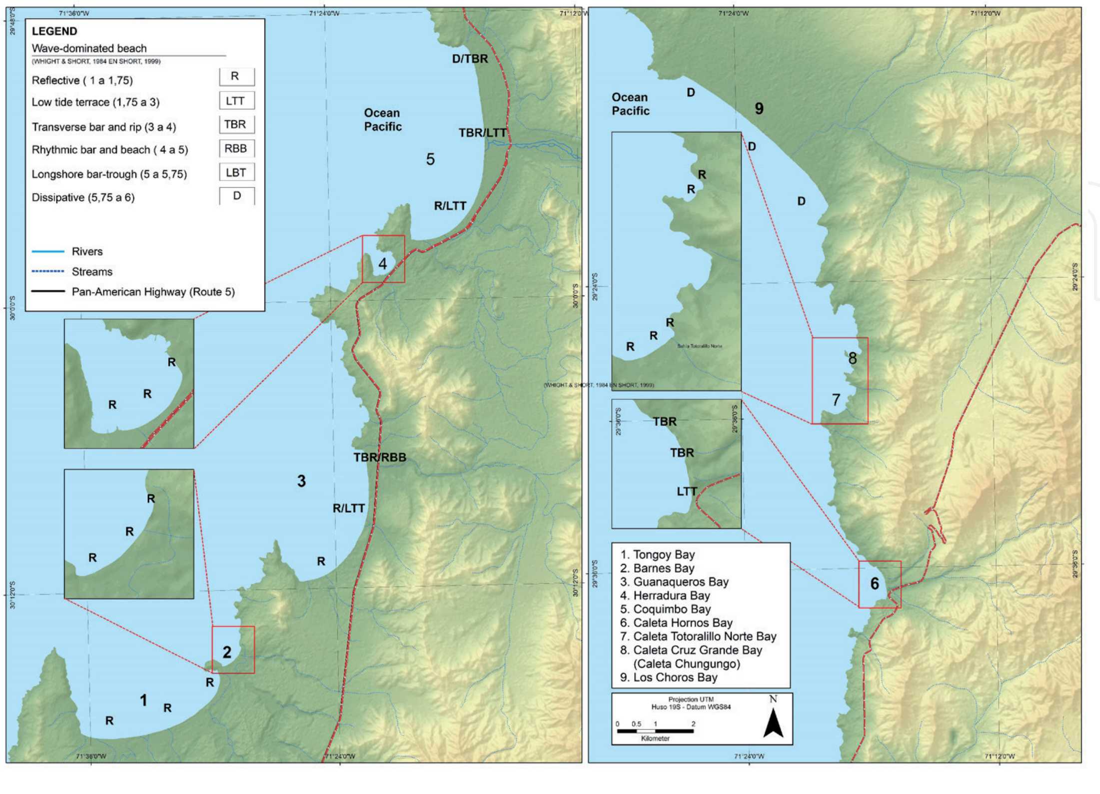

Figure 3.
Wave-dominated beach. Source: Based on [37].

