

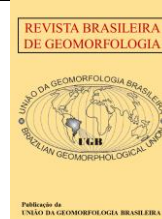


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Research Article

# Geomorphology of Topocalma's active dune field, Central Chile: Contributions of the photogrammetric method through the use of UAV

*Geomorfologia do campo de dunas ativo de Topocalma, Chile Central: Contribuições do método fotogramétrico com o uso de VANT*

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**Abstract:** The objective of this article was to carry out a geomorphological study of Topocalma's dune field through a photogrammetric survey using a drone, a methodology that has not been used to study dune fields in Chile. As a system with little intervention, the selection of the area particularly lies in the lack of further dune field geomorphological investigation. However, adjacent areas present relevant anthropogenic pressures; therefore, the use of new methodologies could contribute to its conservation and preventive planning. A dense point cloud, a digital elevation model and, an orthomosaic were obtained from an aerial photogrammetric survey carried out with a UAV. Subsequently, a morphometric characterization is carried out based on the height, slope and orientation of shapes, to generate a 3D model and a geomorphological map. The beach morphology and the formation of protodunes (bedform) of these last products were identified, when receiving a greater supply of sand form barchans, barchanoids and transverse dunes. Hence, a transgressive dune field was configured, which evolved towards an aklé pattern and parabolic dunes, at the same time.

**Keywords:** Geomorphology, dunes, photogrammetry, drone, UAV, 3D model

**Resumo:** O objetivo deste artigo foi realizar um estudo geomorfológico do campo de dunas de Topocalma por meio de um levantamento fotogramétrico com drone, uma metodologia inovadora para o estudo de campos de dunas no Chile. Por ser um sistema com pouca intervenção, a seleção da área se deve, particularmente, à falta de investigação geomorfológica mais aprofundada do campo de dunas. No entanto, áreas adjacentes apresentam pressões antrópicas relevantes; portanto, o uso de novas metodologias poderia contribuir para sua conservação e planejamento preventivo. Uma nuvem de pontos densa, um modelo digital de elevação e um ortomosaico foram obtidos a partir de um levantamento fotogramétrico aéreo realizado com um VANT. Posteriormente, é realizada uma caracterização morfométrica com base na altura, declive e orientação das formas, para gerar um modelo 3D e um mapa geomorfológico. A morfologia da praia e a formação de protodunas (forma de leito) destes últimos produtos foram identificadas, ao receber um maior suprimento de areia, formando barcanas, barcanoides e dunas transversais. Assim, configurou-se um campo de dunas transgressivas, que evoluiu para um padrão aklé e dunas parabólicas, ao mesmo tempo.

**Palavras-chave:** Geomorfologia, dunas, fotogrametria, drone, VANT, modelo 3D

## 1. Introduction

In recent decades, coastal areas worldwide and in Chile—specifically since 1985 in the Coquimbo and Valparaíso regions—have experienced an explosive increase in real estate and tourism pressure, negatively impacting the natural system (Andrade; Hidalgo, 1996 cited in Andrade; Lagos; Arenas, 2004). In this way, wetlands and dunes of Chile are already showing the effects of anthropogenic pressures, reflected in a 38.7 % reduction in water bodies and alterations in the dune fields wind and morphological dynamics, even causing the elimination of dune units due to land use competition (Contreras-López et al., 2017; Manríquez, 2020).

Coastal dunes in central Chile have been the subject of poor territorial planning (Andrade; Lagos; Arenas, 2004). The destruction of these systems and the lack of planning in coastal territories is revealed by the construction of real estate projects; a prominent case being the collapse of the Kandinsky building in the Concon dunes (Martínez; Rangel-Buitrago, 2023). However, anthropic intervention in dune areas started at the beginning of the 20th century with movement control of active dunes—those with mobile sands—which meant the stabilization of the dune field in its final stage through tree planting and subsequent wood production, according to Paskoff and Manríquez (2004).

Since the 2000s, Andrade, Lagos and Arenas (2004) indicate that the O'Higgins region coast has been positioned as a replacement area for the regions of Coquimbo and Valparaíso in the face of the real estate and touristic pressure. In this vein, the decision-making process of the territorial administration, entailing environmental implications, must consider geomorphological issues to avoid what happened to the rest of the central coast. Thus, since it allows preventive planning, spaces with little intervention seem attractive for applied geography (Andrade; Arenas; Lagos, 2010).

Morphogenetic processes of dune fields using field and office work methodologies were mapped in Chile by authors Araya-Vergara (2003; 1983; 1996), Castro (1987; 2015), Paskoff, Cuitiño and Petiot (1998), Paskoff and Manríquez (2004), Soto (2005), Soto et al. (2010). In this way, the most recent works on dune geomorphological mapping were carried out by Arriagada, Soto and Sarricolea (2014), Peña-Cortés et al. (2008; 2014), Martínez et al. (2016) using photointerpretation for aerial images taken by manned aerial vehicles at a 1:20,000 scale, Landsat 5, 7 and 8 satellite images, with a 30m resolution. Subsequently, the information was corroborated in field research and processed in GIS environments.

Currently, traditional methodologies have been complemented and updated by digital photogrammetry and the greater accessibility of unmanned aerial vehicles (UAVs), also known as drones. Unlike traditional methods, which involve greater time and cost, UAVs offer rapid field deployment and data delivery with high spatial and temporal resolution (Hackney; Clayton, 2015). Thus, UAVs allow greater ease in logistics for rapid organization after an event has occurred or even repeat monitoring in a simpler way, as they acquire this type of data at a low cost compared to the use of LiDAR technology that can provide data with similar accuracy in terms of resolution (Scarelli et al., 2016). For these reasons, the use of drones is highly recommended in the study of natural processes and their associated effects in coastal areas, showing significant results in their monitoring (Prodanov et al., 2019). However, in Chile, there are no precedents of dune studies with UAVs.

Casella et al. (2020) carried out a compilation of studies on beach topographic surveys using photogrammetry with drones, as a result of the effectiveness in the use of UAVs, pointing out that there was an exponential increase in the last 5 years in the use of unmanned aerial systems (UAS). Of the 47 studies reviewed, 52 % were carried out on the European continent, while the rest were conducted in Australia, Asia and America (15 % each) and only one was carried out in Africa. Meanwhile, photogrammetry through UAV has been applied in dunes only a few times and in very small areas to address a beach-dune geomorphological context, as mentioned by Laporte-Fauret et al. (2019). In Chile, studies of photogrammetric surveys of dune fields remain scarce.

The literature on coastal studies using UAVs focuses mainly on the validation of this methodology and on the quality of the products that can be obtained through multi-temporal analysis of beaches for the monitoring of coastal areas of interest. In this sense, the use of different sensors and/or image rectification to evaluate and reduce precision errors was compared by Gonçalves and Henriques (2015); Casella et al. (2016); Yoo and Oh (2016); Laporte-Fauret et al. (2019); and Grottoli et al. (2019). All of them reported positive monitoring results, achieving centimetric vertical accuracies and high spatial resolution, and demonstrating the capability of UAVs to detect and quantify morphological changes in beaches and dunes (erosion, accretion, shoreline displacement, and volumetric variations), thereby validating their applicability for multi-temporal coastal monitoring.

Regarding validation methods, Casella et al. (2020) indicate that the quality of the products obtained through drone photogrammetry (e.g., digital elevation models–DEMs) must be corroborated by comparing them with independent measurements, which are carried out with GNSS-RTK, LiDAR or Total Station. The error between the data obtained by UAVs and that obtained by independent control points is measured by the use of these tools in the georeferencing process, from which the vertical precision of the points can be obtained, known as the root mean square error (RMSE).

Based on the compilation of different studies carried out by Casella et al. (2020), the vertical accuracy (RMSE) of topographic models obtained using unmanned aerial vehicles (UAVs) was evaluated by comparison with independent measurements such as GNSS-RTK, total station, LiDAR, or TLS. Most of the reviewed studies reported vertical errors lower than 20 cm, with the highest accuracy reaching 0.5 cm (Casella et al., 2020). On average, digital elevation models (DEMs) generated from drone photogrammetry present a vertical error of approximately ~5 cm when validated with independent control points. This level of accuracy is sufficiently precise for coastal morphodynamic studies, where topographic changes typically occur at the decimeter to meter scale. Therefore, the magnitude of these changes largely exceeds the margin of error (RMSE), confirming the suitability of UAVs for coastal morphodynamic studies (Casella et al., 2020). In contrast, UAV surveys conducted without the support of independent measurements can reach RMSE values ranging from 15 to 40 cm (Harwin; Lucieer; Osborn, 2015; Jessin et al., 2023).

After image acquisition in post-processing, 2D and 3D surveys can be generated through software combining computational algorithms and conventional photogrammetry (Papakonstantinou; Topouzelis; Pavlogeorgatos, 2016). In this sense, among other data, software used and products obtained were collected by Jessin et al. (2023), who carried out a systematic review on coastal monitoring in island territories. Agisoft Metashape© and Pix4D Mapper© are predominantly used for georeferencing, and generate point clouds, orthomosaics and 3D models. Finally, there is a predominant use of ArcGIS for spatial analysis and cartography production.

On the other hand, there are studies that used UAVs for geomorphological mapping purposes in distant areas and with access restricted by adverse topographic conditions (Hackney; Clayton, 2015) or to experiment with three-dimensional mapping with high-resolution techniques in areas that have not yet been mapped (Prodanov et al., 2019). In this way, due to its difficult access, the use of UAVs provides advantages for the study of the Topocalma's beach and dune field, in addition to delivering high-resolution three-dimensional products that will contribute to a geomorphological survey of the area.

