Geomorphic and geologic controls on alluvial-fan processes along the Coastal Cordillera (northern Atacama Desert, Chile)

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Abstract

Interactions between alluvial fans and their drainage basin have been studied in the literature, but several questions remain unanswered. In particular, understanding which controls determine dominant depositional processes on alluvial fans has proved quite difficult. The extremely rare runoff and total absence of vegetation in the Coastal Cordillera of the Atacama Desert (northern Chile) offer perfect conditions for the analysis of geomorphological and geological controls on alluvial fans and drainage basins. In this study, a complete analysis has been carried out on all the geomorphic and geological characters of alluvial fans developed along the Coastal Cordillera. Both coastal fans (37) and fans located farther inland (10) have been investigated for 39 different geomorphological and geological variables. The number of examined variables is considerably higher than in previous studies. Analyses have been conducted by integrating data from satellite images, a geological map of Chile, and elaborations on a Geographical Information System (GIS).

Five principal types of fan-surface morphologies have been distinguished in the Coastal Cordillera, controlled by primary depositional (sediment-gravity and fluid-gravity) processes and secondary reworking processes. Since climate, tectonics and catchment geology (lithology) are generally similar for all of the studied fans, catchment geomorphology is probably the ultimate control on different types of depositional processes and fan-surface morphologies. Mass-flow-dominated fans are characterized by small fan areas, steep fan slopes, small basin areas, great basin slopes, high relief, high basin Melton-ratio, low highest stream-order, low BA/BP ratio, a low sinuosity for the feeder channel and stepped hypsometric curves. Deposits are also important to differentiate between types of fan-surface morphology, but visual inspection by GIS fails when surfaces are reworked. Based on statistical analysis, the main discriminants between different types of surface morphology are, in decreasing order of importance: the BA/BP-ratio, basin slope, basin area, drainage density, fan radius, fan slope, fan width and fan area. This means that for alluvial fans in the Coastal Cordillera the stage of catchment development is very important, since larger, well-developed catchments have a more pronounced round shape (high BA/BP-ratio), and smaller undeveloped basins have a rectangular shape (low BA/BP-ratio). The most influential geomorphological relationship is between basin slope and drainage density.

Table of contents

Introduction

Alluvial fans are depositional landforms formed where a confined feeder channel emerges from a drainage basin, i.e. between a mountain range and a plain (Figure 1). The confined feeder channel ceases to exist and therefore unconfined flow is initiated at the intersection point. The occurrence of unconfined flow is fundamental to the genesis and evolution of alluvial fans. Reduction in stream power as flow emerges from the feeder channel and spreads laterally results in a semi-conical or fan-shaped landform. However this only takes place if sufficient sediment in the drainage basin is produced to construct the alluvial fan, and if a triggering mechanism, usually high water discharge or less commonly earthquakes, is active to incite the transfer of drainage basin sediment to the alluvial fan. The dynamics between drainage basin and alluvial fans can be very sensitive to changes in tectonics and climate. Also geology and geomorphology of drainage basins may affect the character of the fans. This together with the fact that alluvial fans occur in a large variety of environments, makes it hard to understand the dynamics between drainage basins and alluvial fans. Two main depositional processes occur on fans: (1) fluid-gravity flows and (2) sediment-gravity flows. These two depositional processes can be subdivided into more specific types of depositional processes, e.g. sheet floods or debris flows. Since a certain threshold has to be passed for these primary depositional processes to occur, there is enough time for secondary processes to affect alluvial fans (e.g. reworking, weathering). A problem resulted from secondary processes, since they usually dominate the surface because of their greater frequency, is that they can mask the primary processes constructing the fan.

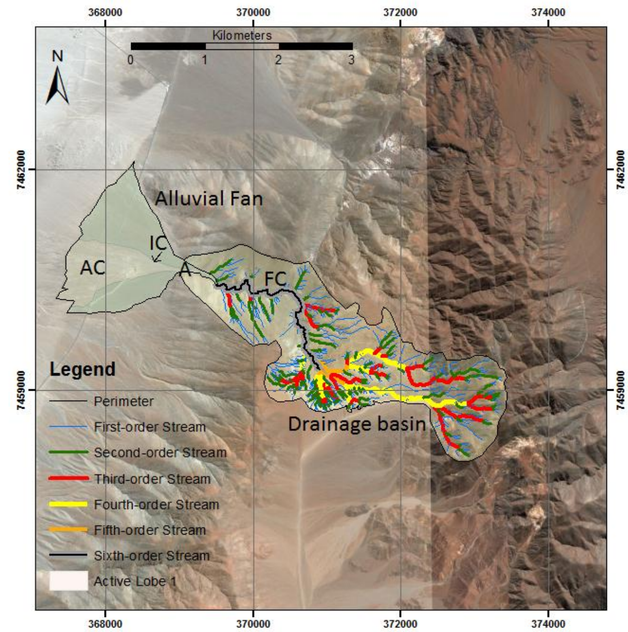

Figure 1: Alluvial Fan and Drainage Basin. AC = Active lobe, IC = Intersection point, A = Fan apex and FC= Feeder Channel.

The main objective of this paper is to study the relationship between drainage basins and alluvial fans in the Coastal Cordillera (the Atacama Desert, Chile), in order to understand their interrelated dynamics. One of the necessities of understanding their interrelated dynamics lies in the fact that alluvial fans can be a source of major hazards. Recognizing the type of depositional process (e.g. debris flows, rock avalanches, and sheetfloods) in the early stage of urban planning and land development will prevent loss of lives and damage to infrastructure (Bull, 1972; Harvey, 2011). Alluvial fans may also be important for their groundwater resources, for their potential under irrigation for agricultural development (Bull, 1972; Harvey, 2011). For hydrocarbon exploration, the distinction between types of depositional processes is crucial for prediction of reservoir quality. Overall, fluid-gravity controlled alluvial fans, if compared to sediment-gravity controlled alluvial fan deposits, consist of much better sorted, sandier facies with fewer fines and therefore potentially have good reservoir properties. The relative homogeneity of facies and lack of cohesive debris-flow beds allow good vertical permeability and therefore higher internal connectivity (Moscariello, 2005). Moreover, alluvial fans formed in large meteorite craters on Mars are an attractive research objective, because details of their surface morphology are easily visible on satellite imagery (Moore and Howard, 2005). Understanding the dynamics of drainage basins and alluvial fans will provide information whether fluid-gravity flows are and/or have been active on Mars.

Earlier studies on alluvial fans have tried to establish differences between rivers and alluvial fans (Hooke, 1966; Bull, 1972; Bull, 1977; Blair and McPherson, 1994). More recent studies on alluvial fans try to classify alluvial fans into different types based on their most dominant depositional processes by means of analyzing their deposits (Harvey, 1997; Nichols and Hirst, 1998; Smith, 2000; Blair and McPherson, 2009; Harvey, 2010; Harvey, 2011). The study of the geomorphology of both alluvial fans and drainage basins has been a big contribution to a better understanding, since much information on the evolution and dynamics of alluvial fans has been derived by geomorphological surveys (Patton and Baker, 1976; Crosta and Frattini, 2004; Scally and Owens, 2004; Wilford et al., 2004, Rowbotham et al., 2005). Several geomorphological relationships between alluvial fan and drainage basin are well established in the literature (Bull 1977; Harvey 1997; Scally and Owens, 2004; Harvey, 2011). Two important ones are:

1. $F = {}_{p}A^{q}$
2. $G = -{}_{a}A^{b}$

where A is the drainage area (km^2), F is the fan area (km^2) and G is the fan gradient (dimensionless). Although these relationships have been studied thoroughly, drainage basin controls on other morphological and sedimentological characters of alluvial fans remain mostly unexplored. Therefore, this study will focus on the geomorphological analysis of both alluvial fans and drainage basins in the Coastal Cordillera of the Atacama Desert (northern Chile). The extremely rare runoff and total absence of vegetation in the Coastal Cordillera offers excellent opportunity for studies of the geomorphology and sedimentology of alluvial fans and drainage basins. With this paper I contribute new data on fan and catchment geomorphology in the region, with an aim to form better and more predictive hypotheses on local fan-drainage basin dynamics. This will be done by: (1) determining the most important variables that characterize different types of fan surface morphology; (2) define the most related variables and establish new geomorphological relationships between alluvial fan and drainage basin; (3) determine the dominant depositional processes responsible for different types of fan surface morphology; and (4) provide guidelines for possible future fieldwork in the area.

Study area

The Atacama Desert (figure 2A) in the north of Chile is one of the oldest continuously hyperarid regions on Earth. The arid climate was already established during the Middle Miocene (Hartley and Chong, 2002; Clarke, 2006; Nalpas et al., 2008), but possibly has been continuous in the region, without much variability, since the Late Jurassic (Harley et al., 2005; Clarke, 2006). At present, the region is classified as hyperarid and the average precipitation is less than 5 mm/year. The alluvial fans that will be studied are located along the coastal flank of the Coastal Cordillera (Figure 2B), which is a prominent topographic feature. The Coastal Cordillera consists of the erosional remnants of the lower Jurassic to Lower Cretaceous Andean Arc, which comprises large plutonic complexes of Jurassic andesites and associated granitic intrusions and upper Jurassic to lower Cretaceous andesitic to dacitic lavas (Nalpas et al., 2008). In addition Lower Cretaceous conglomerates and limestones, and Paleozoic metamorphic rocks are present (Hartley et al., 2005). In some instances alluvium stored in the drainage basins may also form source material. The Coastal Cordillera is up to 3 km high and 50 km wide. The cordillera is bounded to the west by the Coastal Scarp, which is up to 1 km high. To the east the Atacama Fault Zone separates the Coastal Cordillera from the Central Depression, which is the main tectonic feature formed in the Jurassic as a trench-linked structural system. Uplift of the Cordillera is considered to have occurred since the Late Eocene to Early Oligocene (Hartley and Evenstar, 2010). Boulders on top of the alluvial fans in the Coastal Cordillera have been dated with ^{39}Ar-^{40}Ar dating at 5.9-6.0 Ma (Nalpas et al., 2008). The age of the alluvial-fan deposits has been estimated at 80 to 40 Ka (Hartley et al., 2005).