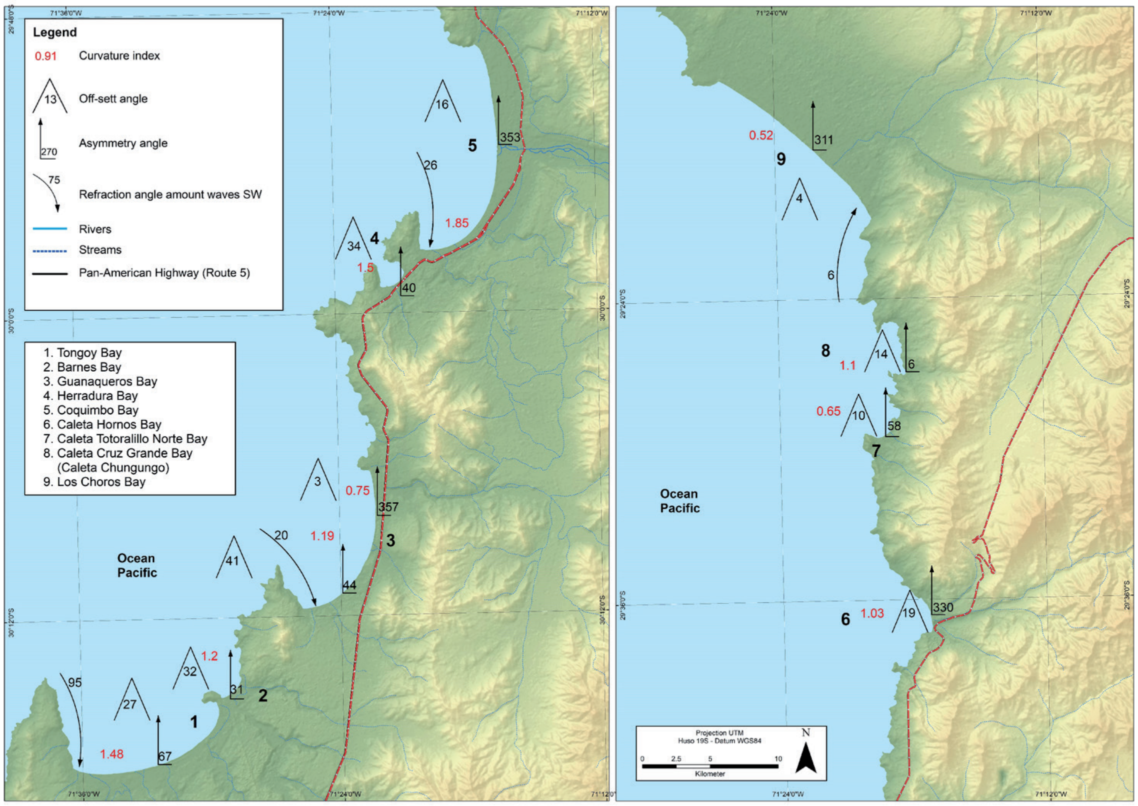

Figure 4.
Coastline morphometry of the mega bay of Coquimbo. Source: Based on [37].

In the northern area, Los Choros sand dune field is clearly distinguished. The coastline is a 16 km long sandy beach with a big dune field which is 15 km wide, which climbs the hillslope of the Coastal Range. Theses dunes have been stable since Holocene – Pleistocene [38].

The northern zone of the mega bay is the accumulation zone of the general system. It is a Dissipative beach, with breaking waves higher than 2 meters. Nonetheless, by analyzing the beach as an individual subsystem we observed some variations in the type of wave-dominated beaches, between Intermediate-Dissipative (2002, 2007, 2013 and 2014). During the years of analysis, we never observed a Reflective state. Villagrán [26] established that this zone shows a bathymetry associated to a lower relative depth, functioning as a trap for sediment entry. The relative position of the coastline (NW-SE orientation), which is transverse to the predominant wind system, shows an asymmetry angle of 311° and a refraction angle of 6° (**Figures 3** and **4**).

Table 1 shows the relationships between the offset angle, the refraction angle of the waves and the type of wave-dominated beaches for 8 bays that have been analyzed. Also, we can see how these latter form the mega bay system, with a dynamic relationship in terms of longshore current direction and associated sediment transfer. Tongoy Bay has an offset angle of 27° in the southern area and 4° in the northern area (**Figures 3** and **4**).

The dissipation of energy up to the middle and northern zones of each bay is characteristic of the presence of headlands in big bays. The southern zone, with a 95° refraction angle, shows a predominance of wave-dominated beaches of Reflective type and low energy; the middle zone with a rocky coast tends to be more Intermediate and the northern zone, with a 6° refraction angle is Dissipative with high energy, which matches the biggest deposit of dunes in the mega bay. The headland bay beach model is totally applicable to the Coquimbo mega bay. It also applies to the smaller bays that compose the mega bay's system.

N°	Bay	Asymmetry Angle	Refraction Angle	Off-set Angle	Waves-dominant Beach
1	Tongoy	67	95	27	R
2	Barnes	31	—	32	R
3	Guanaqueros	44S / 357 N	20	3	R/LTT - TBR/RBB
4	Herradura	40	—	34	R
5	Coquimbo	353	26	16	R/LTT - TBR/ LTT - D/TBR
6	Caleta Hornos	330	—	19	TBR
7	Caleta Totoralillo Norte	58	—	10	R
8	Caleta Cruz Grande (Chungungo)	6	—	14	R
9	Los Choros	311	6	4	D

Reflective (R); Low tide terrace (LTT); Transverse bar & rip (TBR); Rhythmic bar & beach (RBB); Dissipative (D)

Table 1.
Morphometric parameters in Coquimbo's structural bays system and classification of wave-dominated beaches.

4. Beach-dune relationship

Previous studies on headland bay beaches in central Chile have allowed for the establishment of the conditions for a beach-wave interaction system [12, 16–22, 24, 25, 27, 39–41], the morphologic expression of which are foredunes and transgressive dunes. This dynamic system is associated with the coastline orientation and the balancing of internal mass, the changing structure and the balancing of external mass, as well as the relationship with wave-dominated beaches (**Figures 3** and **4**). The presence of foredunes and transgressive dunes are directly related to the availability of sediments from their supplying sources (mainly from the Andean catchment) and also the capacity of transportation in the littoral zone.