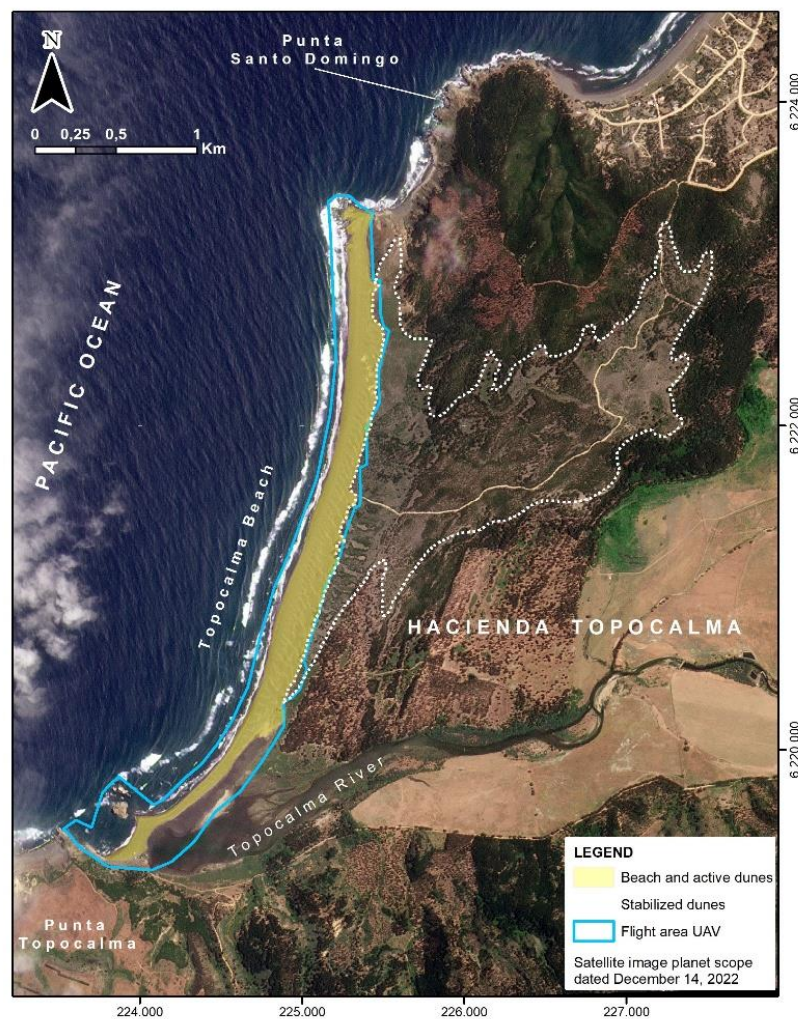
The present study focuses on the geomorphological characterization of the Topocalma dune field. This area: i) lacks detailed information regarding its geomorphology, except for the early work of Araya-Vergara (1983); ii) is currently subject to increasing real estate pressure in adjacent zones, mainly in Puertecillo (north of the study area), which is relevant as it indicates a potential physical and environmental threat to the system; iii) exhibits minimal anthropogenic disturbance, providing ideal conditions for observing natural geomorphological processes. Accordingly, the results of this research may support future conservation measures and/or preventive planning initiatives; iv) presents favorable conditions for the application of innovative methodologies in the characterization and analysis of coastal dune systems in Chile. For instance, the absence of human alteration prevents disturbances to the natural dynamics of sand transport and accumulation, enabling the analysis of aeolian processes from their origin, as well as the study of complete dune forms and evolutionary sequences. Moreover, the low level of anthropogenic impact provides optimal conditions for remote sensing approaches, as demonstrated by the development of a high-resolution digital elevation model in this study.

The use of photogrammetric techniques with UAVs is expected to allow the identification of dune units in the Topocalma system with high resolution and morphological accuracy, even in the absence of ground control points (GCPs), thus validating this methodology as a useful tool in coastal contexts with difficult access. Furthermore, this study is proposed as an initial step toward the systematic incorporation of UAVs in the geomorphological analysis of dune systems in Chile

## 2. Study area

The study area, surveyed using a UAV, corresponds to the beach zone and the active dune field of Topocalma (Figure 1). The dune field is associated with Topocalma's estuary subbasin, inserted in the coastal basins between the Rapel River and the Nilahue estuary, exoreic and pluvial in nature and has a 545.28 km<sup>2</sup> area (Dirección General de Aguas [General Water Directorate], 2014). According to Araya-Vergara (1983), the size of the basin, along with the action of the wind in the area, allows the bay to be associated with an important dune system with a primary dune predominance, the barchan and coalescent types, transverse barchans, longitudinal dunes, and wind sprays. The formation of longitudinal dunes develops immediately to the north of the estuary near the mouth, while the beach contributes the sediment for barchan formation.

The sandy coastline extends for 4.4 kilometers, delimited by two rocky outcrops: Punta Santo Domingo to the north and Punta Topocalma to the south. The waters of Topocalma's estuary flow into the Pacific Ocean in the southern sector of the study area. At its mouth, and separated from the sea, a brackish lagoon is formed by a barrier and the dune field. A high value is given to the different environments in this ecosystem that, added to the use of artisanal fishing and the collection of algae, gave rise to a protected area called Piedra del Viento and Topocalma Nature Sanctuary, enacted in 2021 in accordance with the Ministry of the Environment's 10th Decree (MMA [Ministry of the Environment], 2021).



**Figure 1.** Study area. The location and distribution of Topocalma's dune field is identified, from the beach to active and stabilized dunes. The flight surface includes part of the surf zone, beach and active dunes in its entirety.

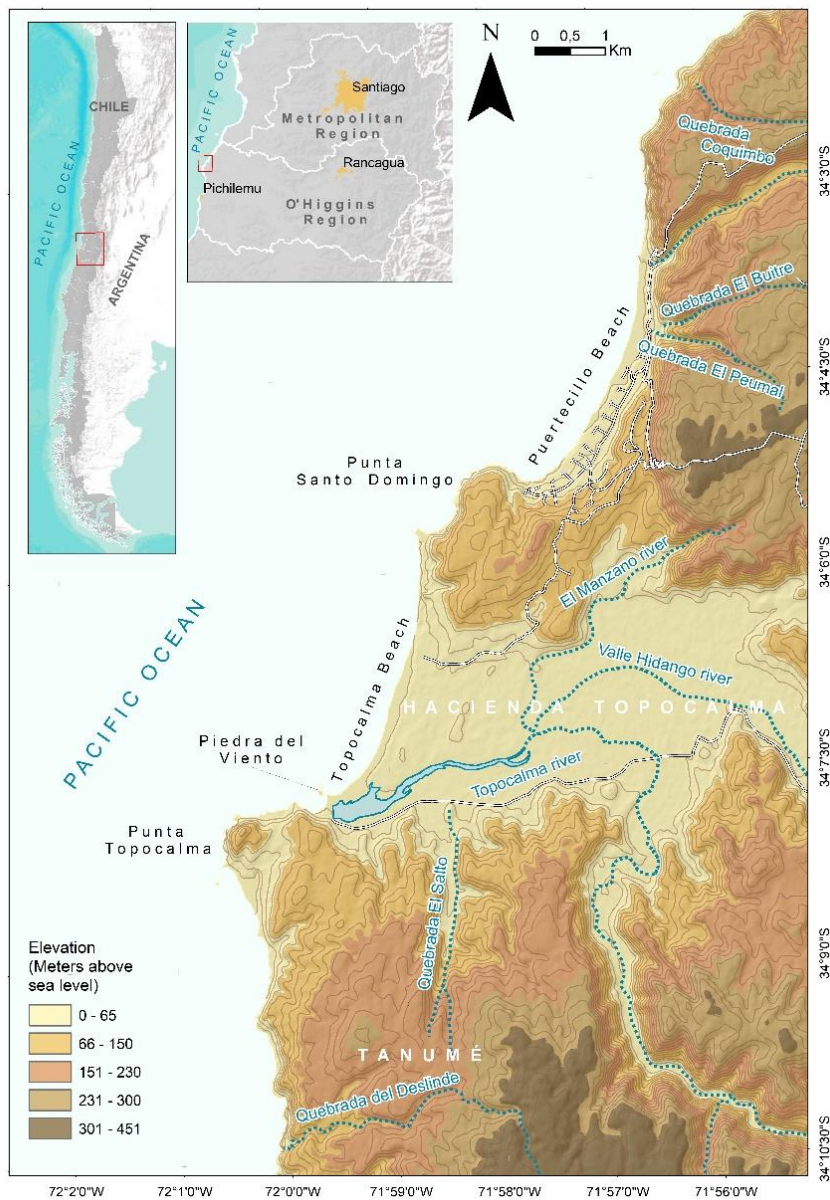
## 2.1 Overview of the Topocalma region

The Topocalma bay is located in the Litueche western area, Libertador Bernardo O'Higgins region, between 34°05' - 34°07' S and 71°58' - 72°00' W, in central Chile. The coast of this region alternates sectors of semi-regularized cliffs with zeta-form inlets associated to important dune systems, such as the bays of Puertecillo, Topocalma and Pichilemu (Araya-Vergara, 1983).

The bay under study has a field of primary dunes—those nearest the beach—limiting north with Puertecillo's inlet and an abandoned rectilinear granite cliff N-S orientation. In Tanumé, heading south, the granitic cliff changes its NNW–SSE orientation weakly (Araya-Vergara, 1983) (Figure 2).

The formation of marine terraces that were modeled on intrusive Paleozoic basement (Topocalma-Puertecillo) and metamorphic (Tanumé) is found towards the east. In turn, these are covered by marine strata from the Upper Cretaceous, known as the Punta Topocalma formation, marine sediments from the Neogene or Navidad formation and Quaternary sediments corresponding to alluvial, colluvial deposits, dunes and beaches (SERNAGEOMIN [National Geology and Mining Service], 2003; Farías et al., 2011; Encinas; Stinnesbeck; Valencia, 2014; Jara-Muñoz et al., 2015).