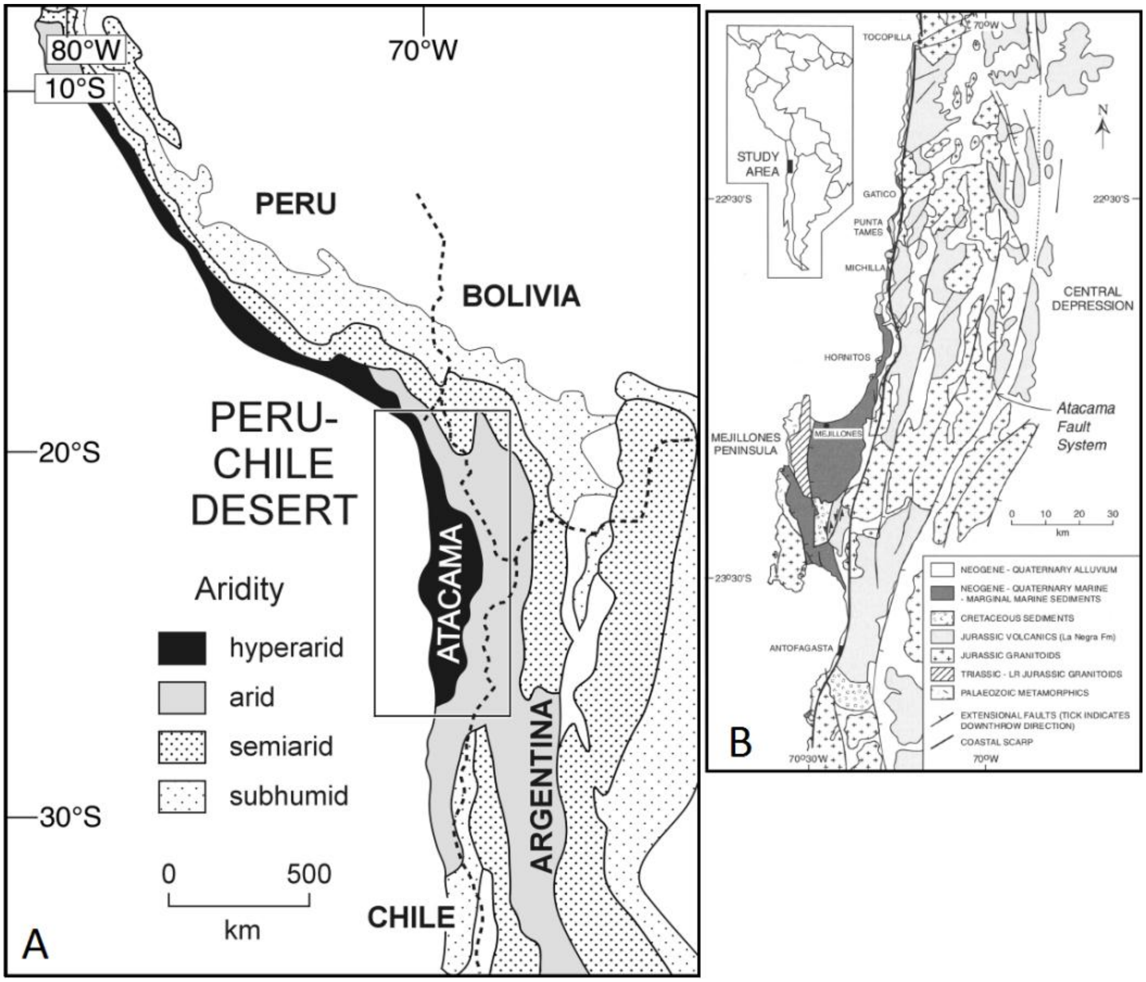

Figure 2: Study area. 2A = location of the hyperarid Atacama Desert. 2B = geological map of the Coastal Cordillera and location of Atacama Fault System and Central Depression. Modified after Hartley et al., 2005.

Methods

Quantification of geomorphological and geological variables

In order to collect the necessary data on the fans and the corresponding drainage basins, a preliminary inspection has been carried out on their geomorphological and geological aspects by means of: (1) a digital elevation model (DEM); (2) Bingmaps©, a 2D satellite imagery overlay with excellent coverage of the Coastal Cordillera region); (3) Google Earth (uses Bingmaps©), a 3D projector program; (4) a geological map of Chile; and (5) ArcInfo 10.0©, a geographic information system (GIS).

Figure 3 shows the specific workflow followed in this preliminary phase. The first step is to use the satellite imagery (Bingmaps©) for locating all the alluvial fans and their drainage basins, as well as to digitize their boundaries. The end-product of digitization is a polygon object stored in a shapefile.

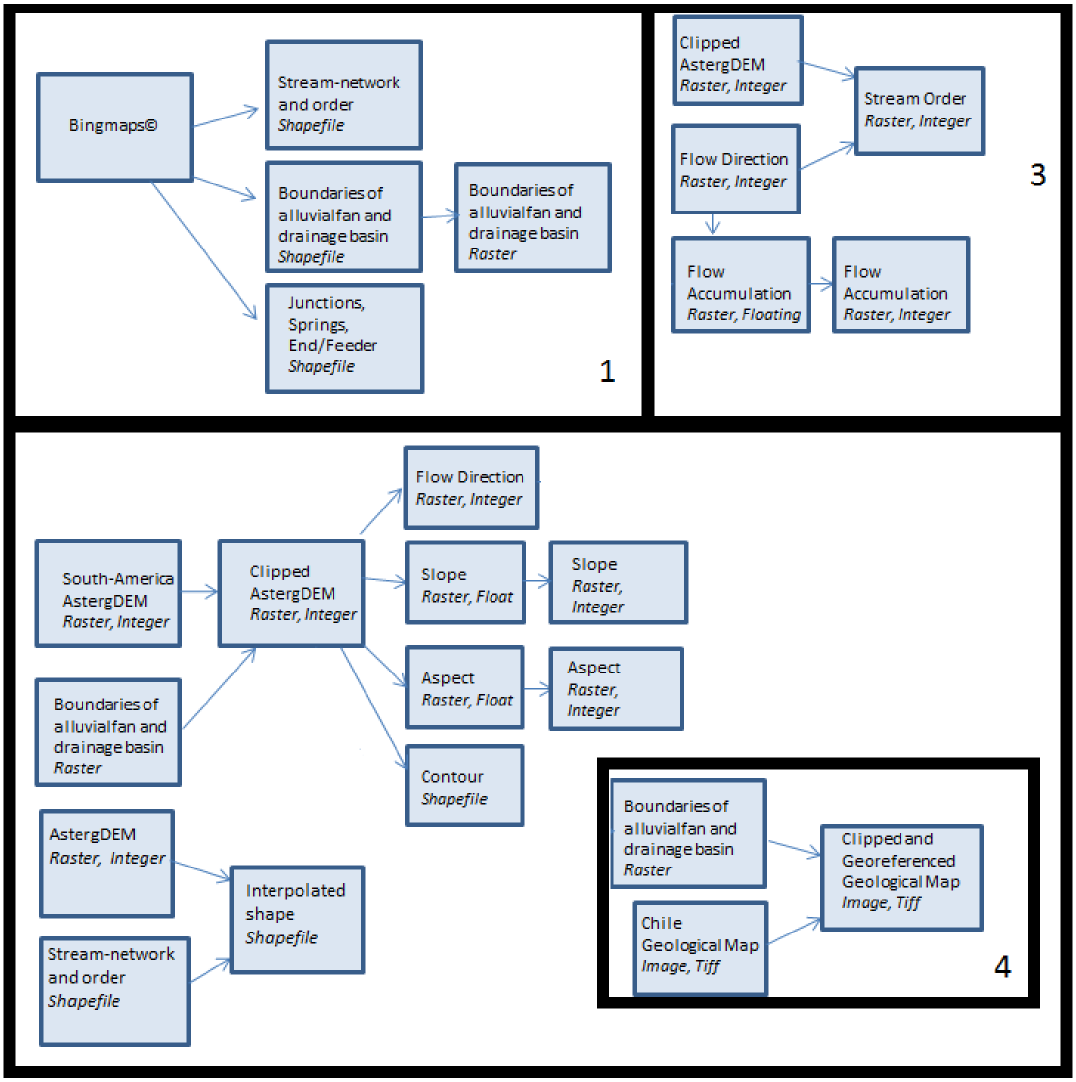

Figure 3: Workflow of digitizing and analysing alluvial fan and drainage basin. There are 4 steps required.

When fully recognizable, the internal channel network of drainage basins has also been digitized. This will be done in polylines and points. The polygons, polylines and points are georeferenced (i.e. linked to a coordinate-system) for further geometric and statistical calculations. The second step is to calculate the geomorphic properties of alluvial fans and drainage basins from the DEM. A DEM is a digital representation of the topography and therefore of the surface morphology of an area. It has been proven to be a good basis for geomorphic analysis (Rowbotham et al., 2005). The DEM used in this study is the AstergDEM with a cell size of 30x30 meters. ASTER (Advanced Spaceborne Thermal Emission and

Reflection Radiometer) is a Japanese sensor which is one of five remote sensory devices on board the Terra satellite launched into Earth orbit by NASA in 1999. The instrument has been collecting superficial data since February 2000. ASTER provides high-resolution images of the planet Earth in 15 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. On 29 June 2009, the Global Digital Elevation Model (GDEM) was released to the public. For this study the AstergDEM is georeferenced to the coordinate system WGS 1984 - UTM ZONE 19S. Due to the curvature of the Earth it is important to choose the appropriate coordinate system. The Coastal Cordillera is located in the centre of the WGS 1984 - UTM ZONE 19S system. This causes less effect of the curvature of the Earth and therefore fewer errors in spatial calculations. The polygon that represents the alluvial fans and drainage basins is stored in vector data and should be converted to raster data in order to make calculations possible (Figure 4).

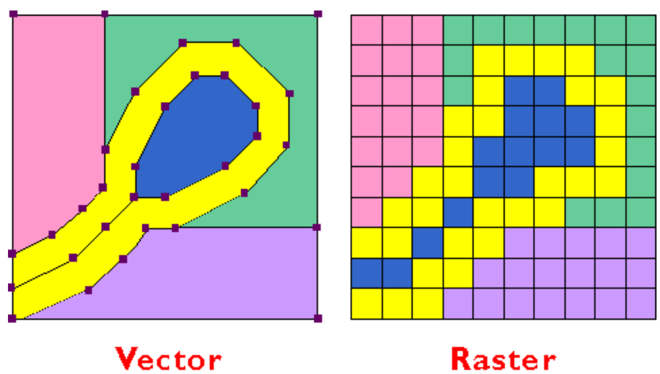

Figure 4: An example of polygon to raster conversion. With raster data it is possible to make calculations, since values can be ascribed to each cell. However detail of boundaries is lost, due to the squared shape of the cells.

With the raster maps of alluvial fans and drainage basins, it is possible to clip (Figure 5) the AstergDEM to the areas of the alluvial fans and the drainage basins. This is done with raster calculator, which allows you to create and execute Map Algebra expressions.

From the clipped DEM, slope, aspect / flow direction and heights of the geomorphic surfaces of interest have been calculated. Aspect identifies the downslope direction, where the maximum rate of change in height occurs from each cell to its neighbours. It can be thought of as the slope direction and flow direction. The values of each cell in the output raster indicate the compass direction that the surface faces at that location. It is measured clockwise in degrees from 0 (due north) to 360 (again due north), coming full circle. Flat areas having no downslope direction are given a value of -1 (Figure 6).

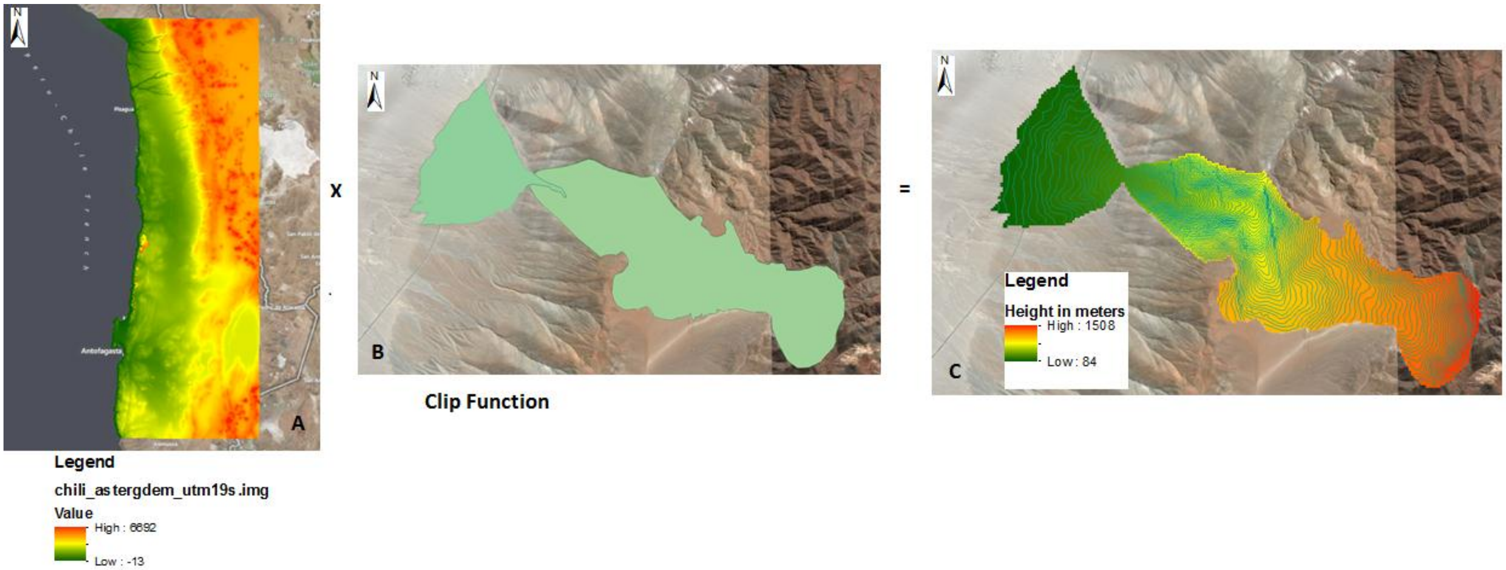

Figure 5: Clipping creates a new coverage by overlaying two sets of features. The polygons of the Clip Coverage define the clipping region. The AstergDEM contains the data for the input coverage feature. Only those input coverage features that are within the clipping region are stored in the output coverage. A: The AstergDEM WGS 1984 - UTM ZONE 19S. B: The raster representing the boundaries of the alluvial fan and its drainage basin. C: The clipped DEM with the boundaries of the alluvial fan and its drainage basin.

