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Janek Walk, Georg Stauch, Melanie Bartz, Helmut Brückner and Frank Lehmkohl

ABSTRACT
The evolution of alluvial fans on the narrow coastal plain of the Atacama Desert in northern Chile is so far poorly investigated. Therefore, a detailed geomorphological map at a scale of 1:7500 of a coastal alluvial fan complex at Guanillos (21°58'S, 70°10.5'W) is provided as a first step to understand the fan's morphogenesis. Geomorphological mapping was based on a digital elevation model with a resolution of 2 m generated from Pleiades-1 tri-stereo satellite imagery, derived terrain parameters, and on-site field mapping. The resultant map is used to characterize and categorize the overall morphology of the alluvial fan complex. In particular, linear features constructed by primary alluvial fan processes can be differentiated successfully from those developed by secondary processes. Furthermore, the advanced evolutionary state of the fan complex is revealed. We introduce a morrophstratigraphic model comprising the fan's prograde evolution, dissection, and successive abandonment of surface generations.

1. Introduction
Alluvial fans are conical depositional landforms that accumulate where a confined stream emerges from a mountainous catchment (Blair & McPherson, 2009; Bull, 1977; Goudie, 2013; Graf, 1988; Harvey, 2011). Deposition occurs as a result of abrupt reduction of stream power; thus, progressively, a fan-shaped sediment body is formed. Although in principle, alluvial fans occur in any climatic zones, a strong focus in literature is placed on those in drylands. Until the 1970s, studies almost exclusively dealt with the alluvial fans of western North America, but research has expanded to different alluvial fan environments since then (for an overview see Harvey, 2011; Lecce, 1990; Ventra & Clarke, 2018).

In contrast to the numerous studies conducted in arid and semiarid mountainous inland regions, little research focuses on coastal alluvial fans bordering and interacting with the coastal environment. The narrow coastal plain of northern Chile between 20.5°S and 25.5°S represents such an environment, where alluvial fans emerge from the Coastal Cordillera and encounter the Pacific Ocean after a maximum of 3–4 km distance. The hyperarid conditions in the Atacama Desert, and the strongly limited denudation related to the climate, favor the preservation of landforms and make the Atacama Desert a key area for studying long-term geomorphological processes (e.g. Evenstar et al., 2017; Haug, Kraal, Sewall, Van Dijk, & Diaz, 2010; Kober et al., 2007; Nishizumi, Cañete, Finkel, Brimhall, & Mote, 2005; Starke, Ehlers, & Schaller, 2017). However, the climatic conditions of the coastal plain substantially differ from those in the inland desert. Although the coast likewise experiences barely any rainfall, the vicinity to the Pacific, which constantly provides high air moisture and controls the frequent occurrence of fog, causes a contrasting geomorphic environment (Cereceda, Larraín, Osses, Farias, & Ñaña, 2008; Hartley, Mather, Jolley, & Turner, 2005; Houston, 2006).

There, Ratusny and Radtke (1988), Radtke (1989), Leonard and Wehmiller (1991), Ortlieb, Goy, Zazo, Hillaire-Marcel, and Vargas (1995), Ortlieb et al. (1996), Vargus, Ortlieb, and Rutilus (2000), and Hartley et al. (2005) carried out first geomorphological studies on alluvial fans or associated marine terraces. However, neither the special geomorphic characteristics nor the morphogenesis of the coastal alluvial fans are fully understood. Detailed mapping of alluvial fan features is the basis to understand the fans’ geomorphic evolution, since those different alluvial fan features can be related to the constructing processes (Blair & McPherson, 2009; Harvey, 2010; Hooke, 1967). We therefore present for the first time a large scale geomorphological map of an alluvial fan complex at the coast of the Atacama Desert. Examples for detailed geomorphological mapping of coastal alluvial fans can be found for southern Crete (Nemec & Postma, 1993; Pope, Wilkinson, Skourtos, Triantaphyllou, & Ferrier, 2008) and the coast of southeast Spain (Harvey et al., 1999).