In Puertecillo and 28.6 km south of the study site, sediments from marine terraces in Pichilemu were dated using the infrared stimulated luminescence (IRSL) method by Jara-Muñoz et al. (2015), providing an estimated date of  $88.2 \pm 6.9$  ka (MIS 5b). However, the dating was correlated with MIS 5c, given that the deposits were identified in a wind environment, therefore, they belong to the last phase of sedimentation after the drop in sea level. In addition, the marine terraces were associated to the MIS 5e and developed along the Pichilemu fault, with an elevation of 40 m reaching 180 m in Topocalma. A normal fault moved this last level of MIS 5e to 150 m in Puertecillo. The terrace levels to the north of Puertecillo are of lower elevation, with a terrace of 17 m elevation correlated to the MIS 5e in Navidad.



**Figure 2.** Topocalma region on the central coast of Chile. The figure shows the elevation of the area, highlighting the steep cliffs located to the north and south of the study area, as well as the drainage network dissecting the marine terraces.

### 3. Materials and methods

#### 3.1 Aerial photogrammetric survey with UAV

A flight was carried out on the morning of 14 December 2022 from 07:55 to 10:58 am. The meteorological conditions during the flight were: 7 knots with gusts of 8 knots wind speed; wind and wave direction, northeast; tides, falling (low tide at 10.20 am); 14°C temperature; 11 to 19 % variation on cloudiness.

A DJI Mavic 2 Pro model drone was used, which has a 1" CMOS sensor, a 20 mp image size (5,472 × 3,648 pixels), a 2.41 × 2.41 microns per pixel resolution and a global navigation satellite system (GNSS) GPS + GLONASS. It has a planimetric (horizontal) accuracy of ±1.5 m and an altimetric (vertical) accuracy of ±0.5 m when using GPS positioning.

A 66-minute flight was determined in the pre-flight planning (Figure 3) carried out with the DroneDeploy application. Once on the ground, 1,252 images were obtained with a 2.37 cm/pixel resolution, at 106 m average height, covering a 4.81 km<sup>2</sup> total area from the surf zone in the west to the active dune field to the east (Figure 1). A 70 % frontal overlap and lateral 60 % overlap were obtained from the images. The flight direction was 89°, carried out at a 10 m/s speed and a -90° Gimbal angle.

Due to the size of the study area and its difficult access, the area was not georeferenced with ground control points (GCP) on this occasion, therefore, there is no vertical precision calculation. Placing GCPs requires carrying precision equipment (GNSS-RTK, physical markers) to specific positions and georeferencing them, which can be challenging in active dunes or areas with dense vegetation. However, it was possible to capture field photographs by walking only along the beach area, as this activity does not require centimeter-level precision or the installation of heavy equipment, allowing qualitative documentation of the site.

In any case, the photogrammetric survey was used to morphologically characterize the study area and the measurements made correspond to real measurements within the same survey. In this sense, it is important to clarify that if these data are used for the system's subsequent monitoring, this survey must be georeferenced to calculate its precision and, hence, the comparison will be valid.



Figure 3. Flight plan on the DroneDeploy app.

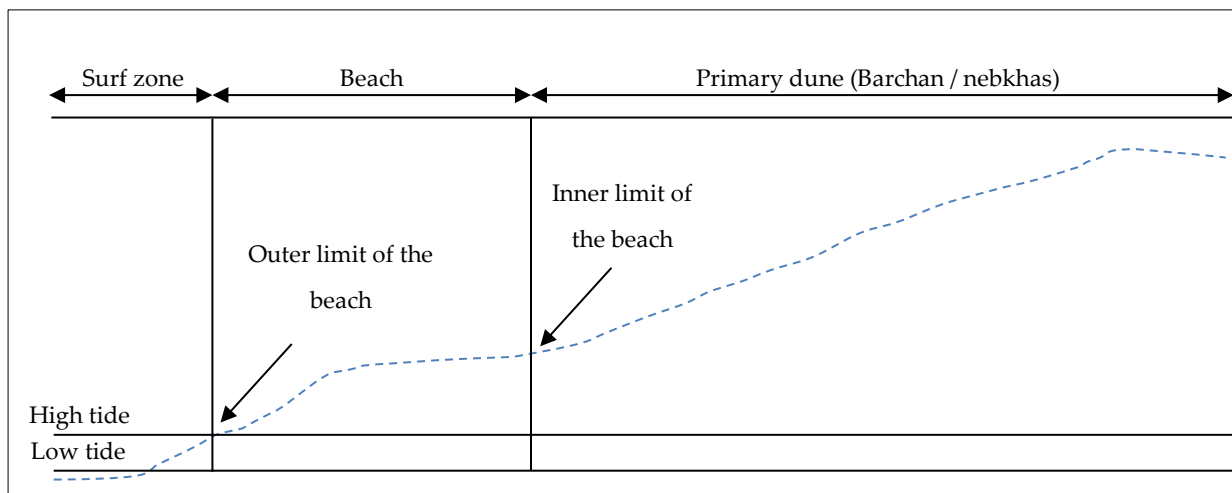
### 3.2 Data processing

Once obtained, the images were processed in the Agisoft Metashape Professional software. 1,072 images were aligned using the UTM WGS 84 19 S zone coordinate system. Subsequently, a dense point cloud was generated (a set of agglomerated points containing information in X, Y and Z; that is, position and elevation information), a digital elevation model (DEM) with a 9.48 cm/pixel resolution and a 2.37 cm/pixel resolution orthomosaic, both exported in .tiff format for subsequent GIS processing.

The study area was delimited using ArcGIS, excluding the flight area and the surf zone, since the UAV was not equipped to obtain bathymetric data. Therefore, the morphology of the beach was delimited using two geomorphological criteria, leaving geometric criteria aside (0 m contour line) proposed by Ojeda et al. (2013) (see Table 1 and Figure 4).

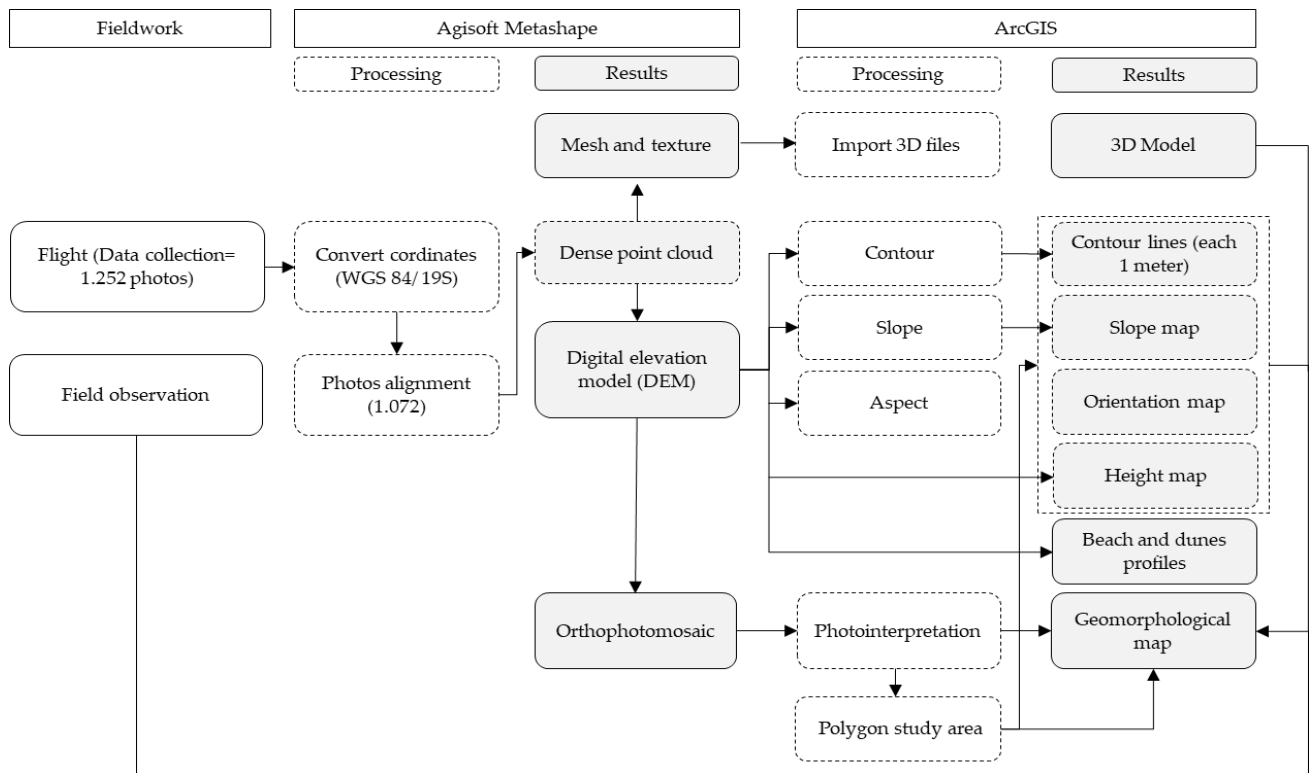
**Table 1.** Delimit beach criteria based on Ojeda et al. (2013).

Geomorphological/physiographic criteria	High-tide line	Beach-dune contact line
Use	Commonly for management, statistics, etc	Due to its stable nature, it is used in long-term evolutionary studies.
Trait to identify	Outer limit of the dry beach (backshore).	Interior limit between the dry beach (backshore) and the coastal dune (foredune).
Scale	1:2,000 (this scale was permanently used to guarantee geometric coherence).	
Input	Orthomosaic	
Method disadvantages	<ul style="list-style-type: none"> <li>• Photointerpretation subjectivity (performed by only one digitizer).</li> <li>• Difficulty in delimiting a transition phase and high dynamism on a short spatial and temporal scale.</li> </ul>	



**Figure 4.** Beach profile based on Miot da Silva and Hesp (2010) and Ojeda et al. (2013).

Subsequently, altitude, slope and orientation maps adapted from Vallejo et al. methodology (2009) were generated, along with a 3D model and elevation profiles to identify and analyze the morphology of the area (Figure 5).