By analyzing the geomorphological map (**Figure 2**), we identified that there are foredunes in each bay with sandy beaches. We found the following sequence of forms in Tongoy (**Figure 5**): Holocene vegetated foredunes-terraces with beach ridges-vegetated transverse dunes [39]. In Coquimbo (N°3 in **Figure 2**), there is a sequence of vegetated foredunes and beach ridges (destroyed by urban expansion) and Pleistocene sand dunes. In the extreme north of the mega bay, we observed the following sequence (**Figure 6**): foredunes-active transgressive dunes and the mega field of stabilized sand dunes.

Figure 5.
Beach ridge succession in the marine terrace of the Holocene. Source: Fondecyt project 1120234.

Figure 6.
Vegetated foredunes in Los Choros dissipative beach. May 2014. Source: Fondecyt project 1120234.

Figure 7.
Mixed sand and gravel beach, vegetated-foredunes eroded by the waves. Source: Fondecyt project 1120234.

In the case of the study area, the permanence of foredunes was noted. Pulse erosion and seasonal deposits existed and we identified that the foredune reconstructs itself [12, 21], thus reinforcing the conditions of a sediment transfer to sandy beaches. This is important to highlight due to the fact that in the area's semi-arid climate there has been a drought for the past decade that has reduced the volume of the Andean catchment. Nonetheless, we have seen evidence of changes in Los Choros dune system, indicating that the development of embryonic dunes and foredunes, which in conjunction with barchan and elongated dunes are evidence of the current supply of sand to the beach. Another relevant factor is the strong condition of erosion in the mixed sand.

The condition of a predominantly Dissipative wave-dominated beach is a consequence of the condition of obliquity (4° of offset angle, **Table 1**), a bathymetry of superficial platform that facilitates/provides the transfer of sediments from the south via the longshore current (**Figure 7**).

The beach-dune relationship in the system of bays that constitute the Coquimbo mega bay shows a dynamic of constant sand supply leading to a positive sediment budget. This is demonstrated each time that sandy beaches show sequences of beach-active foredunes, even if they are seasonally eroded or affected by offshore storms or tsunamis [12].

5. Final considerations in respect to the present dynamic and evolutionary trend of the Coquimbo mega bay

We analyzed the current geodynamics conditions of the Coquimbo mega bay coastal zone in terms of littoral morphology, beaches and dunes, as indicators of

Figure 8.
Tongoy beach, oblique section of the Coquimbo mega bay. Erosion of the sandy beach due to the impact of September 2015 tsunami and reconstruction of the same beach in November 2016, showing evidence of sand supply to the beach [12].

mass transfer. Previous studies have analyzed the relationship between the semi-arid river catchment and the current dynamic coastal processes, focusing mainly on the source areas for sedimentary supply, the pulse of delivery of mass to the shoreline and responses to extreme climatic events. It has been possible to identify an increase in the erosional process in the sandy beaches, nevertheless, with seasonal patterns [27, 42].

The characteristics of wind deposits in the Coquimbo mega bay show that the general distribution of the sand dynamic is replicated in each individual bay and all of them constitute the Coquimbo mega bay where the biggest concentration of sand is accumulated in the northern part of the bay (Los Choros), which corresponds to the oblique zone of the system.

From the dynamic system point of view, Los Choros dune field is very similar to Hesp's scenario model (2013 in Ref. [12]); as a matter of fact, it had a sequence of nearshore-beach-foredunes-transgressive dunes and the evolution of old and present dunes. This dynamic condition has been verified through observation over a 20-year period, showing the permanence of a sandy beach with embryonic dunes and foredunes as evidence of sediment supply.

Foredunes and embryonic dunes are also present in the Reflective low energy beaches of the oblique zone in the south. This condition has been verified as a seasonal dynamic trend. The extreme events of the 2015 tsunami (**Figure 8**), winter and offshore storms over the past.

years have generated a systematic process of destruction of the foredunes which then are newly rebuilt, proving that sediment supply comes from external sources other than the local catchment [12, 21].

The mouth of the Limari River located in the Coastal Range mega cliff does not have a dune deposit matching the size of Andean catchment. As a consequence, it shows that the sand of the Limari river supplies the beaches in the south, Coquimbo partially and mainly the dunes in the north.

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