2. Study area

The studied coastal site is located within the latitudinal core of the Atacama Desert, about 12 km north of Tocopilla at 21°58′S and 70°10.5′W (Figure 1). There, the coast is characterized by a small headland and a large sea stack almost completely covered with guano, the latter giving the location its name ‘Guanillos’. A complex of several neighboring alluvial fans aggraded on the narrow coastal plain (Figure 1(B,C)). Towards the shore, a steep coastal cliff various decameters in height forms the border between the unconsolidated

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Figure 1. (A) Location of the study area at the coast of the hyperarid Atacama Desert; (B) Pleiades true colour satellite image of the coastal alluvial fan complex Guanillos; the radial profiles A-A′, B-B′, and C-C′ are shown in Figure 4; (C) overview photograph of the fan complex; (D) coastal cliff representing the toe of the alluvial fan, and the shore area in front of the cliff. The camera locations and directions of the photographs in C and D are shown in B as white triangles.
terrestrial deposits and the Pacific (Figure 1D). The alluvial fans emerge from the steep escarpment of the Coastal Cordillera which reaches elevations of almost 1900 m above sea level (asl) in this region. The hinterland is a fluvially dissected plateau between ~1600 and ~1900 m asl with a maximum elevation of ~2280 m asl on the Cerro Tolar.

2.1. Climatic setting of the coastal Atacama Desert

The Atacama Desert is considered the world’s driest region with mean annual precipitation (MAP) of <5 mm in the coastal zone of the desert and the majority of the Central Valley (Figure 1, Garreaud, Molina, & Farias, 2010; Houston, 2006). The hyperaridity in northern Chile is controlled by several factors (Garreaud et al., 2010; Garreaud, Vuille, Compagnucci, & Marengo, 2009; Houston, 2006; Houston & Hartley, 2003; Latorre et al., 2007): (i) its location at the descending limb of the Hadley cell leading to prominently stable atmospheric conditions under the presence of the southeast Pacific anticyclone; (ii) the continentality effect, which results from the large landmass of northern South America and subsequent distance of the Atacama Desert to the moisture from the tropical Atlantic; (iii) the rainshadow effect of the Andes as a large longitudinal, orographic obstacle exceeding 4 km in height over its length in tropical and subtropical latitudes; and (iv) the upwelling of the cold Humboldt Current along the coast of Chile and Peru which drives the El Niño-Southern Oscillation and generates a persistent temperature inversion over the coastal region of the southeast Pacific.

Along the coast of northern Chile aridity increases from S to N. From this gradient, a MAP of ~2–3 mm can be inferred for the study site at Guanillos (Garreaud, Barichivich, Christie, & Maldonado, 2008; Houston, 2006). Rainfall events occur infrequently and show high seasonal as well as inter-annual variability. Precipitation at the coast predominantly originates from extratropical frontal systems during austral winter (Houston, 2006). Furthermore, the majority of large rainfall events that trigger debris flows or floods can be attributed to phases of El Niño and corresponding positive sea surface temperature anomalies over the eastern Pacific (Bozkurt, Rondanelli, Garreaud, & Arriagada, 2016; Vargas et al., 2000; Vargas, Ruttlant, & Ortlieb, 2006). Five debris flows are reported for the Antofagasta region in the twentieth century; all of them occurred during austral winters with moderate to strong El Niño conditions (Vargas et al., 2000, 2006). The most recent, debris flow triggering event in March 2015 can also be associated with El Niño (Bozkurt et al., 2016).

Moreover, the Coastal Cordillera has a significant relevance for the regional climate of the coastal desert. The mountain range blocks the extensive stratocumulus clouds developing over the southeast Pacific at the top of the marine boundary layer from further inland penetration wherever the height of the Coastal Cordillera exceeds the level of the temperature inversion. Closely associated to the blocking of low stratocumulus clouds is the development of advective fog, locally known as camanchaca, at an elevation between ~600 and ~1000 m asl in the study area (Cereceda et al., 2008; Garreaud et al., 2008). In this hyperarid environment, the advective fog constitutes the main moisture source (Cereceda et al., 2002; del Río et al., 2018). Accordingly, vegetation around Tocopilla is restricted to mostly endemic Loma formations on the steep slopes of the mountain front between ~450 and ~950 m asl. It can be subdivided in a lower belt reaching up to ~700 m asl, which is characterized by a very sparse vegetation cover (1–2%) of dwarf-shrubs with single individuals of the cactus species Eulychnia iquiquensis, and an upper belt rich in E. iquiquensis and comprising a more diverse shrub community. Vegetation cover in the upper belt reaches about 10% (Luebert, García, & Schulz, 2007; Schulz, 2009). Eventually, the foggy climate adjacent to the Pacific has an important influence on the geomorphic processes. Intense salt weathering of rocks but also the cementation of unconsolidated sediments may result from the frequent occurrence of fog and associated high air humidity (Abele, 1990; Goudie, Wright, & Viles, 2002; Hartley et al., 2005; Viles & Goudie, 2007).