**Figure 5.** Methodological scheme divided into 3 phases; i) fieldwork where the UAV flight was carried out; ii) photos processing to obtain point cloud and DEM; iii) ArcGIS processing for mapping results.

### 3.3 Dune field and beach morphology

The morphological analysis of the active dune field was carried out based on Pye and Tsoar’s morphological classification (2009), modified and complemented with Hesp’s transgressive typology (2013) (see Table 2). This is complemented with morphometric data such as the dunes slope and orientation proposed by Paskoff and Manríquez (2004), Vallejo et al. (2009), Pye and Tsoar (2009) and Sanjaume, Gracia and Flor (2011). Orientation is analyzed on the prevailing wind; as obtained from simulated meteorological data for Topocalma, based on 30 years of hourly weather model simulations, in the Meteoblue weather forecast system (2024). The Python Windrose package was used to process data to draw wind roses.

**Table 2.** Morphodynamics of dunes based on the classification of Pye and Tsoar (2009) and Hesp (2013).

<i>Dunes formed by topographic obstacles</i>	Shadow dune (Lee dune)	Formed from topographic obstacles such as rocks and, preferably, in areas with unidirectional wind. They are characterized as static dunes, that is, they do not undergo variations in their shape. First, there is a horseshoe-shaped accumulation of sand (in front and on the sides of the obstacle), which then merges into the center line, behind the obstacle (Pye; Tsoar, 2009).
	Echo dunes	Commonly formed in front of cliffs (windward). Vortices are formed between the cliff and the sand accumulation; their arms climb where the water network dissects the cliff (Pye; Tsoar, 2009).
	Climbing dunes	Formed from echo dunes. When the echo dune is in a lower position, there is a lower wind speed at its crest compared to the vortex flow. Therefore, the echo dune grows in height, reaching stability at one third of the obstacle’s height (cliff), and sand falling from the crest into the vortex (Tsoar, 1983b cited in Pye; Tsoar, 2009). On the other hand, an intense flow vortex cannot be generated if the cliff is not steep enough, therefore, the sand will climb the scarp. Climbing dune formation is generated in less than 60° angles (Tsoar, 1983b cited in Pye; Tsoar, 2009).

Self-accumulating dunes	Barchan	Crescent-shaped isolated dune; its arms point in the same direction as the wind. The windward side is a convex gentle 12° slope. The leeward side has a 33 to 34° steeper slope. Barchans are ephemeral dunes forming rapidly on free-of-vegetation beaches on a relatively hard substrate, where the sand supply is limited and the winds are almost unidirectional (Pye; Tsoar, 2009).
	Barchanoid or transverse dunes	Individual barchan union due to increased sand supply, forming a sinuous crest perpendicular to the dominant wind, forming a 75° – 90° angle between its crest and the resulting long-term sand transport. Many transverse ridges show elements linked to their sinuosity: barchanoid highs (downwind) alternating with lingual lows (upwind) (Momiji; Warren, 2000 cited in Araya - Vergara, 2001; Pye; Tsoar, 2009).
Dunes formed by vegetation	Hummock dunes	Irregular-shaped mound of sand partially or completely covered by vegetation. Commonly 10 meters tall, but may reach up to 30 m high and 100 m wide (Pye; Tsoar, 2009). The morphology of mound dunes—nebkhas—depends on the type of vegetation (size, shape of stems and leaves, plant structure, among others), since high flow resistance causes their formation. The wind decelerates upon reaching vegetation, then accelerates around the plant and a flow separation occurs behind it (Bressolier and Thomas, 1977; Hesp, 1981; Greeley and Iversen, 1985; Wasson and Nanninga, 1986; Clemmensen, 1986; Nickling and Davidson-Arnott, 1990; Pye and Tsoar, 1990; Thomas and Tsoar, 1990 cited in Hesp, 2002); therefore, this type of dune accumulation occurs the vegetation’s upwind, within and downwind (Hesp, 2002; Hesp; Smyth, 2019).
	Parabolic dune	U or V shaped dune with arms pointing against the wind. Some have a steep leeward slip face. The arms outer surface is partially or completely covered by vegetation (Pye; Tsoar, 2009).
	Protodunes	Transient bedforms, low relief or low angle and without slip face occur as ephemeral wavy strips on a flat sand surface, which form prior to more complex dunes during high-energy sand transport (Nield; Wiggs; Squirrell, 2011; Phillips et al., 2019). Its formation has been linked to the wet-dry transition: the beach dries and sand availability increases (Nield; Wiggs; Squirrell, 2011), thus, a temporary transition occurs from patches accumulation to a protodune formation. An increase in the latter’s amplitude and a lee slope increase characterizes the protodune to dune transition, generally to barchan-type dunes (Kocurek et al., 1992 cited in Phillips et al., 2019).
Others		Large-scale dune fields, partially or completely vegetated. They may have a tabular shape or climbing dunes fields associated with echo dunes (Hesp, 2011). When active, they may migrate transversely along the coast depending on the direction of the prevailing wind (Gardner, 1955; Hesp et al., 1989; Hesp and Thom, 1990; Hesp et al., 2011 cited in Hesp, 2013). They occur especially on high-wind and high-wave-energy coasts (west and south coasts) and have a significant sediment supply, such as the west coast of South America, particularly Chile and Peru (Hesp, 2011).
	Transgressive dunes	There are 3 initiation scenarios for transgressive dunes: i) evolving from the beach; ii) evolving from the frontal dune erosion (previous dune) and/or dune fields, and; iii) parabolic dunes breakdown or fusion, each of these types can have several evolutionary paths (Hesp, 2013). When there are no frontal dunes, it evolves directly from the beach due to a high supply of sediments which is complemented by a predominant wind direction, favoring the formation of mobile dunes (barchan, barchanoid and transversal) and nullifying vegetation growth on beach-dune system. As the dune field grows, fronts build up on the leeward margins. They may present interdune depressions with a high phreatic level or with a rock or soil deflation base. Parabolic dunes may be formed reaching areas with dense or high vegetation, since vegetation will retain dune arms and the lobe or the main body will advance in front of the dune field. Barchanoid and transverse dunes may prevail in transgressive dune fields in warm weather with a high sediment supply, and become a more complex system, the formation of an aklé pattern is quite common (Hesp, 2013).

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Aklé	Complex dune networks are dominated by transverse ridges. Their downwind longitudinal ridges, termed leeward projections, were described by Cooper (1958 cited in Pye and Tsoar, 2009) as erosional residues formed by vortex convergence from the dominant transverse ridge (Pye; Tsoar, 2009).
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## 4. Results

### 4.1. Morphometric characterization

#### 4.1.1. Height

In the middle zone of the bay, predominant heights go up to 14 meters (Figure 6.A), consistent with the beach and interdune depressions between barchan and barchanoid type dunes. Heights between 15 and 19 meters were identified in the same area towards the inner limit of the active dune field, coinciding with dune crests (dune's highest point).

Similarly, these heights between 15 and 19 meters, are distributed on the beach in the northern sector of the bay. This would explain greater sedimentation in this area, therefore, greater heights than those in the beach sector described above. On the other hand, in the inlet northern sector, a 20- and 57.6-meter sustained increase matches the area's cliff relief.

Height rises from 15 to 25 meters in the southern sector. The lowest height corresponds to the coastal barrier, increasing towards the coastal cliff.

#### 4.1.2. Slope and orientation

There is a predominance of low slopes on the western edge of the area (Figure 6.B). These slopes range from 0° to 12°, coinciding with the lowest heights, therefore, lower slopes also coincide with the beach morphology, the dunes' windward side and interdune depressions. The beach (Figure 6.C) is oriented towards the west in the central and northern area of the inlet, while in the southern area it is oriented towards the northwest, due to the curvature of the coast.

The 0-12° low slopes are oriented towards the southwest in the middle zone dunes, while the highest slopes (21-35°) are oriented towards the north and northeast (Figure 6.B and 6. C). This reveals the shapes of transverse dunes (whether barchan, barchanoid or transversal) and the direction of the predominant wind from the south and southwest (see Figure 7). The slope increases to 35° in the northern area, even to 50° in some sectors, and its orientation tends towards the west (Figure 6.B and 6.C). Furthermore, if the height increases up to 57 meters, there is an evident topographic change in the cliff.

A predominance of low slope (0-12°) is identified in the southern area of the bay, the space occupied by the lagoon and coastal barrier. However, changes in the slope parallel to the beach indicate the existence of smaller barchans and variations in orientation. The beach face extends towards the northwest; while the internal face faces southeast (Figure 6.C), which would indicate the occupation of the coastal lagoon during flooding times.