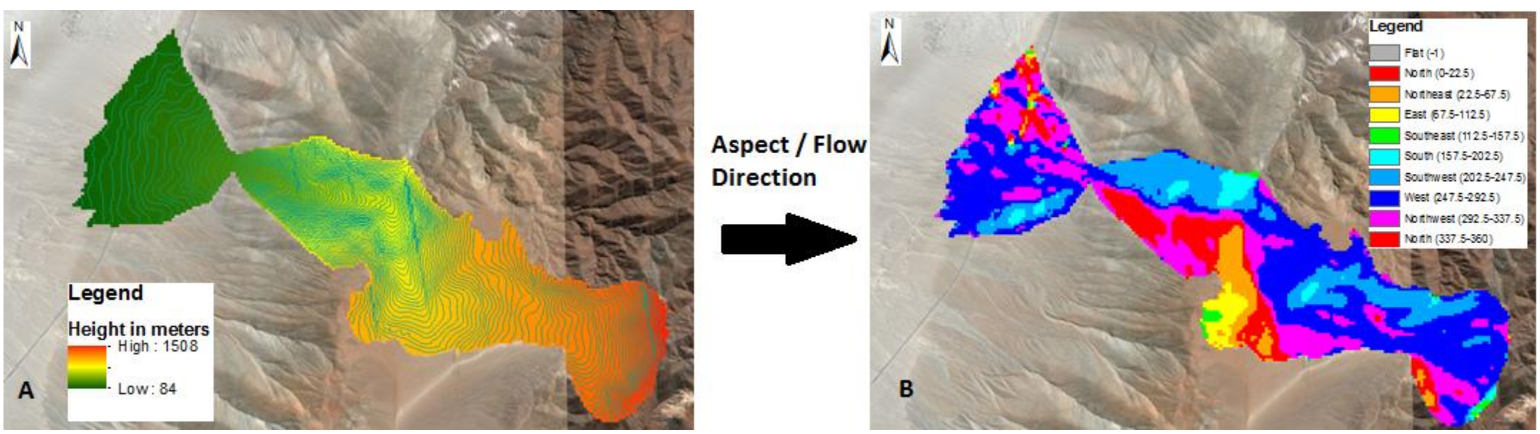

Figure 6 : Aspect / Flow direction map (B) calculated from the clipped DEM (A).

The third step consists of calculating the flow accumulation and channel order from the flow direction and the DEM. Flow accumulation is a function that calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. If no weight raster is provided, a weight of 1 is applied to each cell, and the value of cells in the output raster is the number of cells that flow into each cell (Figure 7).

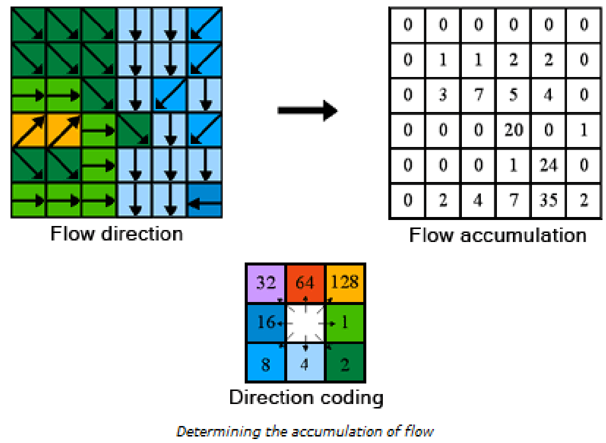

Figure 7: How flow accumulation works. Modified from ArcInfo 10.0 ©.

Channel ordering is a method of assigning a numeric order to links in a channel network. This order is a method for identifying and classifying types of channels based on their numbers of tributaries. This is done according to the Strahler (1952) method (Figure 8).

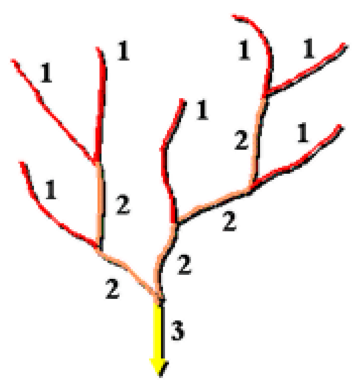

Figure 8: In the Strahler (1952) method, all links without any tributaries are assigned an order of 1 and are referred to as first order. The channel order increases when channels of the same order intersect.

The final step is the collection of geological information from a geological map of Chile at scale 1:1.000.000. Identical to the DEM, the geological map of Chile will be clipped to distinguish the relevant geological aspects for each drainage basin. These aspects are the lithologies that occur in outcropping bedrock and whether fault lines have an important function in determining the geomorphology.

The following list presents all the geomorphic and geological variables that were obtained for each fan and its drainage basin:

1. Basin area (km^2): area of the drainage basin above the fan apex.
2. Basin height (m): the average height of the whole basin area.

3. Basin slope (degrees): the average slope of the whole basin area.
4. Basin aspect (degrees): the downslope direction, where the maximum rate of change in height occurs from each cell to its neighbours, for the whole basin area.
5. Highest-order length (m): the length of the highest-order channel (according to the Strahler (1952) method; Figure 8), within the whole basin area.
6. Sinuosity: the length of a straight-line (in plain view) joining the initial and final points of the highest-order channel divided by the actual length of the highest-order channel. Sinuosity is derived with two different systems: ArcInfo 10.0 © and GoogleEarth ©. This is because four drainage basins were so large; it was not efficient to have their channels digitized. An example of the sinuosity is shown in Figure 9.

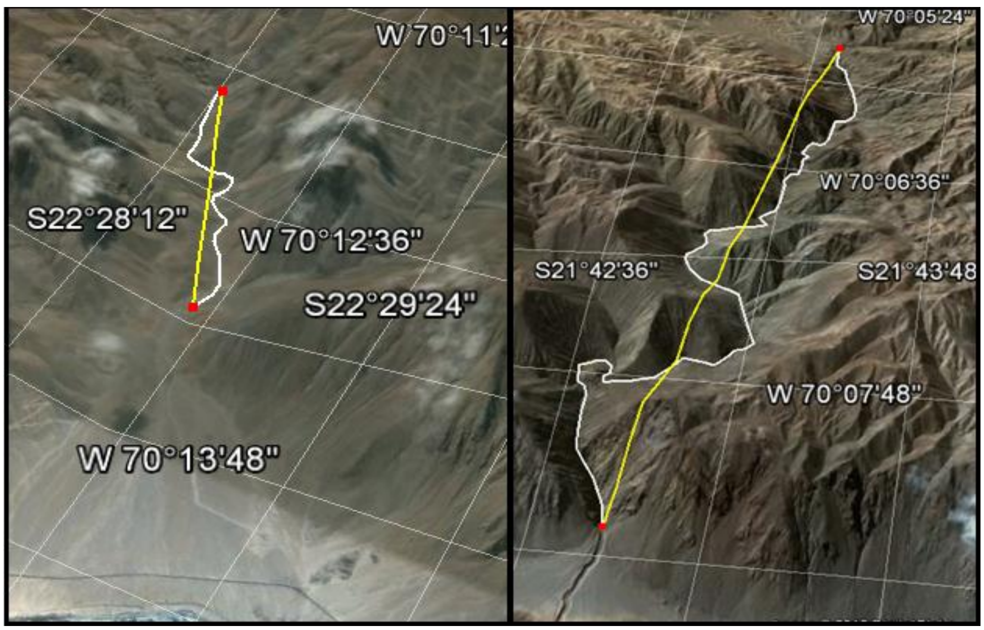

Figure 9: The sinuosity in basin 17 (left picture) and basin 37 (right picture). The white-line indicates highest-order channel. The yellow-line indicates the straight line joining the initial and final points of the highest-order channel. Source: Google Earth©.

7. Basin perimeter (km): perimeter of the whole basin area.
8. Basin length (km): the length of a straight-line from the fan apex to the most distant point on the basin boundary.
9. Basin crest (m): maximum elevation of the basin.
10. Basin end (m): minimum elevation of the basin.
11. First-order channel length (km): the total length of first-order channels (Strahler (1952) method) identified on Bingmaps©.

12. Number of first-order channels (-): number of first-order channels (Strahler (1952) method) identified on Bingmaps©.
13. Total channel length: the total length of all identifiable channels in the drainage network, as recognized on Bingmaps©.
14. Drainage Density (km/km^2): the total channel length divided by the basin area.
15. Basin relief (km): the elevation difference between the highest and lowest points in a basin area.
16. Basin Melton-ratio (km/km): Basin relief (km) divided by the square root of basin area (km^2).
17. Basin relief-ratio (km/km): basin relief (km) divided by basin length (km)
18. Basin elevation/relief-ratio (km/km): basin height minus the basin end, divided by the basin relief.
19. Fan area (km^2): area of the alluvial fan.
20. Fan height (m): the average height of the whole fan area.
21. Fan slope (degree): the average slope of the whole fan area.
22. Fan aspect (degree): the downslope direction of the maximum rate of change in value from each cell to its neighbours for the whole fan area.
23. Fan perimeter (km): perimeter of the whole fan area.
24. Fan apex (m): elevation of the fan apex.
25. Fan toe (m): elevation of the fan toe.
26. Fan concavity: an index of concavity along the fan axis, defined as the ratio of a to b, where a is the elevation difference between the fan axis profile and the midpoint of a straight line joining the fan apex and toe, and b is the elevation difference between the fan toe and this midpoint.
27. Fan relief (km): the elevation difference between the fan apex and fan toe.
28. Fan Melton-ratio (km/km): fan relief (km) divided by the square root of fan area (km^2).
29. Fan elevation/relief-ratio (km/km): fan height minus the fan toe, divided by the fan relief.
30. The fan radius (km): the radius of the fan whole fan area.
31. The BA/BP-ratio: the basin area divided by the basin perimeter will provide information about the shape of the basin. A low ratio will indicate a more rectangular shape; oppositely a high ratio will indicate a more round shape.
32. The FA/FP-ratio: the fan area divided by the fan area will provide information about the shape of the fan.
33. Fan width (m): the width of the fan, at about halfway of the radius.