2.2. Geology of the source area

The fan complex is fed by two separate catchments draining the Coastal Cordillera: a 14.6 km² large catchment in the north and a small catchment with a size of 1.9 km² in the south (Main Map B). Despite their large difference in size, they cover a similar relief of 1890 m and 1560 m, respectively.

The western Coastal Cordillera is mainly composed of the Lower to Middle Jurassic La Negra Formation characterized by basaltic, partly andesitic, lava with intercalations of pyroclastic breccia (Mpodozis, Congejo, & Mora, 2015). This formation makes up almost the entire upper northern catchment (Main Map B). In contrast, the downstream part of the northern catchment as well as the complete southern catchment, both cut into the western flank of the Coastal Cordillera, are situated within the Tocopilla plutonic complex – one of many Middle Jurassic granitoid plutons that intruded into the volcanic rocks of the La Negra formation. Those intrusions show variable compositions (Skarmeta & Marinovic, 1981). According to Rogers and Hawkesworth (1989) they vary from quartz gabbro and quartz diorite through quartz monzodiorite and granodiorite to granite. Parts of the Tocopilla pluton have undergone late magmatic alkali metasomatism.
leading to an enrichment of monzonites (Rogers & Hawkesworth, 1989). More recent investigations subsumed in the map of Mpodozis et al. (2015) state the composition of the Tocopilla pluton as gabbros and diorites.

The stream network and catchment shape is at least partly controlled by the tectonic setting (Main Map B). In particular, the feeder channel of the northern catchment incised along a WNW−ESE trending fault crossing the entire catchment. The faults in the region are part of the superimposed Atacama Fault System (González, Dunai, Carrizo, & Allmendinger, 2006). However, the fault type has not been specified as yet. Recent studies show that to the south NW−SE to N−S striking normal faults dominate (Allmendinger & González, 2010; Mpodozis et al., 2015), whereas to the north the W−E to NW−SE fault system is of reverse type (Carrizo, González, & Dunai, 2008; González et al., 2008).

3. Methods

For the detailed geomorphological mapping we used high-resolution optical satellite imagery from the Pleiades-1 mission (Centre National d’Études Spatiales (CNES), 2016). From those satellite scenes a digital elevation model (DEM) with a resolution of 2 m was stereoscopically derived (Section 3.1.). Based on the DEM, specific morphometric terrain parameters were calculated to facilitate the mapping of microscale alluvial fan features (Section 3.2.). Following the scale definitions after Brunsden (1996), the microrelief comprises landforms with a basal footprint between 10⁰ and 10² m. Typical alluvial fan elements within this scale are rockfall deposits, incised channels, abandoned palaeochannels, debris flow channels and levees, margins of lobe deposits, and headward-eroding gullies (Blair & McPherson, 2009; Bull, 1977; Harvey, 2010; Hooke, 1967, 1987). In addition to the remote sensing, we conducted on-site mapping and high-precision geographical positioning during field work in March 2017 and March 2018 for validation purposes.

3.1. DEM generation from Pleiades tri-stereo satellite imagery

The Pleiades-1 mission comprises two equally equipped satellites, Pleiades 1A (PRH 1A), and Pleiades 1B (PRH 1B), for optical observations of Earth’s surface with 2.8 m nadir resolution for the four multispectral bands and 0.7 m nadir resolution for the panchromatic band. Pleiades-1 is the first satellite system capable of providing almost synchronous stereoscopic triplets, which are composed of one forward looking, one backward looking, and one quasi-nadir looking image of the same area (Gleyzes, Perret, & Kubik, 2012). This tri-stereo constellation, in particular the quasi-nadir viewing perspective, enables surveys in steep terrain where the applicability of classic stereoscopic pairs is limited by, for instance, shadow effects (Bagnardi, González, & Hooper, 2016).