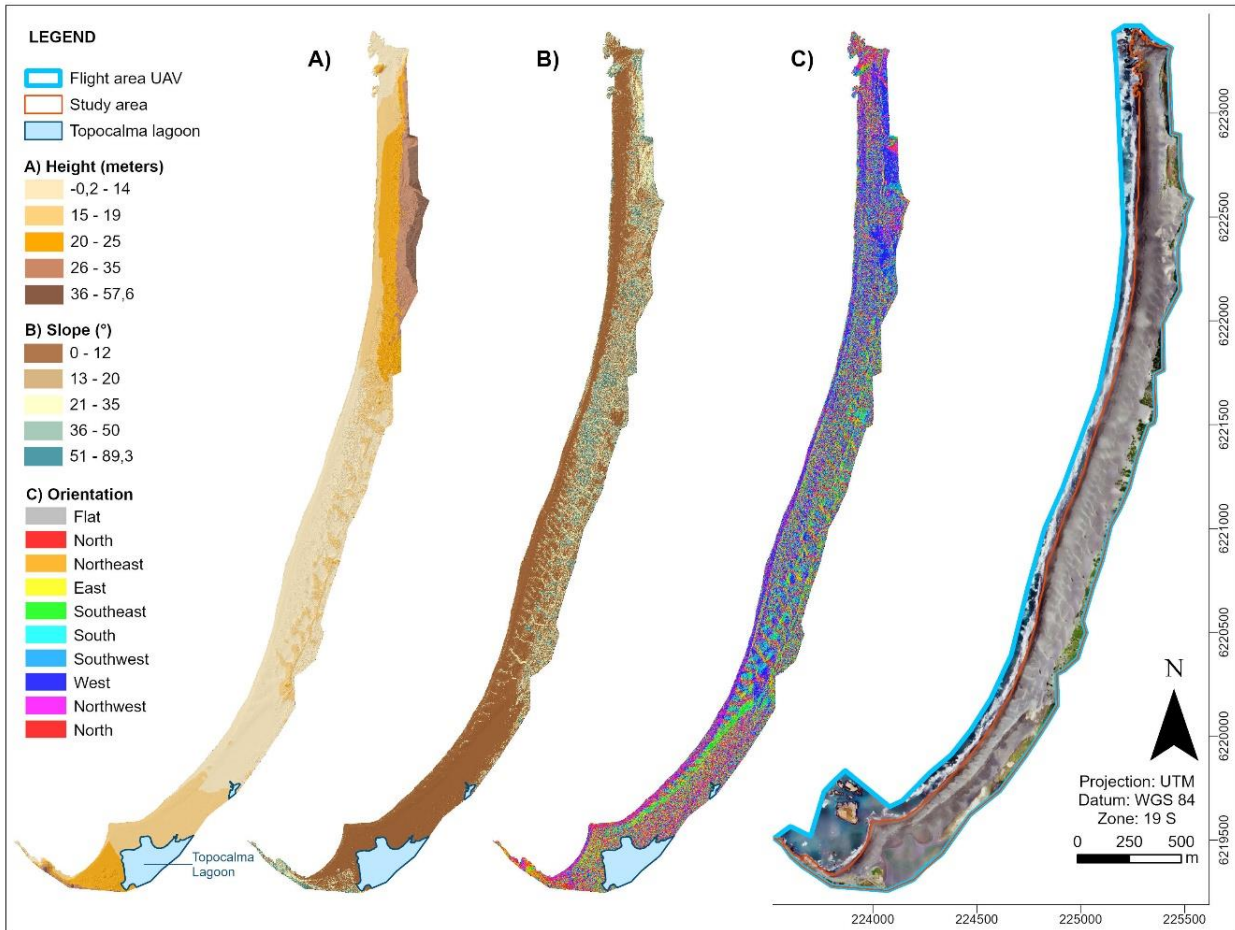


Figure 6. Morphometric map of height, slope and orientation obtained from a Digital Elevation Model (DEM).

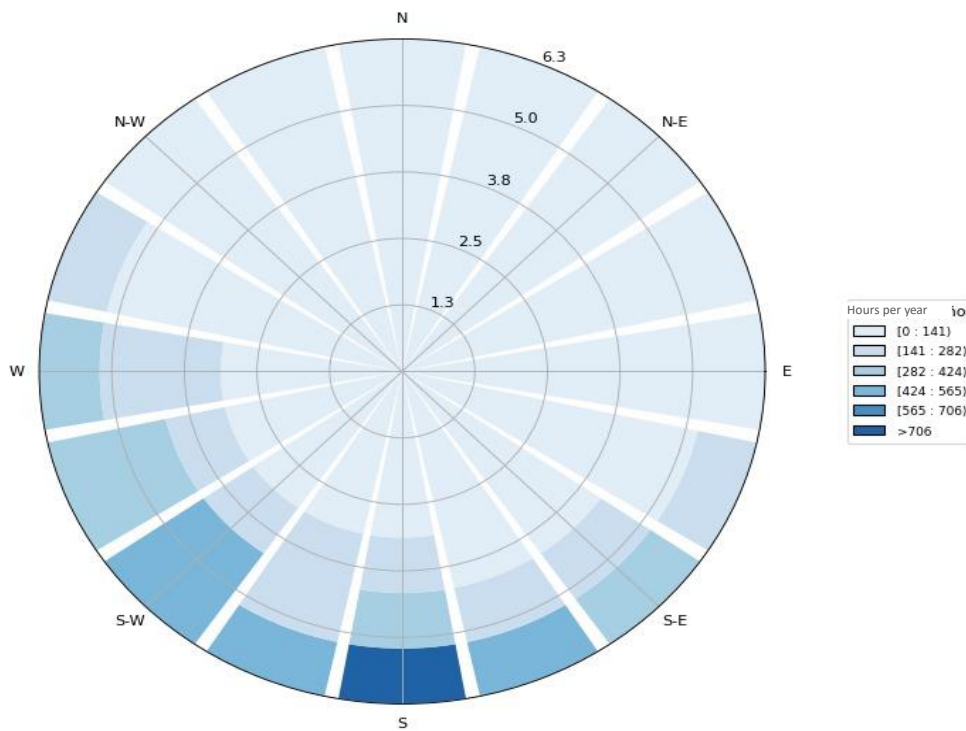
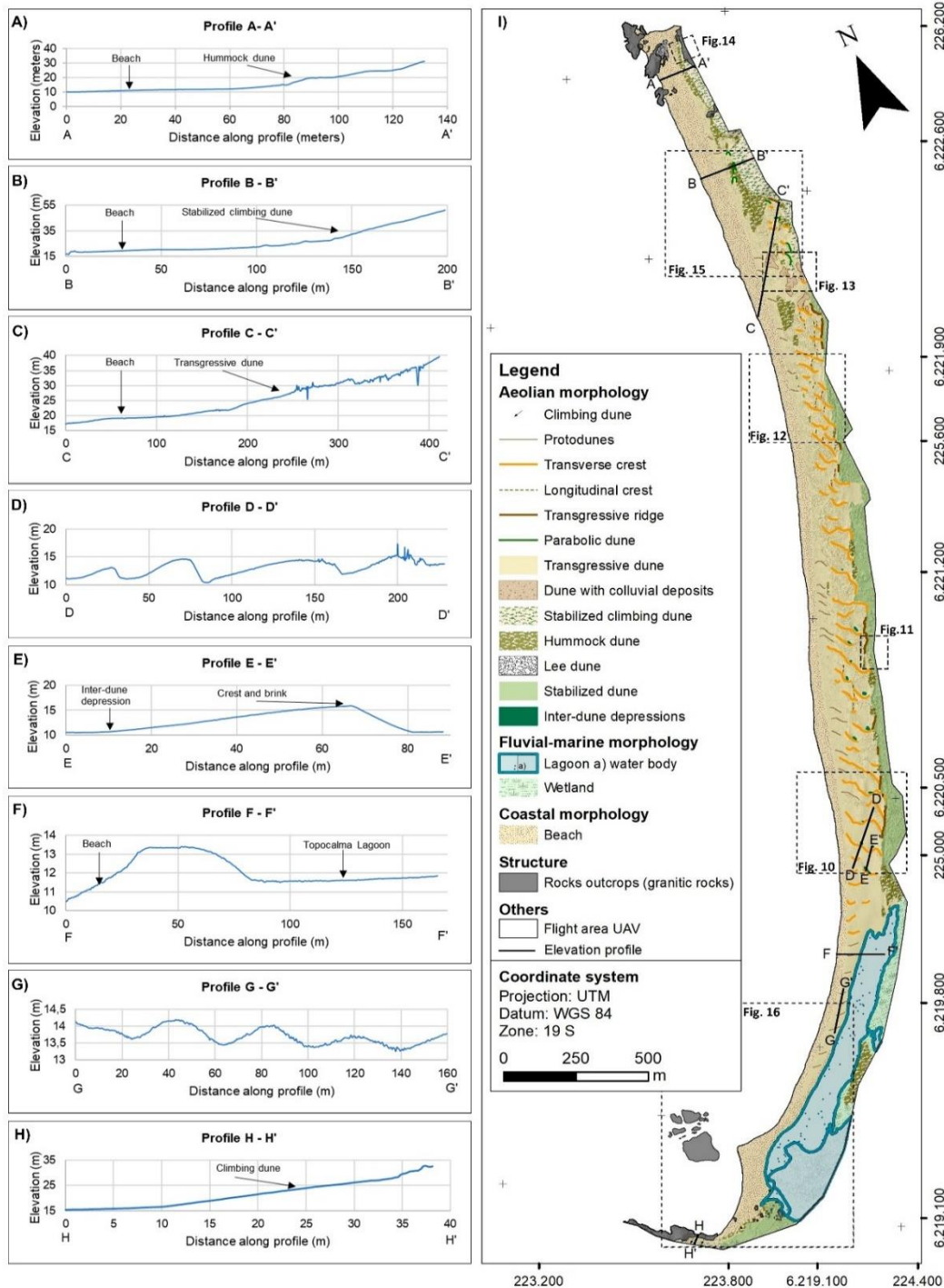


Figure 7. Wind rose for Topocalma made with data simulated by Meteoblue (2024).

4.2. The feeding area prior to dune formation

The beach is the area that receives the sediments transported by the waves, which are subsequently mobilized by the wind, forming dunes. In this bay, the coastline is configured in such a way that it is curved towards the northwest in the southern sector and it tends to be rectilinear and open towards the west in the north (Figure 6). The above implies that erosion processes prevail in the southern sector and accretion processes towards the northern sector. This is evidenced in the elevation profiles F and H (Figure 8), the profile first meters corresponding to the beach, and present a concave morphology, indicating beach erosion; while profiles A, B and C (Figure 8) show a convex morphology, which translates into sediment accumulation.