34. Highest-order (stream) channel (Manual): the highest-order channel that is manually digitized for each drainage basin. The Strahler (1952) method is used (Figure 8). The highest-order channel can be interpreted as the feeder channel.
35. Highest-order (stream) channel (Automatic): assigns a numeric order to segments of a raster representing branches of a linear network. In ArcInfo 10.0 ©, again the Strahler (1952) method is used (Figure 8). Can be interpreted as the feeder channel.
36. Maximum flow accumulation: highest value of flow accumulation.
37. Basin geology : each drainage basin is investigated for the geological composition of outcropping bedrock. This is done to indicate whether "soft" or "hard" rocks are present, which may play a major role in determining the type of sediment produced and of sediment-transport processes. The fault lines are investigated for their influence on the geomorphology of the drainage basin.
38. Hypsometric curves (Strahler, 1952; Ohmori, 1993; Perez-Pena et al., 2009): a hypsometric curve is derived for each basin in order to characterize the general geomorphic configuration of single basins and to compare the general morphology of different basins. A hypsometric curve is the empirical cumulative distribution function of elevations for a predefined geomorphic surface. Differences in hypsometric curves between landscapes arise because the processes that shape the landscape may be different, as further explained in results. The curve is created by plotting the proportion of total basin height against the proportion of total basin area (Figure 10).

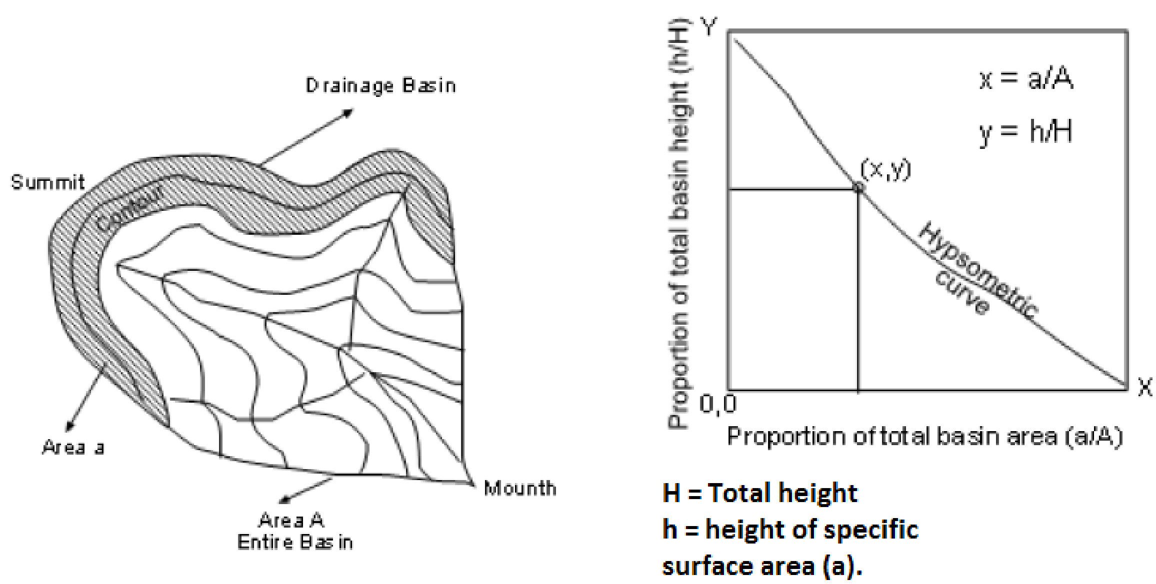

Figure 10: Hypsometric curve, an empirical cumulative distribution function of elevations for a predefined geomorphic surface.

39. Types of alluvial-fan surfaces: different types of fan-surface morphology are defined on the basis of visual interpretations from Google Earth©, taking into account: colour differences, specific surface pattern (braided networks, types of channels, etc.), relief and recognizable deposits (debris-flow levees, debris-flow lobes, etc.). This is an important variable because it is independent of all other variables. Also, the assumption is made that the type of surface morphology depends on all the others variables. The type of surface morphology is linked to weathering, reworking or a type of depositional process. This study will analyse whether a type of depositional process is the most important aspect in determining the type of the surface morphology and which variables are linked to that type of surface morphology.

Analysis of geomorphological and geological variables

To define which of these variables are the most important in controlling the occurrence of different types of fan-surface morphology, statistical analyses were carried out with the program PAST (Hammer et al., 2001). It is crucial is to keep in mind which variables are independent. Gaps in the available data were filled with average values. To compare different types of surface morphology, the variables are averaged for each type. To guarantee that these averages have a real significance, one-way ANOVA (analysis of variance; Hammer et al., 2001) tests were performed to determine whether two datasets differ significantly. One-way ANOVA is a statistical procedure for testing the null hypothesis that several samples are taken from "groups" (in this case types of surface morphology) with the same mean. The samples are assumed to be close to normally distributed and have similar variances. If the sample sizes are equal, these two assumptions are not critical. The samples should also be independent. The one-way ANOVA test is expressed in F, which is the "between groups" sum of squares divided by the "within groups" sum of squares. If the null hypothesis is correct, F should be ~1, which means that there is no difference between groups for that specific variable. Before it is possible to reject or accept the null hypothesis, the P-value should be analysed. F can be expressed in P and depends on the amount of samples and the amount of groups. If the overall P value is large, the data do not give any reason to conclude that there are significant differences. If the overall P value is small, then it is unlikely that the observed differences are due to a coincidence of random sampling.

For determining which variables are the most important and which variables are most closely related, canonical variates analysis (CVA) has been used (Hammer et al., 2001). CVA will make linear combinations of all variables, enabling to identify relationships between multiple independent and dependent variables, especially when little is known about their actual relationship. The analysis can be performed on both metric and nonmetric data. CVA places the fewest restrictions on the variables that are analysed, but the correlation coefficient between two variables is based on a linear relationship. Thus, while CVA is the most generalized multivariate method, it is still constrained to identifying linear relationships. The *Pillai trace* is the sum of explained variances and will indicate the significance of the test (Hammer et al., 2001). A lower value for the *Pillai trace* will indicate a more significant test. The canonical loadings will indicate which variable is most important and which variable is most linked to one other. Most data needs to be standardized. No generally accepted guidelines have been established regarding suitable sizes for canonical loadings. Rather, the decision is usually based on the contribution of the findings to better understanding of the research problem being studied.

Results

Both coastal alluvial fans (37) and fans located inland (10) have been investigated (Figure 12) for their geomorphological and geological variables. A total of 47 selected fans were classified into five categories based on different types of fan surfaces. The entire dataset is available in appendix 1 up to and including appendix 19. The analysis has shown that not all variables have the same weight. For example, it has been observed that basin aspect, flow direction and basin height have no relationship with fan-surface morphology, and are therefore irrelevant for this study. This is probably because these variables are more dependent on the specific geographic location than on any dynamic process. Other variables such as highest-order length, first-order channel length, number of first-order channels, perimeter, basin crest, basin end, fan apex, fan toe and the elevation/relief-ratio were also not taken into consideration for further study, since these resulted to be highly dependent on other variables of more fundamental importance, further discussed here. Due to the low resolution of the DEM, some errors occurred while deriving maximum flow accumulation and the automatic highest channel-order. These errors caused spurious observations, such as apparent channel cut-offs which do not appear to be confirmed by image analyses, and that may result in lower values of maximum flow accumulation and lower values of highest channel-order. Thirteen geomorphic variables have been verified to be of importance for the analysis. These are basin area, basin slope, drainage density, basin Melton-ratio, highest channel-order (manual), fan area, fan slope, fan concavity, fan radius, sinuosity, the fan width, the FA/FP-ratio and the BA/BP-ratio.

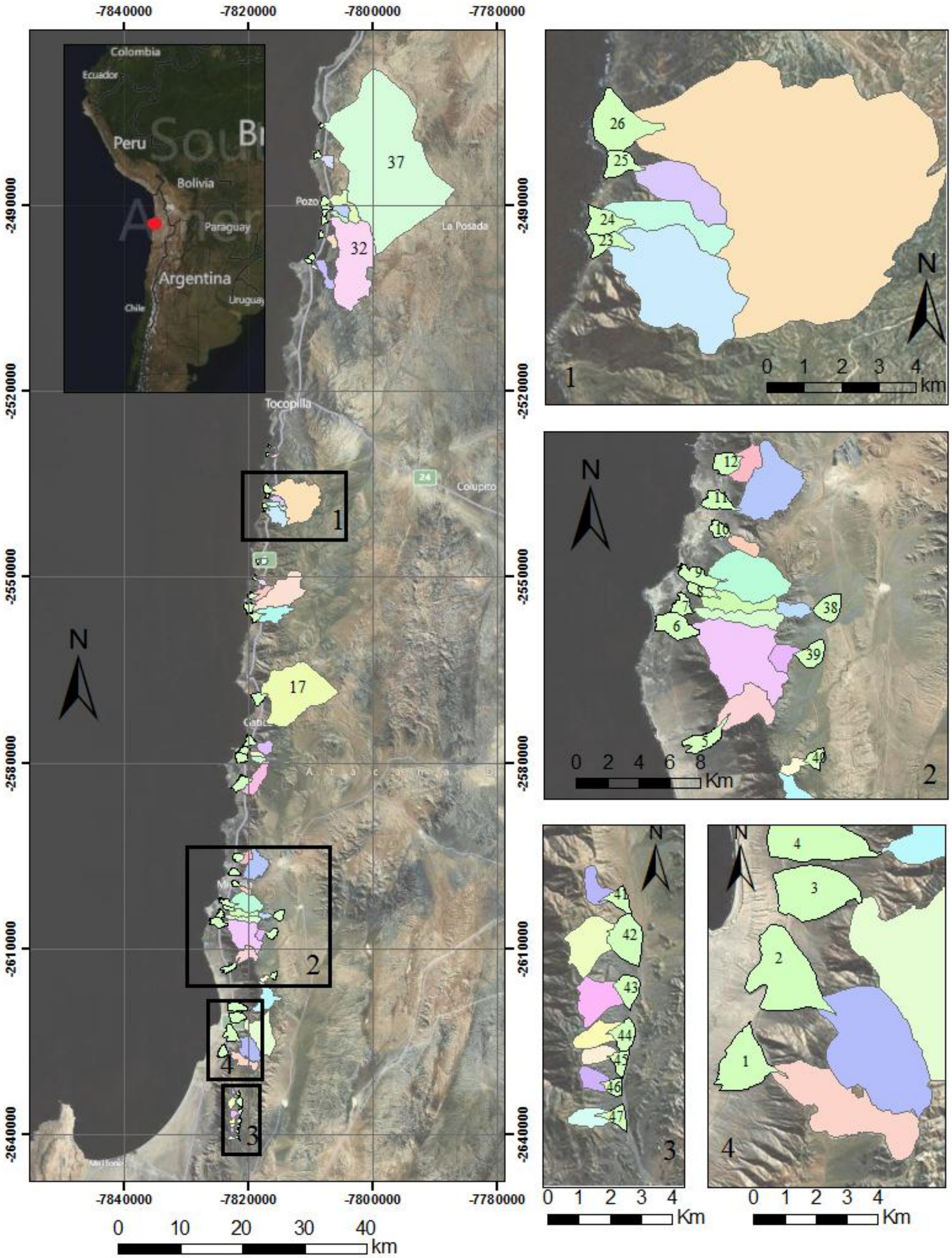

Figure 11: Overview of all 47 fans studied along the Coastal Cordillera in the Atacama Desert, Chile. Highlighted are (1) some fans in the northern part, (2) some coastal and inland fans next to each other, (3) the inland fans, in the southern part, (4) the first four fans that have very distinctive features. Source: Bingmaps©.