We used Pleiades tri-stereo satellite imagery of the study area acquired on 22 November 2016 by the CNES (2016). Along-track incidence angles of the three images are −9.9°, 6.2°, and 20.3° for the forward, quasi-nadir, and backward looking geometries, respectively.

Initially, the images from each of the three perspectives were pansharpened by nearest neighbor diffusion and orthorectified using a rational polynomial coefficient model with elevation information from a SRTM 1 Arc-Second Global DEM distributed by the USGS (2014). The resulting multispectral composite has a ground resolution of 0.59 m. In a second step, this orthoimage was used as reference for automatic ground control point (GCP) collection using Fast Fourier Transform Phase matching (Wisetphanichkij & Dejhan, 2005). 213 GCP with residuals <4 m were computed. The resulting model features a root mean square error of 1.83 m in x-direction and of 0.94 m for the y-direction. Subsequently, three epipolar pairs were generated from each stereoscopic combination of the forward, quasi-nadir, and backward viewing perspective. Based on those pairs, digital surface models (DSM) were computed (Figure 2). Due to the steep terrain, especially along the western flank of the Coastal Cordillera, the DSM based on the forward and backward looking images is the most erroneous. The epipolar pair of the quasi-nadir and the backward looking images features the best viewing geometry in relation to the surface topography and, thus, although showing the smallest difference in incidence angles, yields the best model result. The final DSM was generated using a Wallis filter designed for local contrast enhancement, which is suitable in desert environments and areas with significant shadows (Mastin, 1985). Finally, the DSM was resampled to a spatial resolution of 2 m, and in order to reduce the slightly noisy surface texture on the micro-scale a 3 × 3 low pass filter was applied on the DSM. As there is barely any vegetation and no anthropogenic objects extruding above the terrain height, the resampled DSM can be considered a DEM.

To achieve absolute heights, the relative elevation has been adapted with respect to the reference height of the SRTM 1 Arc-Second Global, that is the EGM96 geoid (Farr et al., 2007). The absolute vertical error of the product was assessed by taking 33 GCP measured with a TOPCON HiPer Pro positioning instrument in real-time kinematic mode and amounts to 1.8 m in average with a standard deviation of 0.6 m.

3.2. Geomorphometric terrain analysis

As a first step of terrain analysis, basic primary topographic attributes were derived from the 2 m Pleiades
DEM: the elevation itself illustrated as contour lines, slope, and curvature. Slope and curvature are the first and second-order local derivatives of the topographic surface, respectively (Gallant & Wilson, 2000).

Furthermore, a terrain roughness parameter was used to better differentiate the local alluvial fan features on the scale of the microrelief. For this purpose, the Slope Position according to Weiss (2001) was selected. The Slope Position is primarily based on thresholding of the standardized Topographic Position Index (TPI), and secondarily of the slope (Weiss, 2001). The TPI quantifies terrain roughness by subtracting the mean elevation of a defined neighborhood from each cell (Guisan, Weiss, & Weiss, 1999). Depending on the scale of the neighborhood, the TPI enables discrimination of local differences in elevation within a larger landform (Gallant & Wilson, 2000). The Standardized TPI can be calculated for each cell i as the quotient of the TPI cell value in relation to the arithmetic mean of the TPI raster ($\bar{X}_{\text{TPI}}$) and its standard deviation $\sigma_{\text{TPI}}$ (modified after Weiss, 2001):

$$TPI_{\text{std},i} = \frac{(TPI_i - \bar{X}_{\text{TPI}})}{\sigma_{\text{TPI}}}$$  \hspace{1cm} (1)

For the special case of characterizing the microrelief of coastal alluvial fans, we used the adapted approach of standardization which Jenness, Brost, and Beier (2013) implemented in their ArcGIS tool for land facet analysis. Dividing the $TPI_i$ by the standard deviation of elevation within the specified neighborhood of cell i ($\sigma_{zi}$) results in the Standardized Elevation $z_{\text{std},i}$ (Jenness et al., 2013):

$$z_{\text{std},i} = \frac{(TPI_i)}{\sigma_{zi}}$$  \hspace{1cm} (2)

A circular neighborhood with a radius of 20 m was selected. This type of standardized TPI is sensitive to local terrain roughness of alluvial fan surfaces, whereas elevation anomalies like ridges or channels in steep areas become slightly underrepresented (Figure 3).