**Figure 8.** (A–H) Elevation profiles in areas of interest, derived from DEM. (I) Geomorphological map of the active dune field developed from photointerpretation of the UAV orthomosaic and the morphometric maps of height, slope, and aspect.

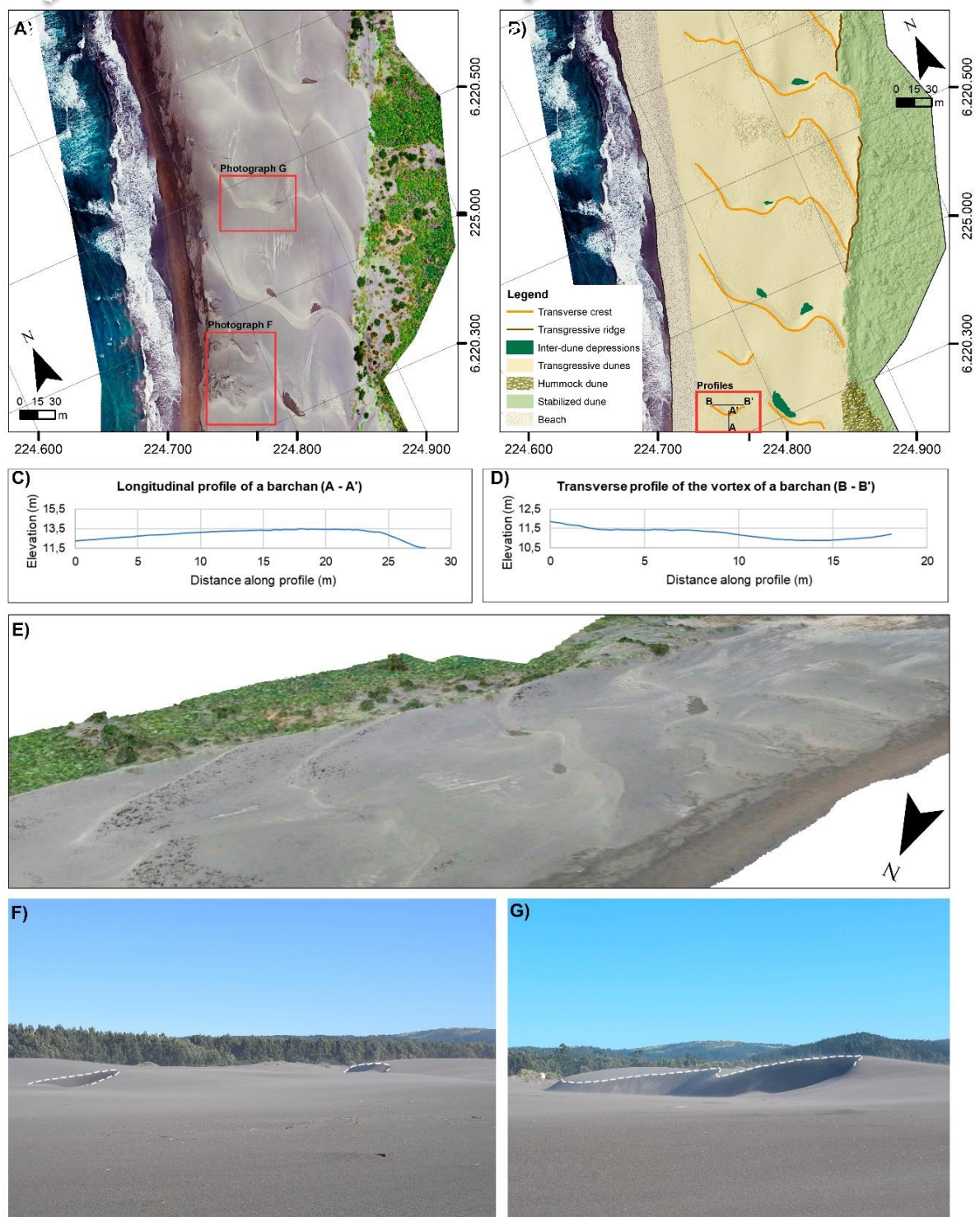
#### 4.3. Active dune field

Topocalma's active dune field extends from the feeding zone (beach) to where free dunes meet a dune field completely stabilized by pine trees. Firstly, the sands dry and are transported and accumulated behind the beach, thus forming protodunes that present a dry-and-wet alternation of sands (Figure 9). They are located transversely to the prevailing wind and along the bay. Profile G (Figure 8) shows that the surface has low undulations approximately 50 centimeters high, 40 meters wide and does not present a precipitation crest or edge (Figure 9).



**Figure 9.** Segmented lines indicate protodunes, where wet sand areas and dry sand accumulation areas stand out. Aerial photography taken on 14 December, 2022.

Once the unidirectional wind (south and southwest, Figure 7) manages to increase the protodune height and generate a precipitation edge a barchan-type dune appears. Currently, individual barchans are located immediately north of the coastal lagoon and very sporadically in the rest of the dune field. They reach an approximate 28-meters length and 18-meter width; while, its vortex reaches a 1-meter depth, approximately. Its windward side (SW) has a low slope (Figure 10).



**Figure 10.** (A–B) Transverse-transgressive dune field, with individual barchans, barchanoids and transverse dunes (from orthomosaic). (C–D) Barchan longitudinal and transverse profile (from DEM). (E) 3D model (from 3D reconstruction). (F–G) Individual barchans and barchanoid dune, respectively (from field photographs, 14 December 2022). Segmented line indicates dune crest.

In the rest of the dune field, individual barchanoids (Figure 10.F) evolved into more complex dunes, uniting their crests and forming barchanoid (Figure 10.G) and transverse dunes. Like barchans, crests are perpendicular to the prevailing wind (SW), but unlike a barchan, its crests are much longer—54.13 meters on average. Those more

developed ridges reached a 170.15-meter maximum length. On the other hand, the windward side of the transverse dunes has been observed as low-sloped and the leeward side high-sloped in elevation profiles D and E (Figure 8), maintaining barchan slopes. The transverse dune length increases up to 80 meters and reaches a 16-meter height (Figure 8, profile E), as these forms evolve. The group of transverse dunes forms a transgressive dune field (Figure 8, profile D and Figure 11).

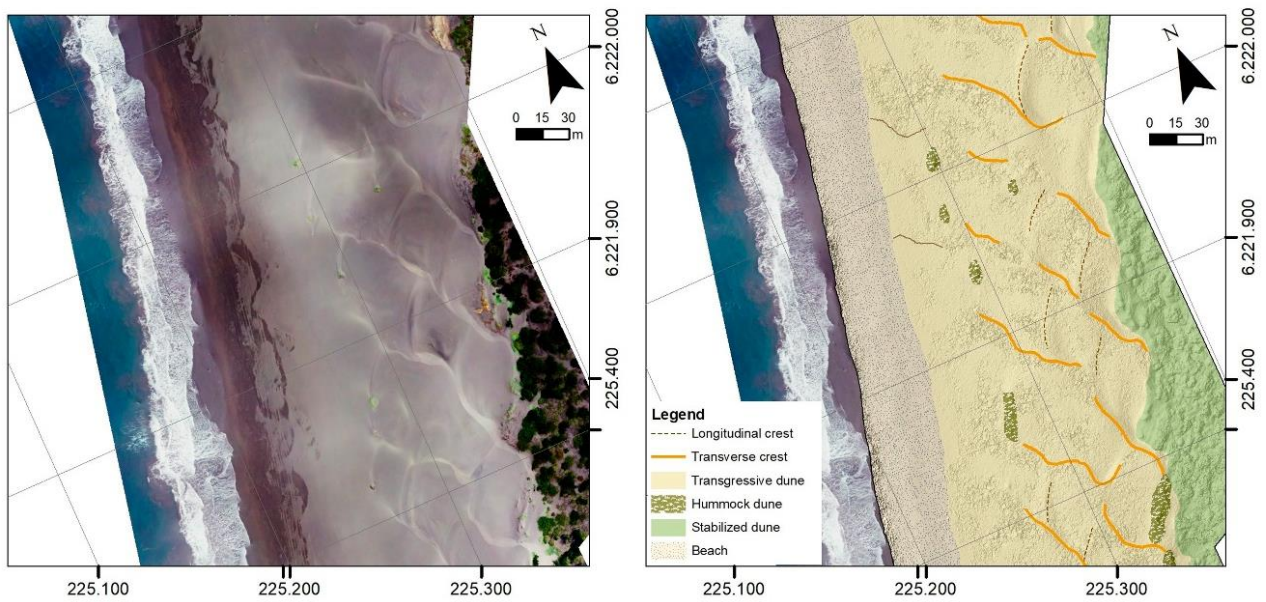
The transgressive dune field is observed largely without vegetation, therefore, barchanoid and transverse dunes are active and move forward the direction of predominant wind (from SW to NE). On its eastern edge, there is a transgressive front reaching a 15-to-19-meter height, its leeward side faces southeast (Figure 6.C). This transgressive front is segmented between free and stabilized sectors that have developed mounded dunes (hummock dunes) (Figure 11), which can evolve into parabolic dunes. In free sectors, the transverse crest coincides with the transgressive front of the dune field.