Figure 12: An illustration of alluvial fan 3. Green colour indicates boundary of the alluvial fan. Red square is a zoomed illustration of the pattern of this fan. Fan 3 is a typical example of a type 1 fan. Scale is indicated with yellow lines. Source: Google Earth©.

Description of different types of fan surface morphology

Type-1

Fans 3, 5, 13 and 39 have been classified as type-1 fans (example shown in Figure 12), which are characterized by a low-relief braided pattern of small channels, 1-3 m wide and very shallow. These channels do not show any levees. The distance between individual channels amounts to 5-30 m, which makes the braided pattern very dense over the fan surface. Scattered boulders are present over the proximal part of the fan. In the medial fan segments, the braided pattern is most dense and boulders are not found. The distal fan surface tends to smoothen, the channels are straighter and no boulders are visible from satellite imagery. Deep incised channels connect the fan toes to the coastline (Bottom of figure 7); these were described by Hartley et al. (2005) as landward gullies cut through alluvium into underlying Plio-Pleistocene marine terraces. On each fan the colours are dark and do not show variety. Only the toe of the fan tends to have more bright colours.

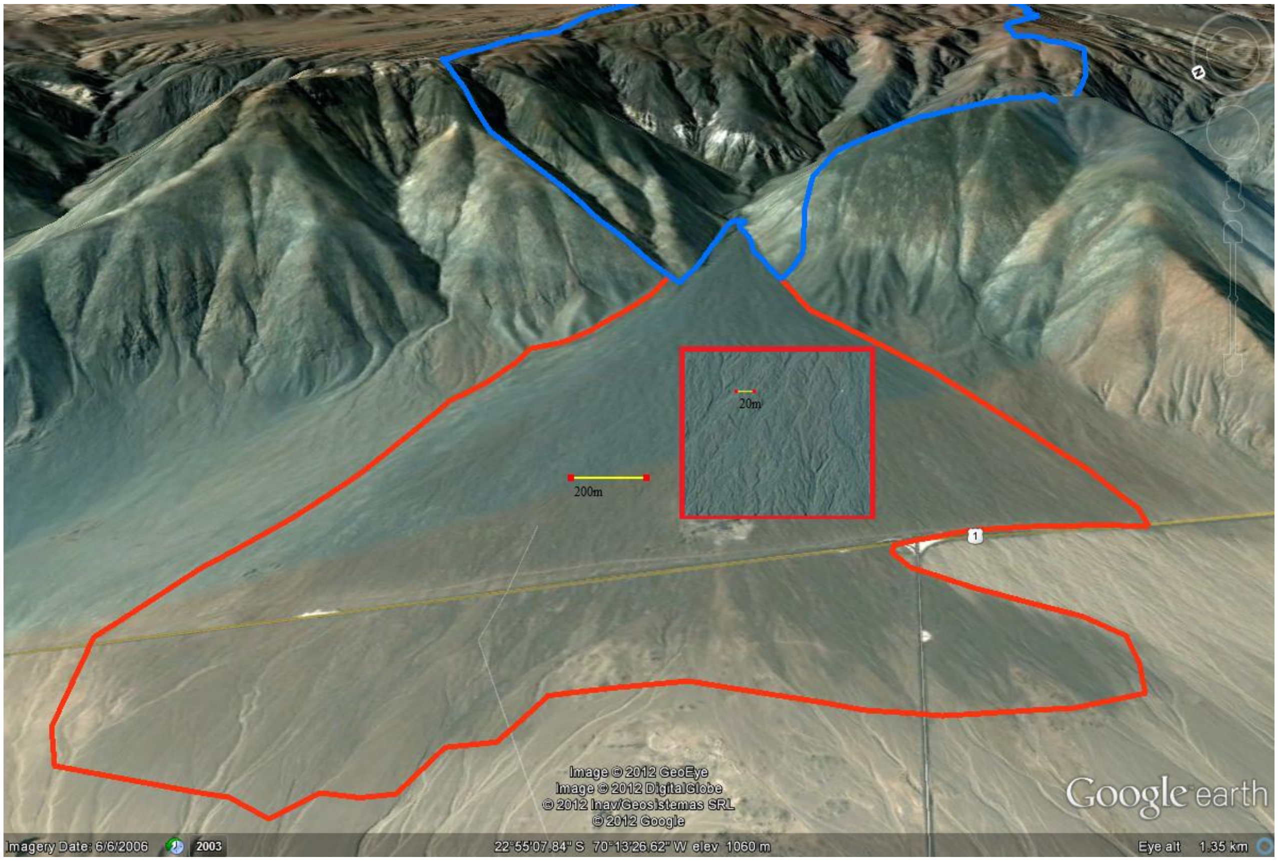

Figure 13: An illustration of alluvial fan 2. Orange colour indicates boundary of the alluvial fan. Red square is a zoomed illustration of the pattern of this fan. Fan 2 is a typical example of a type-2 fan. Scale is indicated with yellow lines. Source: Google Earth©.

Type-2

Fans 2, 4, 8, 9, 11, 12, 38, 40, 41, 42, and 43 are classified as type-2 fans (example shown in Figure 13), characterized by a high-relief braided pattern similar to that on type-1 fans and with a very dense channel network (distances between channels amount to 10-30 m). In type-2 fans, channels are less shallow and up to 10 m wide. Oval-shaped areas between channels are interpreted as bars. However, there is no clear evidence of deposits and therefore these oval shaped areas should be interpreted as relicts formed by erosion. Especially towards the distal part, these oval shaped areas become larger. Numerous boulders are present on the proximal fan segments, but their presence is only minor in central and distal fan segments, although more pronounced compared to type-1 fans. As in type-1 fans, the channels tend to straighten towards the distal part. Some fans also have incised channels at their distal terminations, probably caused by the coastal uplift. The colours on the satellite imagery vary from darker to brighter colours on different parts of the fans.

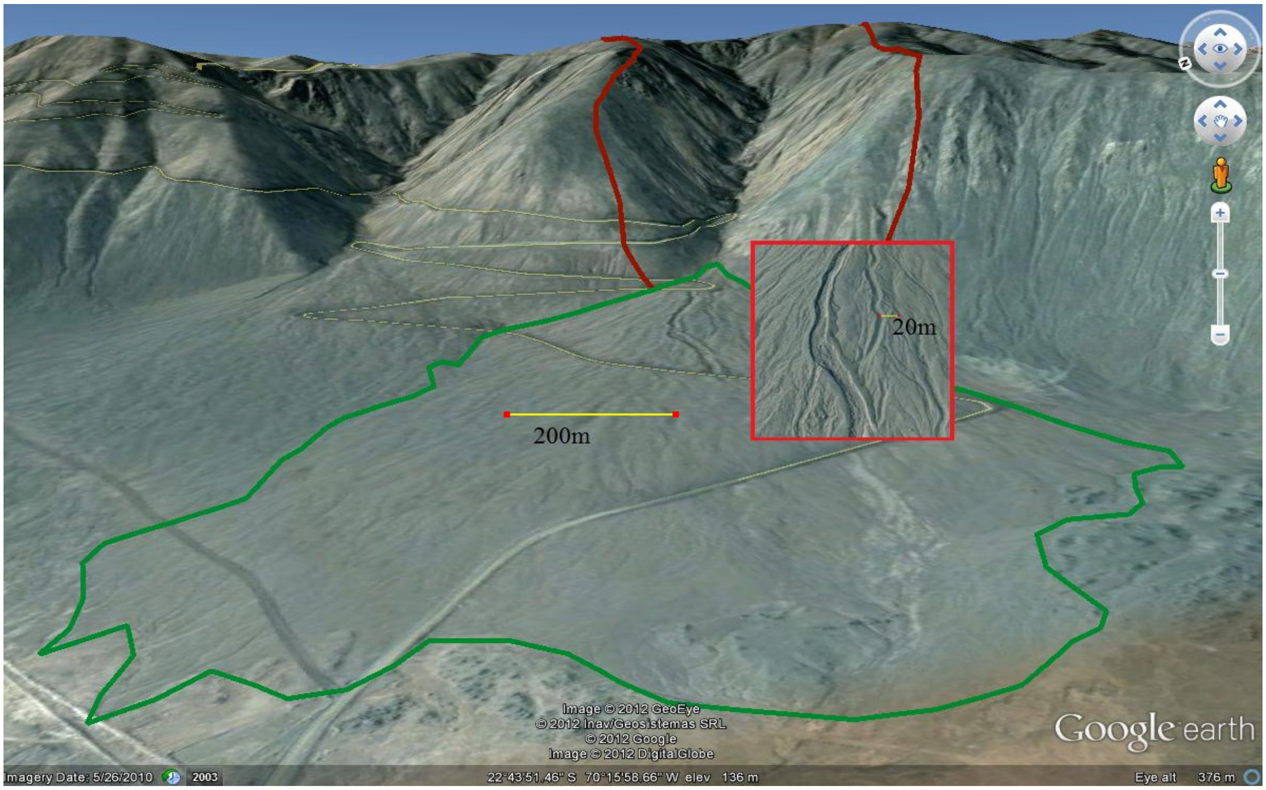

Figure 14: An illustration of alluvial fan 10. Green colour indicates boundary of the alluvial fan. Red square is a zoomed illustration of the pattern of this fan. Fan 10 is a typical example of a type-3 fan. Scale is indicated with yellow lines. Source: Google Earth©.

Type 3

Fans 10, 14, 15, 16, 23, 24, 29, 30, 31, 34, 35 and 36 belong to type-3 (example shown in Figure 14), characterized by channel-levee patterns. Satellite imagery clearly shows large levees on the fan surface, up to 30 m wide. The channels show a large difference in relief from the top part of the levees till the thalweg of the channels. Unfortunately, the resolution of the DEM does not consent accurate measurement of actual channel depths, but a visual estimate indicates depth values from 5 up to 15 m. Boulders are recognized in proximal, central and distal parts of the fans, usually located within a channel or on a levee. The boulders of type-3 fans are bigger then on type-1 and type-2 fans. Based on a visual inspection of images they can reach up to 2 m in diameter. At the end of channels, the accumulation of sediments causes the

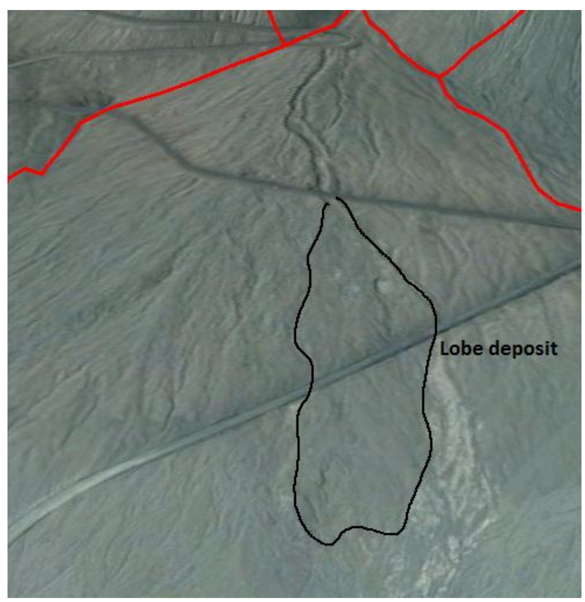

Figure 15: An example of a depositional lobe on alluvial fan 10. Source: Google Earth©.

formation of lobes (Figure 15). Due to erosion, lobes are hard to distinguish, causing the relief of these deposits to have disappeared. A few fans still contain small parts (5% of the surface) that have a braided pattern, but it is nothing compared to type-1 and type-2 fans. In general channels tend to meander but become straighter towards the toe of the fan. Between channels, the surface is smooth and comprises few boulders, but significantly more than on type-1 and type-2 fans. Some fans have more channels (i.e. a denser network), but on average the distance between each channel is about 30 to 50 m, and thus significantly higher than on type-1 and type-2 fans. Fans have a variety of brighter and darker colours on the satellite imagery, but no difference in proximal, central or distal parts. Fan 16, 23, 29, 30, 34 and 35 have a large incised channel extending radially through their centre, from proximal to distal ends.