Subsequently, the Slope Position classes ‘ridge’, ‘upper slope’, ‘steep slope’, ‘gentle slope’, ‘lower slope’, and ‘valley’ were separated using the threshold values shown in Table 1. Standardized Elevation thresholds of ± 0.5 $z_{\text{std}}$ and ± 0.25 $z_{\text{std}}$ were selected for optimal delimitation of linear alluvial fan features validated by on-site field mapping. A slope angle of 16° was used to distinguish steep from gentle slopes, because it approximately marks the maximum surface angles of proximal debris flow lobes and levees investigated along different radial profiles of the fan complex (Figure 4). Our observations correspond with studies by Hartley et al. (2005) on coastal alluvial fans south of Guanillos showing steep fan segments ranging in slope from 4° to a maximum of 19°, with an average of 11°. Significantly larger slope angles are only typical for fans dominated by rock-gravity processes like talus cones (Albjär, Rehn, & Strömquist, 1979; Blair & McPherson, 2009; Bull, 1977).

### 3.3. Geomorphological mapping

Linear geomorphological features dominate the microrelief in the study area. Consequently, representation on the map was restricted to those features. Mapping was conducted at a working scale of 1:3000–1:1000, predominantly on the basis of the 2 m Pleiades DEM and corresponding derivatives. Secondarily, the pan-sharpened Pleiades orthoimage was consulted. We finally revised individual cases by means of the on-site field mapping.

Features covered by the mapping include spurs, escarpments ranging from steps a few m in height to the prominent coastal cliff, levees, and anthropogenic
infrastructure. Simple terrain steps were divided from levees, which, in contrast, are characterized by two opposed drops in height, and classified depending on the height of the steps. Partly, the symbology for 1:25000 geomorphological maps of high mountain areas, published in Otto and Dikau (2004), was used after adaptation for a larger scale. Linear depressions were not mapped separately as they can be directly inferred from the neighboring escarpments or levees as well as the structure of contour lines (Main Map A). Regarding the final scale of 1:7500 for the geomorphological map, generalization was kept at a minimum and was only applied to ensure a sufficient distance between the structures.

4. Results and discussion: morphography and morphogenesis of the Guanillos coastal alluvial fan complex

The results of the geomorphological mapping are shown in Main Map A and the terrain roughness in

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**Table 1.** Thresholds used for the derivation of the six Slope Position classes.

| Slope Position class | Standardized Elevation \( z_{std} \) criteria | Slope criteria |
|----------------------|-----------------------------------------------|----------------|
| Ridge                | \( z_{std} > 0.5 \)                           |                |
| Upper slope          | \( 0.25 < z_{std} \leq 0.5 \)                 |                |
| Steep slope          | \(-0.25 \leq z_{std} \leq 0.25 \)             | \( > 16^\circ \) |
| Gentle slope         | \(-0.25 \leq z_{std} \leq 0.25 \)             | \( \leq 16^\circ \) |
| Lower slope          | \(-0.5 \leq z_{std} < -0.25 \)               |                |
| Valley               | \( z_{std} < -0.5 \)                          |                |

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![Figure 3](image-url). Comparison of (A) the Standardized TPI after Weiss (2001) with (B) the Standardized Elevation after Jenness et al. (2013) at the coastal alluvial fan complex Guanillos. In both cases a circular neighborhood with a radius of 20 m was selected for the computation.

![Figure 4](image-url). Radial profiles A-A’, B-B’, and C-C’ from the apex to the shoreline, and corresponding slope segments between the apex and the escarpment of the coastal cliff; \( \bar{a} \) is the mean slope angle along the profile from the apex to the onset of the cliff; \( C_r \) is an index of concavity along the radial fan profiles adapted after Karymbalis, Ferentinou, and Giles (2016) and defined as the ratio of the elevation difference between the radial profile and the midpoint of a straight line joining the fan apex and the onset of the coastal cliff, and the elevation difference between the onset of the cliff and the midpoint. The course of the profiles is shown in Figure 1. The profiles were generated based on the 2 m Pleiades DEM and are plotted without vertical exaggeration.
form of the topographic Slope Position in Main Map C. The following section describes the deductions that can be drawn from the detailed geomorphological map with regard to specific morphographical characteristics of the Guanillos fan complex and its morphogenesis.