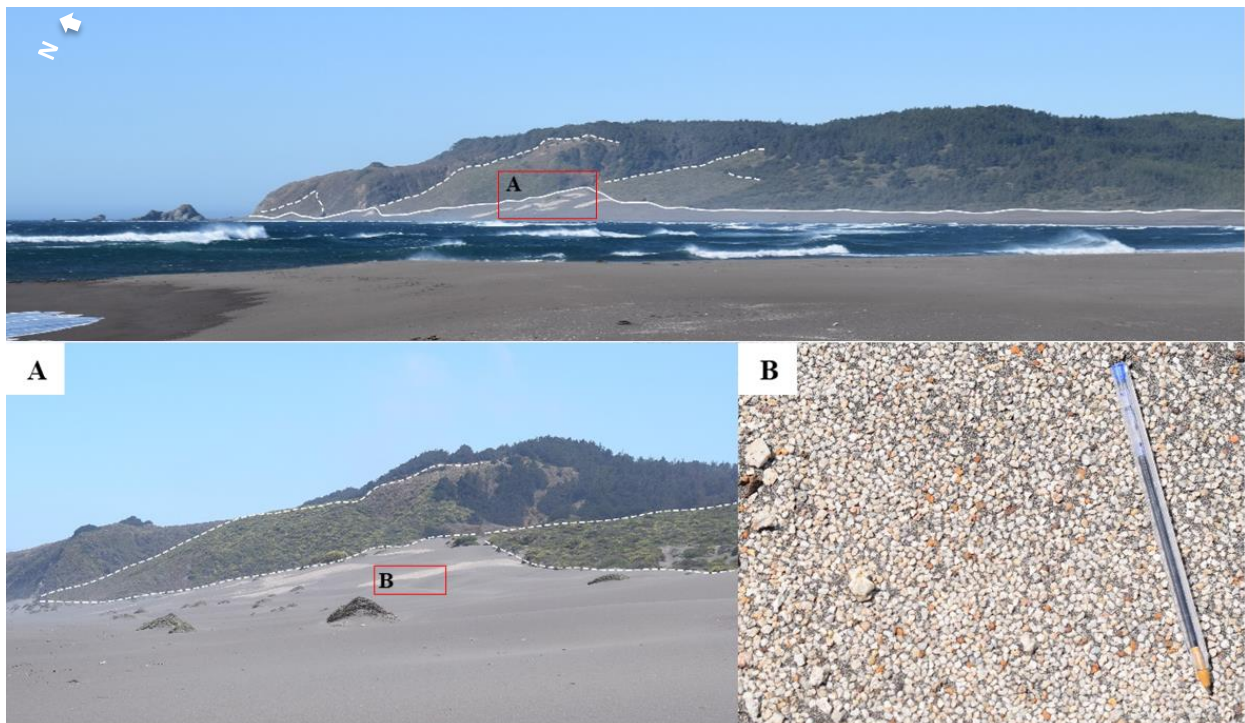
**Figure 11.** In the transverse-transgressive dunes, segmented lines indicate edges and continuous lines indicate crests. The arrows indicate the sliding face or free transgressive front. Photography taken on 14 December, 2022.

Transverse dunes present an incipient aklé pattern in the middle to northern area of the inlet. Longitudinal ridges (SO-NE) were observed extending from the dominant transverse ridge (SE-NW) (Figure 12). Towards the north, this pattern is interrupted by a cover of colluvial sediments over 20 meters high (Figures 8 and 13).

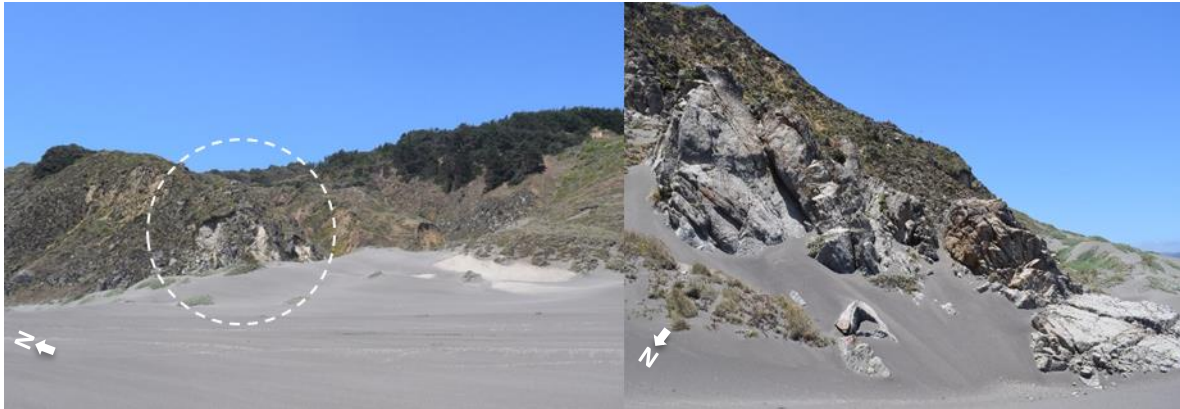
These weathered granite sediments present mineral oxidation, due to water and wind action. It presents the same mineralogy as the rocky outcrops of the coastal batholith (Figure 14). The size of the grains presents poor selection and a subangular shape, which could indicate a short transport distance (Figure 13). These sediments' location is believed to be in the distal area. In this sense, these sediments could be a stratum between layers of sand exposed by the action of the wind or a deflation base in weathered rock.



**Figure 12.** Aklé pattern in transversal-transgressive dune field (from orthomosaic). The lines indicate the aklé pattern longitudinal ridges. Segmented lines indicate ridges from transverse dune erosion



**Figure 13.** Panoramic view of the active dune field and the stabilized climbing dunes in the inlet middle and northern area. Box A is a colluvial deposit location close-up in transgressive dunes and stabilized climbing dunes in the background. Inset B shows in situ weathered granite. Photography taken on 14 December, 2022.

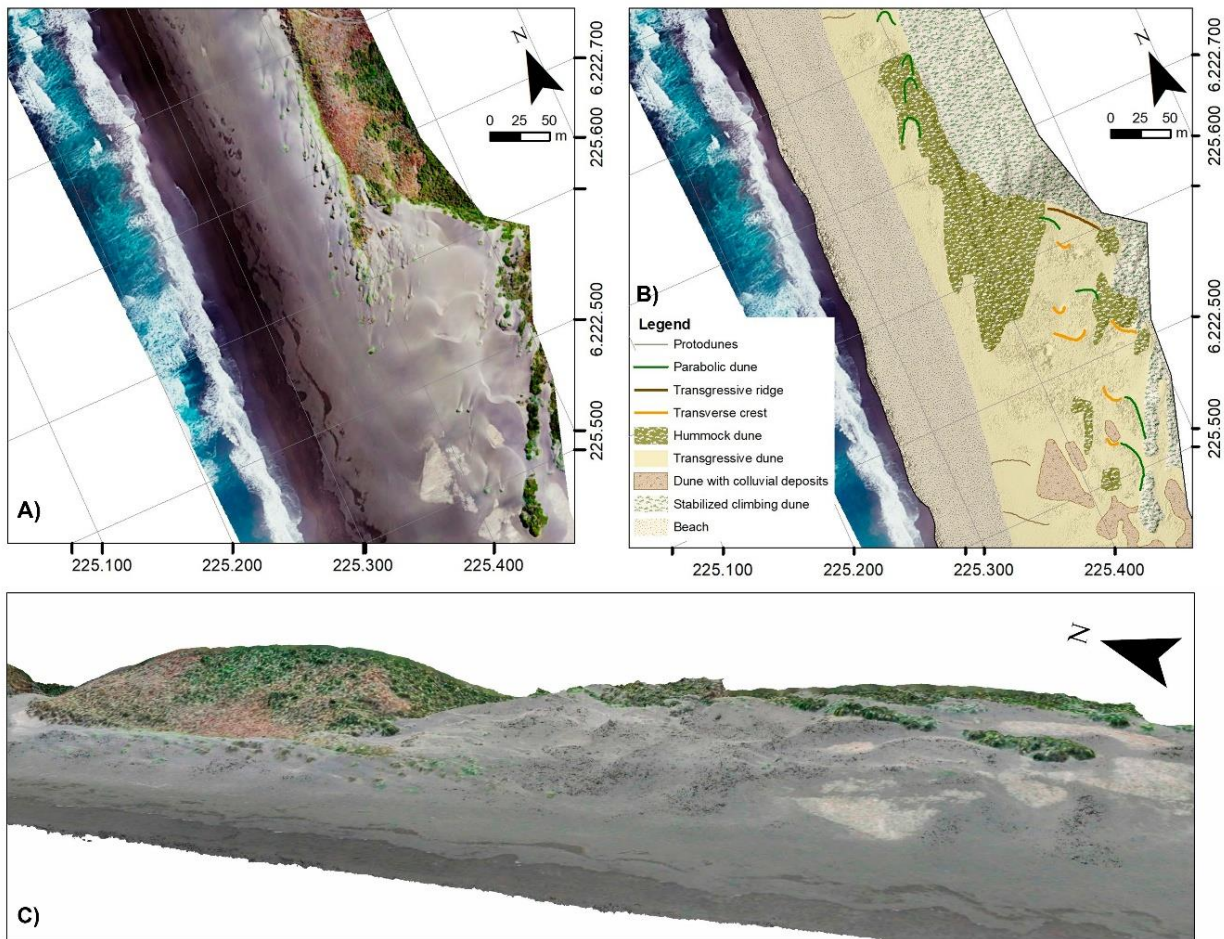


**Figure 14.** Rocky outcrop of the coastal batholith in the inlet northern sector, presenting a climbing dune stabilized by vegetation and a transgressive dune moving inward. Photography taken on 14 December, 2022.

To the north of the inlet, in the cliff, the coastal batholith is exposed (Figure 13 and 14), covered by a climbing dune currently stabilized by vegetation, which is covered by the transgressive dune at the same time (Figure 8, profile C and Figure 15). An abrupt slope facing west is part of the climbing dune (Figure 6.C), which reaches an approximate 55-meter height only in the polygon of the study area, height increases considerably outside the polygon.

There are mounded dunes at the base of the climbing dune giving rise to parabolic dunes (Figure 8, profile A and Figure 15), which arise over the vegetation due to the advance of the transgressive dune. However, this dune form is found in isolation in the northern area of the field (Figures 8 and 15).

Shadow dunes are located to the north of the study area, which were formed as the rock hindered the advance of sand in the area (Figure 8). These rocks are part of the coastal batholith rock outcrop.