Type 4

Fans 6, 7, 18, 19, 32 and 46 belong to type-4 (example shown in Figure 16), characterized by a dominantly smooth surface. Even though some relief patterns are still recognizable, such as shallow channels and low-relief braided networks, these do not present any associated levees and it is thus more likely that such patterns are due to erosion, rather than deposition. These patterns affect only ~20% of the fan and are widely spread on its surface (more than 30 m). Most of the surface is smooth and featureless, without any recognizable morphological patterns. However, numerous small boulders are present, more than on type-1 and type-2 fans, also in the distal reaches. Colours vary from reddish to grey to white, and are generally brighter than for other fan types.

Type 5

Fans 1, 17, 20, 26, 37 belong to type-5 (example shown in Figure 11), characterized by a generally smooth surface with a superimposed shallow channel pattern. As in the previous category, no levees are recognized. The channel network is much denser than on type-3 fans (10-20 m of interchannel distance) and channels are relatively smaller (up to ~10 m wide). Channels appear to be continuously incised from the proximal to the distal fan surface and have meandering or braided patterns. Many large boulders are scattered over the surface in proximal, central and distal parts of the fan, as in type-3 fans. Most boulders in the proximal area of the fan are probably due to rockfalls from mountain slopes adjacent to the fan. In some fans, surface colours vary greatly from dark to bright; in the brighter-coloured areas, channels are more densely packed.

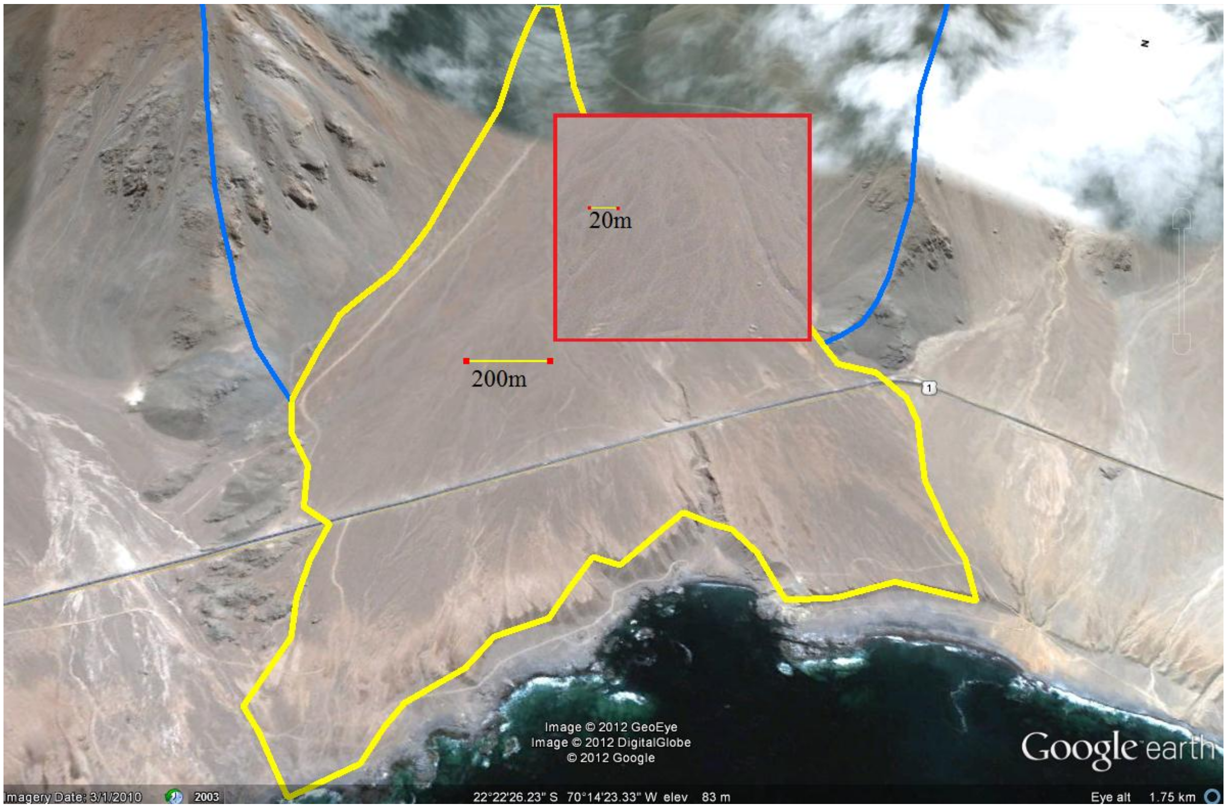

Figure 16: An illustration of alluvial fan 18. Yellow colour indicates boundary of the alluvial fan. Red square is a zoomed illustration of the pattern of this fan. Fan 18 is a typical example of a type-4 fan. Scale is indicated with yellow lines. Source: Google Earth©.

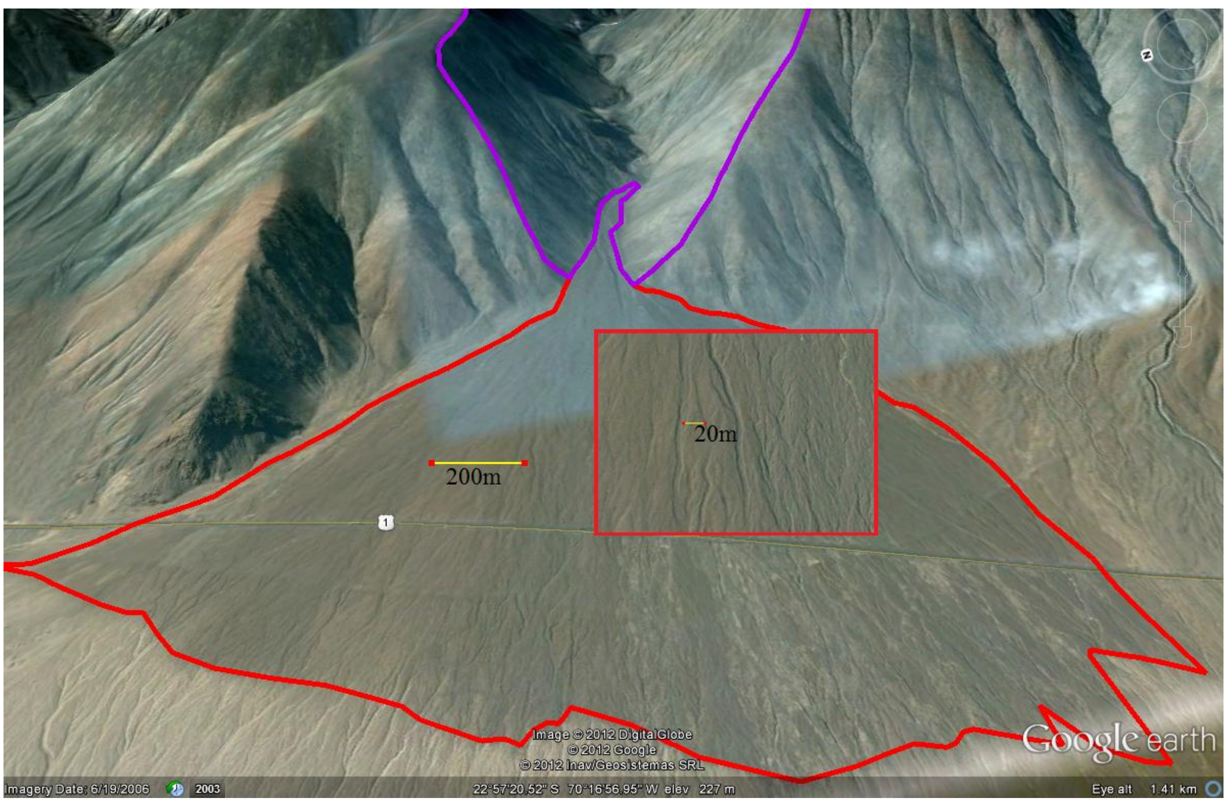

Figure 17: An illustration of alluvial fan 1. Red colour indicates boundary of the alluvial fan. Red square is a zoomed illustration of the pattern of this fan. Fan 1 is a typical example of a type-5 fan. Scale is indicated with yellow lines. Source: Google Earth©.

Composite surfaces

The surfaces of fans 44, 45 and 47 present surfaces with characters of both type-2 and type-4 fans, as described above. Most likely, this is due to different depositional phases succeeding in time. A good example is shown in Figure 18. On the left side, fan 47 has a surface clearly belonging to type-2, with a high-relief braided pattern. On the other hand, towards the centre of the image, the surface has a smooth type-4 pattern. The difference is highlighted by the colour contrast between the two types of surface; the smoother portion of the fan is reddish, while the braided portion is dark-toned. The same kind of surface is observed on fans 44 and 45. Boulders are absent from the surfaces of these fans.

Another fan with a composite surface is alluvial fan 33, which comprises both type-3 and type-4 surfaces (Figure 19). In this case the surface is more of a transitional type, rather than a composite one. It is similar to type 3, with a channel-levee pattern, but it has a lower channel density (~20%). The surface colour is uniform. Numerous small boulders are present around the channels and it could be interpreted that some lobes have been deposited. It has a large incised channel extending radially through its centre, from proximal to distal end.

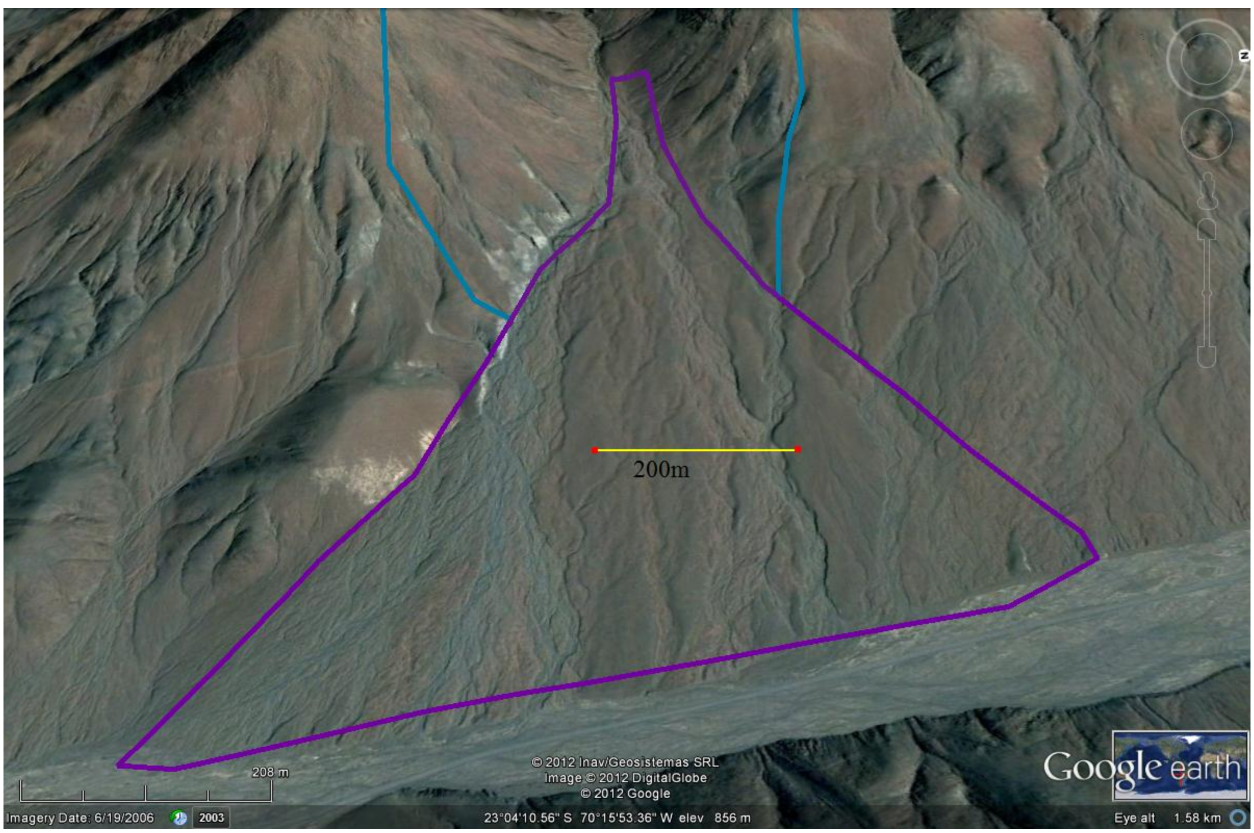

Figure 18: An illustration of alluvial fan 47. Purple colour indicates boundary of the alluvial fan. Fan 47 is a typical example of a type-2/4 fan. Scale is indicated with yellow line. Source: Google Earth©.