### 4.1. Geomorphological characteristics

At present, the deposits of the coastal alluvial fan complex cover an area of approximately 0.9 km² and reach over a total length of 1.2 km from the apex to the coastal cliff. Simply based on the scale of the whole Guanillos fan complex, it can be considered a classical alluvial fan, which typically ranges in length between hundreds of meters to several kilometers (Harvey, 2010).

The fan complex is constrained by a steep debris cone in the north and a smaller fan to the south. Hence, the lateral confinement limits the formation of an ideal cross-radial convexity. Additionally, the coastal cliff limits the fan’s radial evolution. The escarpment reaches heights over 50 m in the central part of the fan and declines to 25–30 m towards the south, while heights of ~45 m have been achieved towards the north (Main Map A). Over the length of 1.2 km a plano-concave radial profile developed. In fact, profile concavity is low along the central fan axis and slightly increases towards the sides (Figure 4). While the proximal fan-cone segment features radial slope angles ranging from 8° to 16°, the more distal parts of the fan apron are characterized by 6° to 8°. The average slope angle from the apex to the coastal escarpment ranges from 8.5° to 9.5°. Not regarding the channels, lateral levee slopes, and area along the coastal highway, only minor parts of the alluvial fan surface show slope angles higher than 16° or lower than 4° (Main Map A). Especially the abundance of proximal debris flow levees with relatively high slope angles between 8° and 16° indicates that debris flows dominate the constructing processes of the alluvial fan (Blair & McPherson, 2009). This morphological observation is in line with sedimentological descriptions of alluvial fans at the coast of northern Chile by Hartley et al. (2005).

A striking characteristic of the morphography are the two incised channels that approach each other in the upper fan section and diverge further downstream (Main Map A). Their courses almost coalesce but are separated by an interjacent levee with a height of 3–4 m. Hartley et al. (2005) subdivided incised coastal alluvial fans in northern Chile in those displaying only distal incision and those that are fully trenched, the latter being the case for the Guanillos fan. To sum up, the Guanillos fan complex can be categorized as a dissected, laterally confined and distally eroded fan after the terminology of Crosta and Frattini (2004). The combination of these three characteristics makes the studied fan a special case.

### 4.2. Deductions on the morphogenesis

Slope Position based on the Standardized Elevation allows differentiation between the landforms generated by primary – constructing –, and secondary – post-depositional – alluvial fan processes: debris flow channels, walls, levees and lobes, as well as the gently to moderately sloping alluvial fan surfaces presenting primary features versus headward-eroding channels and the dominant coastal cliff as secondary processes.
features (Main Map C). The distinction of primary and secondary channels by the Slope Position is exemplified in Figure 5. The morphology of the valley sections barely allows such a differentiation. While abandoned debris flow channels show remnants of levees (Figure 5(A)), these linearly aligned ridges are missing along headward-eroding channels (Figure 5(B)). Additionally, in the case of primary palaeochannels a relative proximity of the uppermost reaches to a younger channel structure causing abandonment is essential. In case of the overflow structure shown in Figure 5(A) the topographic Slope Position enables the reconstruction of the multi-stage channel evolution in the central part of the proximal fan-cone segment. The recent morphological state indicates that the northern incised channel once drained via the southern one.

The fan complex is not only fed but has also been incised by both channels. Despite the southern catchment being ∼7.5 times smaller than the northern catchment, the surface morphology and palaeochannel structures indicate that approximately 30–40% of the abandoned surfaces can be attributed to the southern catchment (Main Map A). However, it is difficult to estimate how the relative contributions of both catchments to the fan’s polygenetic evolution varied over time. Nonetheless, catchment size is not the primary control for sediment input. The high erosion as well as transport potential in the steep flank of the Coastal Cordillera rather seems to be substantial. Therefore, a synchronous activity of the complete southern drainage basin and the downstream third of the northern basin is favored during an intense rainfall event.