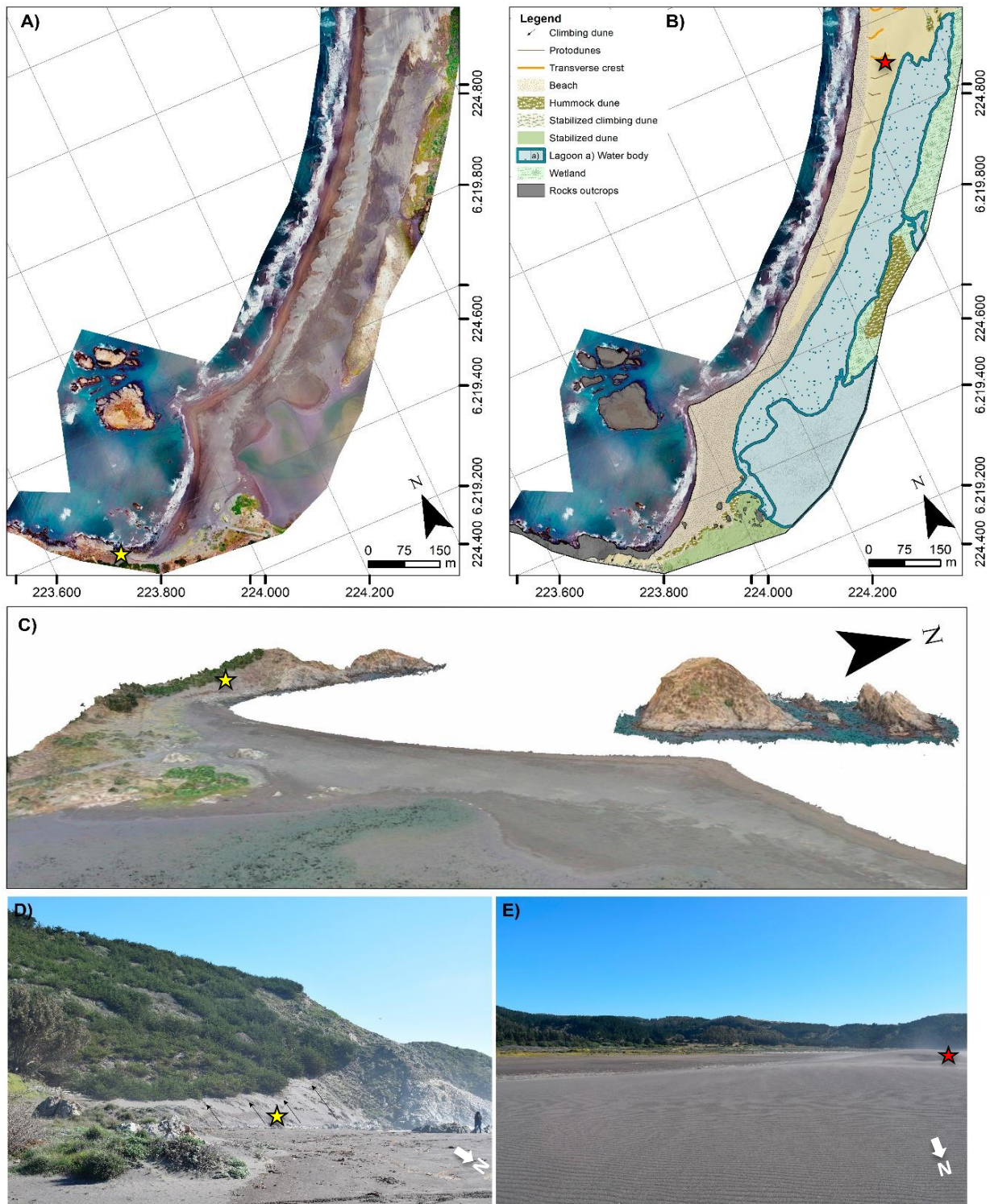


**Figure 15.** (A-B) Transverse-transgressive dune field advances over vegetated dunes, evolving into parabolic dunes (from orthomosaic). (C) 3D model (Agisoft Metashape reconstruction).

On the other hand, the southern sector of the inlet has a different geomorphological dynamic. The rocky islet Piedra del Viento, the orientation of the coastline and the mouth of Topocalma's estuary are blocked by a coastal barrier, a longer beach with no presence of dunes in that sector (Figure 16A and B). The beach reaches approximately 80 meters wide, as shown in the elevation profile F-F' (Figure 8), which gives way to the coastal lagoon (Figure 16.E). The beach reaches a 13.2-meter height and gradually descends to 1.5 meters over 30 meters towards the coastal lagoon.

Piedra del Viento generates refraction and diffraction (changes in wave direction), dissipating the energy of the waves and generating sedimentation on the beach, thus, it extends towards the islet (Figure 16.C). However, when Topocalma's estuary grows, it breaks the coastal barrier in this sector.

At the southern end of the inlet, identified rocky outcrops of the coastal batholith form a cliff. Smaller climbing dunes are also observed in this area (Figure 8, profile H and Figure 16.D). This indicates that there is an important supply of sand on the beach and that the wind is capable of generating dunes in this area.



**Figure 16.** (A-B) Beach-mouth system in the inlet southern sector (from orthomosaic). (C) 3D model (Agisoft Metashape reconstruction). (D) The arrows indicate free climbing dunes on coastal cliffs with vegetation cover (Photograph taken on August 13, 2022). (E) beach and coastal lagoon (Photograph taken on 14 December, 2022).

## 5. Discussion

The geomorphology of the dune field has undergone significant changes compared to what was described by Araya-Vergara (1983). In the 1980s, transverse dunes, aeolian sprays, and longitudinal dunes predominated; these features are now stabilized by introduced vegetation (pine plantations). What remains active, and has been the focus of analysis in this study, corresponds to transgressive dunes advancing over stabilized dunes.

The proposed morphological classification aligns with the evolutionary model of transgressive dune systems described by Pye and Tsoar (2009) and Hesp (2013). This evolution began with dunes climbing an obstacle—in this case, a coastal cliff—favored by a high sand supply. As a result, mobile dunes such as barchans, barchanoids, and transverse dunes migrate in the direction of the prevailing wind. Subsequently, these forms evolve into more complex patterns such as aklé or parabolic dunes, due to their advancement over vegetation. The simultaneous presence of barchanoid dunes, parabolic dunes, and an aklé-like pattern suggests an advanced transitional phase within the transgressive dune field evolution model (Hesp, 2013), indicating both high sediment availability and interruptions in vegetation cover. Moreover, unlike systems such as Ritoque or Chanco, where anthropogenic intervention has reduced dune activity (Castro, 2015), Topocalma presents an active dynamic with an incipient aklé pattern, representing a rare morphological configuration in central Chile.

The identification of new geomorphological patterns in this dune field was conducted using UAV technology, which has not been previously applied to dune systems in Chile, thus serving as a precedent for future research in the country. The delivery of high-resolution data made it possible to generate a Digital Elevation Model (DEM) and an orthomosaic (9.48 and 2.37 cm/pixel, respectively), which served as input for creating a three-dimensional model and facilitated the geomorphological survey. The resulting products enabled a detailed morphological characterization of the dune relief, reaffirming the potential of UAVs as a baseline tool for morphodynamic change monitoring in future studies of Chilean dune fields.

This methodological experience, even without GCPs or subsequent flights on different dates, opens an exploratory line for the study of Chilean dune systems. It is expected that the use of this methodology can be further refined through the incorporation of ground control points (GCPs), the use of UAVs equipped with RTK/PPK positioning systems, and the implementation of multitemporal flights under standardized acquisition parameters. These improvements would increase the spatial accuracy of the generated models and enable comparisons between successive surveys, supporting long-term monitoring of the system and the generation of data that allow for quantitative assessments of dune changes (Prodanov et al., 2019), such as volumetric variations in fragile and threatened dune systems.

In this regard, as highlighted by Andrade, Arenas and Lagos (2010) and Prodanov et al. (2019), it is important to consider the geomorphological baseline provided by this study for preventive decision-making. Considering the urban expansion in Puertecillo and the lack of specific regulations in the current land-use planning instruments, the results of this research could help prevent degradation processes similar to those observed in the dune field of Concón, where real estate pressure led to structural collapse and the loss of dune units (Martínez and Rangel-Buitrago, 2023). In this sense, the identification of highly mobile dune sectors could support the definition of buffer or protected zones within coastal regulatory plans, especially in the face of projected urban development in the commune of Litueche (Ilustre Municipalidad de Litueche, 2005).

In summary, this study not only documents an active and complex dune system in central Chile but also proposes a replicable methodology for its monitoring, providing key information for its management, conservation, and planning.

## 6. Conclusions

This article suggests some of the advantages of using technologies such as UAVs in the study of coastal geomorphology, mainly in beaches and dune fields. Detailed morphometric calculations were obtained due to the orthophotomosaic high resolution and the digital elevation model, such as height, slope and orientation. Additionally, a three-dimensional model facilitated the beach and dunes morphological visualization.

The beach morphology responds to its morphometric configuration and wave attack conditions, according to the above data. The area with the greatest curvature has a concave beach; while it shows a convex profile towards the north, where the beach is straighter, indicating greater sediment deposition.

The dune field reaches its highest points (57 meters) in the northern sector of the inlet climbing the coastal cliff and is currently stabilized by vegetation. Barchan, barchanoid and transversal dunes dominate subsequently along the bay, forming a transgressive dune field moving inland, through a fragmented advancing front into free sectors (active) and mound dunes for stabilization. The high sedimentary contribution and the action of the wind has produced an incipient aklé pattern in the middle to northern sector of the dune field. Furthermore, the advance of transgressive dunes over vegetation has generated parabolic dunes in the northern sector of the dune field, which shows the system's morphological evolution.

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