Figure 19: An illustration of alluvial fan 33. Red colour indicates boundary of the alluvial fan. Fan 33 is a typical example of a type-3/4 fan. Scale is indicated with yellow line. Source: Google Earth©.

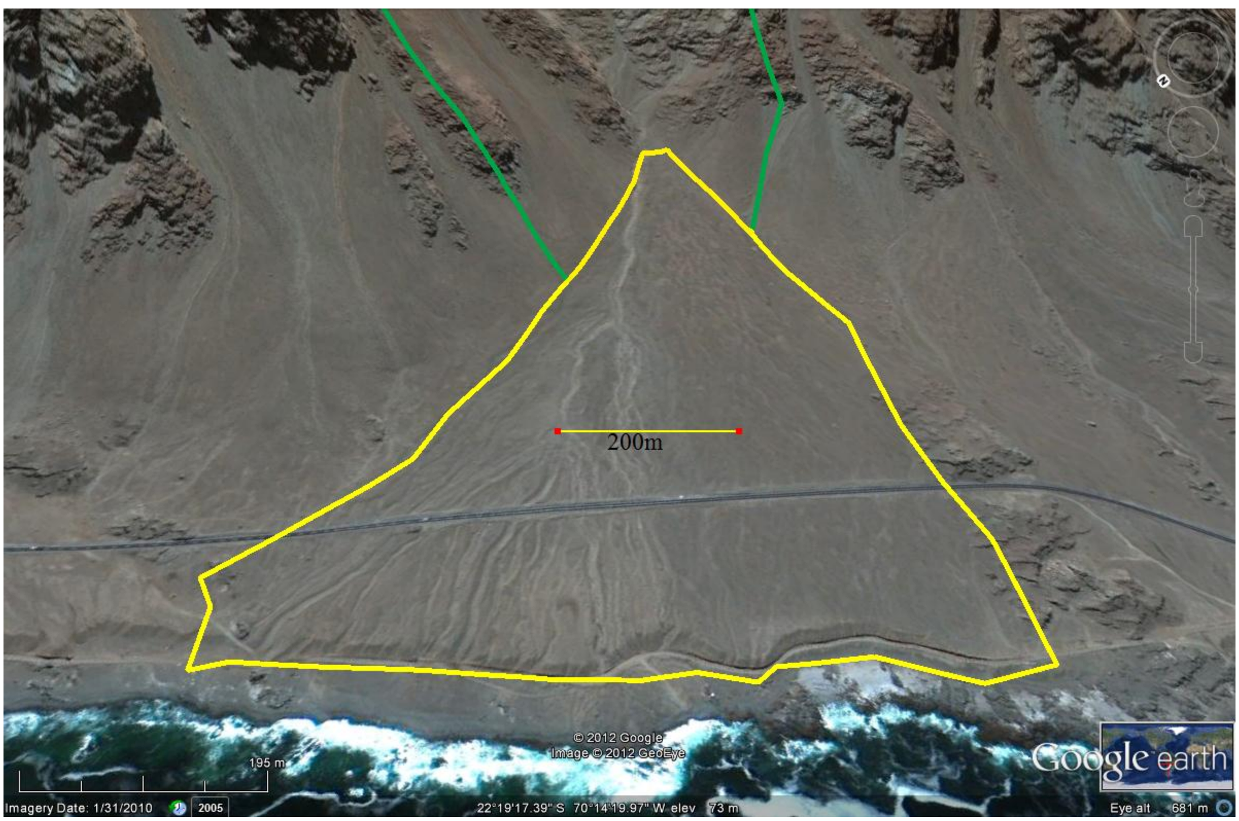

Figure 20: An illustration of alluvial fan 21. Yellow colour indicates boundary of the alluvial fan. Fan 21 is a typical example of a type-3/5 fan. Scale is indicated with yellow line. Source: Google Earth©.

Fan 21 has a surface characteristics of both types 3 and 5 (Figure 20). In figure 11, the left side of the fan has a type-3 surface, whereas the right side has a type-5 surface. The clear colour difference between the two surfaces indicates that they were most likely deposited at different times. Large boulders are scattered over the proximal part of both surface types, but distally they are present only on the type-3 surface. The levees of surface type-3 are very clear and up to 10 m wide.

Colluvial Fans

Some selected fans are colluvial fans, and not proper alluvial fans. They are considered to be colluvial fans because their source area is restricted to the slope of the Coastal Scarp. In other words, they are not fed by a complex drainage network and all deposits are directly provided from the slope. Fans 22, 25, 27 and 28 are of this type (Figure 21). They contain larger boulders then type-3 alluvial fans, with sizes probably up to 5 m, scattered over the whole surface. Small parts (~5%) of these surfaces comprise shallow channels, some of which possibly characterized by small levees.

Figure 21: An illustration of alluvial fan 27. Red colour indicates boundary of the alluvial fan. Fan 27 is a typical example of a Colluvial fan. Scale is indicated with yellow line. Source: Google Earth©.

Geology

Each drainage basin is studied for bedrock lithology and the presence of fault lines. The bedrock lithologies present in the region, as reported on the geological map of Chile, are:

1. **Qa: (Pleistocene-Holocene)** alluvial, colluvial or lacustrine deposits. Composed of gravels, arenites and mudstones.
2. **O1MC: (Oligocene-Miocene**) continental sedimentary sequences of alluvial deposits. Composed of conglomerates, arenites, shales, limestone and coal seams.
3. **MP1c: (Miocene Upper-Pliocene)** clastic sedimentary piedmont sequences of alluvial, colluvial or fluvial deposits. Composed of conglomerates, arenites and mudstones.
4. **J3i: (Jurassic)** continental and marine volcanic sequences: lavas and basaltic to andesitic agglomerates, rhyolitic tuff interbedded with sandstone, marine limestone and continental conglomerates.
5. **JKg: (Jurassic-Cretaceous 150-100 Ma)** granodiorite, diorite, monzodiorite and granite, andesitic and dacitic porphyry.
6. **Jsg: (Middle- Upper Jurassic 180-142 Ma)** monzodiorites quartzite, diorite and granodiorite with biotite, pyroxene and hornblende.
7. **Faults:** the geological map indicates normal faults, strike-slip faults, inverse faults and other type of faults. These faults are a first-order indication of the amount of tectonic displacement in the area.
8. **Boundaries:** each lithology has a boundary-line. More boundary-lines will create more errors, since in reality boundaries are not an actual percentage of the bedrock lithology.

The geological maps created for each alluvial fan and its drainage basin are shown in appendix 3. The composition of outcropping bedrock in catchments for each type of defined fan-surface is shown in figure 22. Catchments characterized by the presence of fault lines, in decreasing order of frequency, are: type-1 (11%), type-4 (8%), type-2 (6%), type-3 (5%) and type-5 (4%). The dominant bedrock lithology in the catchment (equal or higher than 10%) for each type of fan-surface morphology is also determined: type-1 catchments are dominated by extrusive igneous rocks (62%); type-2 by extrusive (50%) and intrusive igneous rocks (27%); type-3 by extrusive (41%); intrusive igneous rocks (32%) and sediments (13%); type-4 by extrusive (48%) and intrusive igneous rocks (30%) and type-5 by extrusive igneous rocks (45%), intrusive igneous rocks (21%) and sediments (19%). The amount of lithological boundaries is equal for each type and therefore the amount of error can be considered equally for each type of fan-surface morphology.

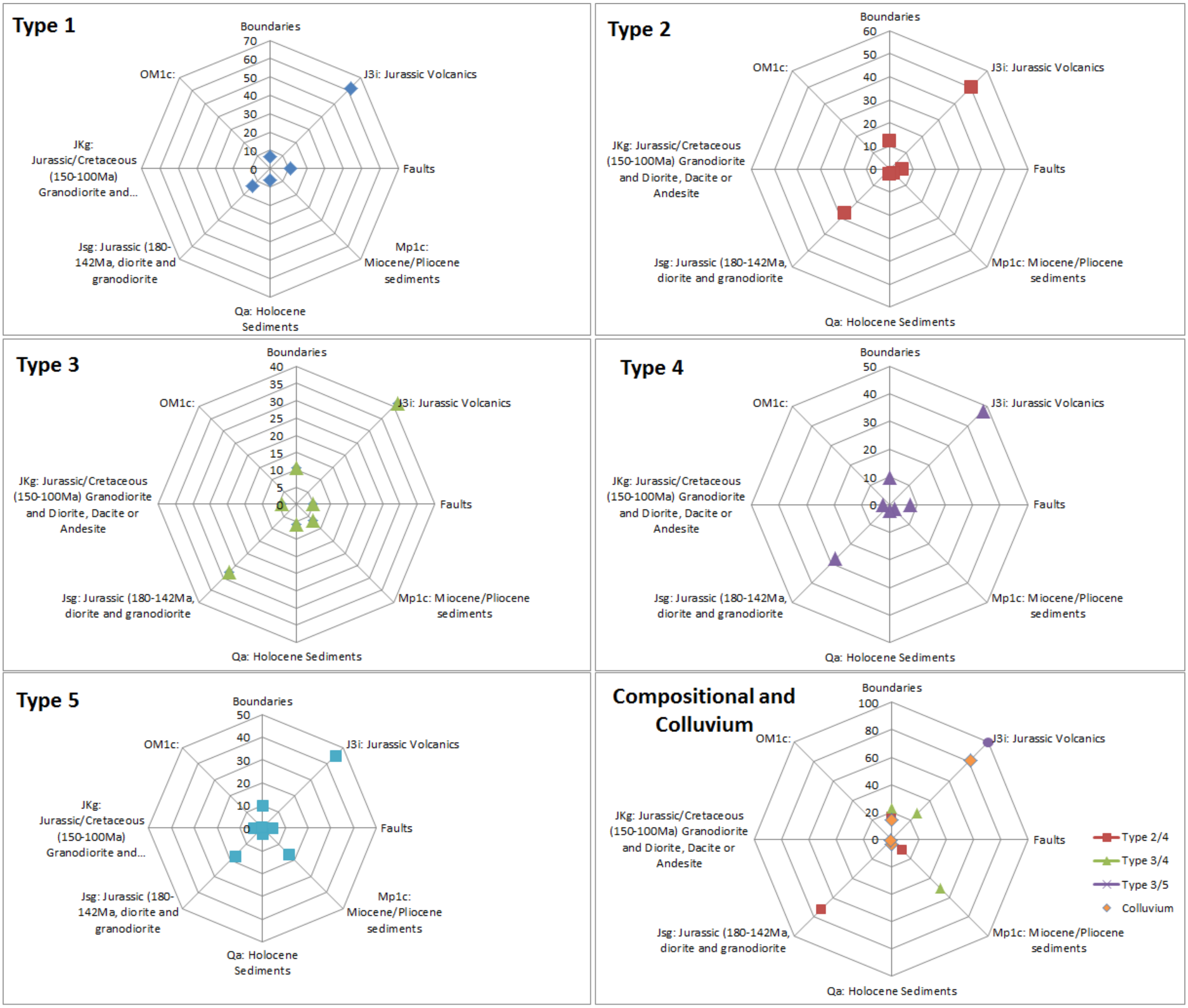

Figure 22: Geological composition of the surface of the basin for each type of fan-surface morphology. Each type of outcropping bedrock is plotted in percentages.