Prograde evolution, dissection and successive abandonment of several surface generations reveal an advanced evolutionary state of the fan complex. Thus, the Guanillos fan can be attributed to a Stage 3 fan after Blair and McPherson (2009). On the scale of the entire polygenetic fan complex, we derived a morphostratigraphic model comprising abandoned surface generations as well as palaeochannel structures from the detailed geomorphological map (Figure 6). Level A0 represents the recently active parts of the two incised channels. Within the incised channels, A3 to A1 are terrace-like structures successively generated by aggradation and incision. The oldest surface generation A7 is preserved at the sides of the uppermost fan-come section and along the central axis of the alluvial fan. Three stages of subsequent prograde evolution

![Figure 6](image-url). Morphostratigraphic units and morphogenetic features of the Guanillos coastal alluvial fan complex.
(A6, A5, and A4) are preserved in the proximal to distal section of the fan complex. Note that although the small seashore fans can be attributed to the recent stage of fan development (A0), they are not included in the morphostratigraphic model because they are mainly decoupled from the apex. Only the seashore fans emerging from the two incised channels may present primary alluvial fan deposits.

5. Conclusions

On the basis of Pleiades satellite imagery in combination with on-site field mapping we successfully performed detailed geomorphological mapping of the Guanillos coastal alluvial fan. The following methodological conclusions can be drawn from this study:

- DEM derived from Pleiades-1 tri-stereo satellite imagery are well suited for the geomorphological mapping of the microrelief due to the high resolution – being 2 m in the study presented. The special geometric characteristics of the tri-stereo constellation allow for the generation of precise DEM in steep mountainous terrain.
- Geomorphometric terrain analysis is a useful tool for the mapping of alluvial fan features. The choice of an adequate terrain roughness parameter strongly depends on the geomorphic environment. For the mapping of primary and secondary features of debris flow dominated alluvial fans the Slope Position based on the Standardized Elevation is a reasonable parameter.
- High-resolution satellite imagery and DEM can support detailed geomorphological mapping, especially in terrain difficult to access. However, ground truthing remains necessary and is generally required for a morphogenetic interpretation of the mapped geometries.

Furthermore, some aspects on the morphography and morphogenesis of the fan complex can be concluded:

- A plano-concave radial profile, complete dissection, lateral confinement, marine distal erosion, and a domination by debris flows characterize the Guanillos alluvial fan complex.
- Prograde evolution, dissection and successive abandonment of several surface generations reveal an advanced evolutionary state of the fan complex.
- A morphostratigraphic model of the Guanillos fan complex is introduced. It can be summarized into seven evolutionary stages preserved as surface generations besides the recent incised channels: the oldest generation in the proximal fan segment, three stages of prograde development, and three terrace-like structures within the main channels.

Software

DSM generation from Pleiades satellite imagery was performed using PCI Geomatica 2017. Processing of the DEM, mapping and the principal map layout was carried out in Esri ArcGIS 10.4.1. The Slope Position was derived using the Land Facet Corridor Tools Version 1.2.884 for ArcGIS by Jenness et al. (2013). The final map design and further graphics were created using Adobe Illustrator CS4.

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References

Abele, G. (1990). Salzkrusten, salzbedingte Solifikation und Steinsalzkarst in der nordchilenis-ch-peruanischen Wüste. Mainzer Geographische Studien, 34, 23–46.
Albjär, G., Rehn, J., & Strömquist, L. (1979). Notes on talus formation in different climates. Geografiska Annaler: Series A, Physical Geography, 61(3–4), 179–185. doi:10.1080/04353676.1979.11879989
Allmendinger, R. W., & González, G. L. (2010). Invited review paper: Neogene to Quaternary tectonics of the coastal Cordillera, northern Chile. From the Trench to the Arc: Subduction along South America, 495(1), 93–110. doi:10.1016/j.tecto.2009.04.019
Bagnardi, M., González, P. J., & Hooper, A. (2016). High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo.
research perspectives. *Geological Society, London, Special Publications*, 440. doi:10.1144/SP440.16
Viles, H. A., & Goudie, A. S. (2007). Rapid salt weathering in the coastal Namib desert: Implications for landscape development. *Geomorphology*, 85(1–2), 49–62. doi:10.1016/j.geomorph.2006.03.025

Weiss, A. (2001). Topographic position and landforms analysis. Presented at the Poster presentation, ESRI user conference, San Diego, CA. Retrieved from http://www.jennessent.com/arcview/TPI_Weiss_poster.htm

Wisetphanichkij, S., & Dejhan, K. (2005). Fast Fourier transform technique and affine transform estimation-based high precision image registration method. *GESTS International Transactions on Computer Science and Engineering*, 20(1), 179–191.