Hypsometric curves

Differences in hypsometric curves between landscapes arise because the processes that shaped the landscape may be different. Vice versa, landscape differences will affect the processes that occur. This concept is important for this study, especially when it comes to weathering processes. Accommodation space will cause sediments to be preserved at one location and to endure more weathering. By consequence, this will lead to production of finer sediments, which in turn will favour the occurrence of sediment-gravity flows. A stepped hypsometric curve indicates that the general catchment morphology comprises steep slopes with relatively flat surfaces in between (i.e. more accommodation space). By contrast, a gradual, smooth curve indicates a gentle gradient and no or relatively less flat surfaces (i.e. less accommodation space) in the catchment. However, these assumptions do depend on basin area and basin relief (Figure 23). Expected would be that there are no steep slopes and no flat areas if the hypsometric curve is continuous curve. In contrast with the expectations, if the basin area for this particular fan is very small, slopes are still quite high. However, no flat areas will be present and such type of drainage basins will not produce fine sediments. Thus, the hypsometric curve is an important attribute to discriminate between catchments prone to sediment-gravity flows or fluid-gravity flows.

The drainage basins of type-1 fan-surface morphologies have gradual hypsometric curves (Figure 24), a low basin relief and a large area. This would suggest gentle slopes and no flat areas. Type-2 drainage basins have slightly more irregular hypsometric curves and small areas. Although type-2 contains smaller drainage basin areas, steep slopes are cancelled out due to a low amount of basin relief.

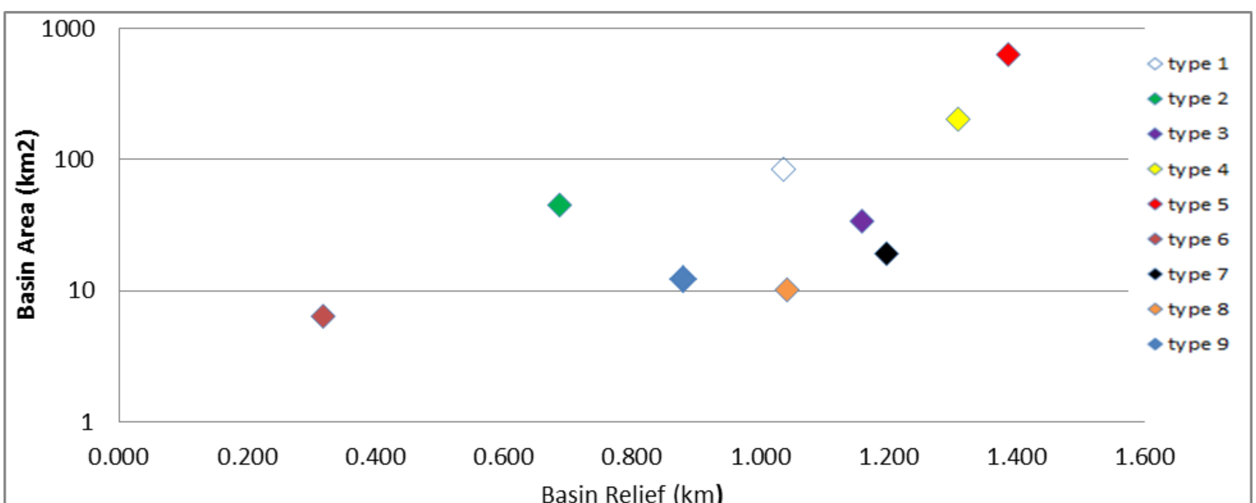

Figure 23: Basin area in km^2 vs. Basin relief in km. Averages are taken for each type. 1 =type 1. 2 =type 2. 3=type 3. 4 = type 4. 5 = type 5. 6 = type 2/4. 7 = type 3/4. 8 = type 3/5. 9 = Colluvial.

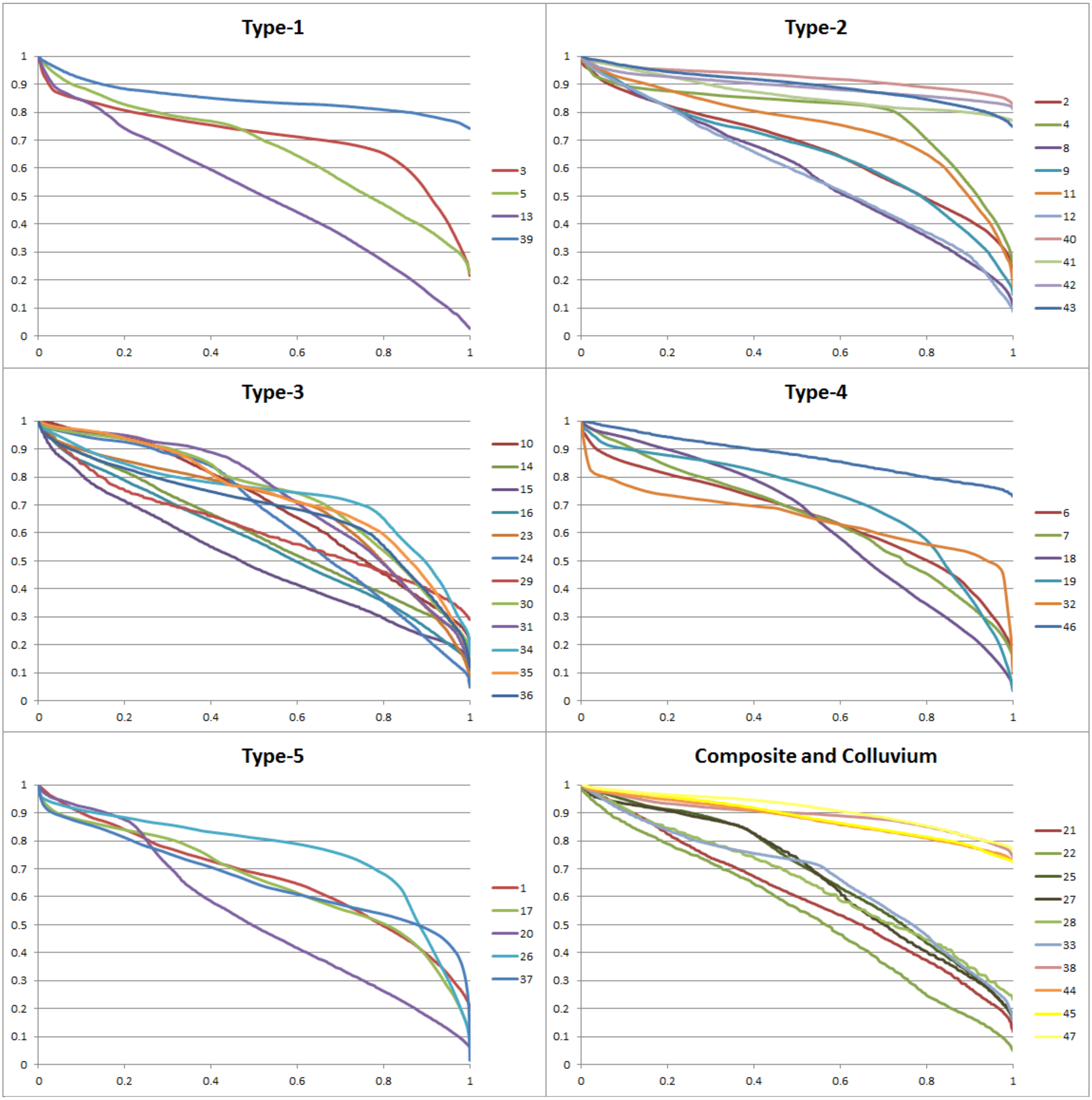

Figure 24 Hypsometric curves for each basin, each graph represents a type of surface morphology.

Type-3 basins have extremely stepped hypsometric curves, the smallest area and a large amount of basin relief. This implies many steep slopes with relatively flat surfaces in between. Type-4 hypsometric curves are similar to type-2 hypsometric curves. Only basin relief is much larger, which would mean extreme slopes. However, this is cancelled out by its large area. Type-5 hypsometric curves show similarities with type-1 hypsometric curves. The large amount of basin relief is again cancelled out by the large area. Hypsometric curves for the composite drainage basins of type-2/4 fan-surface morphologies are extremely gradual. Type 2/4 has the smallest basin area and the lowest amount of basin relief, which means the slopes are gentle. Drainage basins of type-3/4 and 3/5 fan-surface morphologies have large elevation differences and their hypsometric curves are less smooth. Especially type-3/5 has a relatively high drainage basin relief and a small catchment area and therefore matches with steep slopes. The colluvial catchments have extremely stepped hypsometric curves. Again their relatively high drainage basin relief and small drainage basin area corresponds to steep slopes.

Comparisons between the different types of fan-surface morphology

In order to compare the different types of fan-surface morphology, an average is calculated for each geomorphological variable (displayed in figures 25 and 26). Comparisons are first drawn between type-1 up to, and including, type-5, since it is more important to understand differences between fan-surface morphologies than differences between composite types. Composite types will be compared separately to find a link with type-1 up to, and including, type-5 fan-surface morphology.

Type-1 fans are linked to an intermediate basin area, a low basin slope, one of the lowest basin Melton-ratios, an intermediate BA/BP-ratio and a low sinuosity. Characteristic for type-1 fans is that they have six variables of greatest magnitude and two variables of the lowest:

- Greatest: fan area, fan concavity, highest-order channel, fan width, FA/FP-ratio (i.e. a very round shape) and fan radius.
- Lowest: Drainage density and fan slope.

Type-2 has variable averages similar to type-1 fans, but type-2 fans are more intermediate and less distinctive. Type-2 has an intermediate basin area, drainage density and basin Melton-ratio, one of the largest fan areas, a low fan slope, a low fan concavity, a low BA/BP-ratio, an intermediate fan width, one of the highest sinuosities, a high fan radius and an intermediate FA/FP-ratio. Type-2 fans have zero variables of the greatest magnitude and two variables of the lowest:

- Lowest: basin slope and highest-order channel.

Type-3 is very distinctive, compared to all the other types. Type-3 fans correlate with an intermediate to high fan concavity, an intermediate highest-order channel and a high FA/FP-ratio. Type-3 fans have four variables of the greatest magnitude and six variables of the lowest:

- Greatest: basin slope, drainage density, basin Melton-ratio and fan slope.
- Lowest: fan area, basin area, fan width, sinuosity, fan radius and BA/BP-ratio (i.e. very rectangular shape).

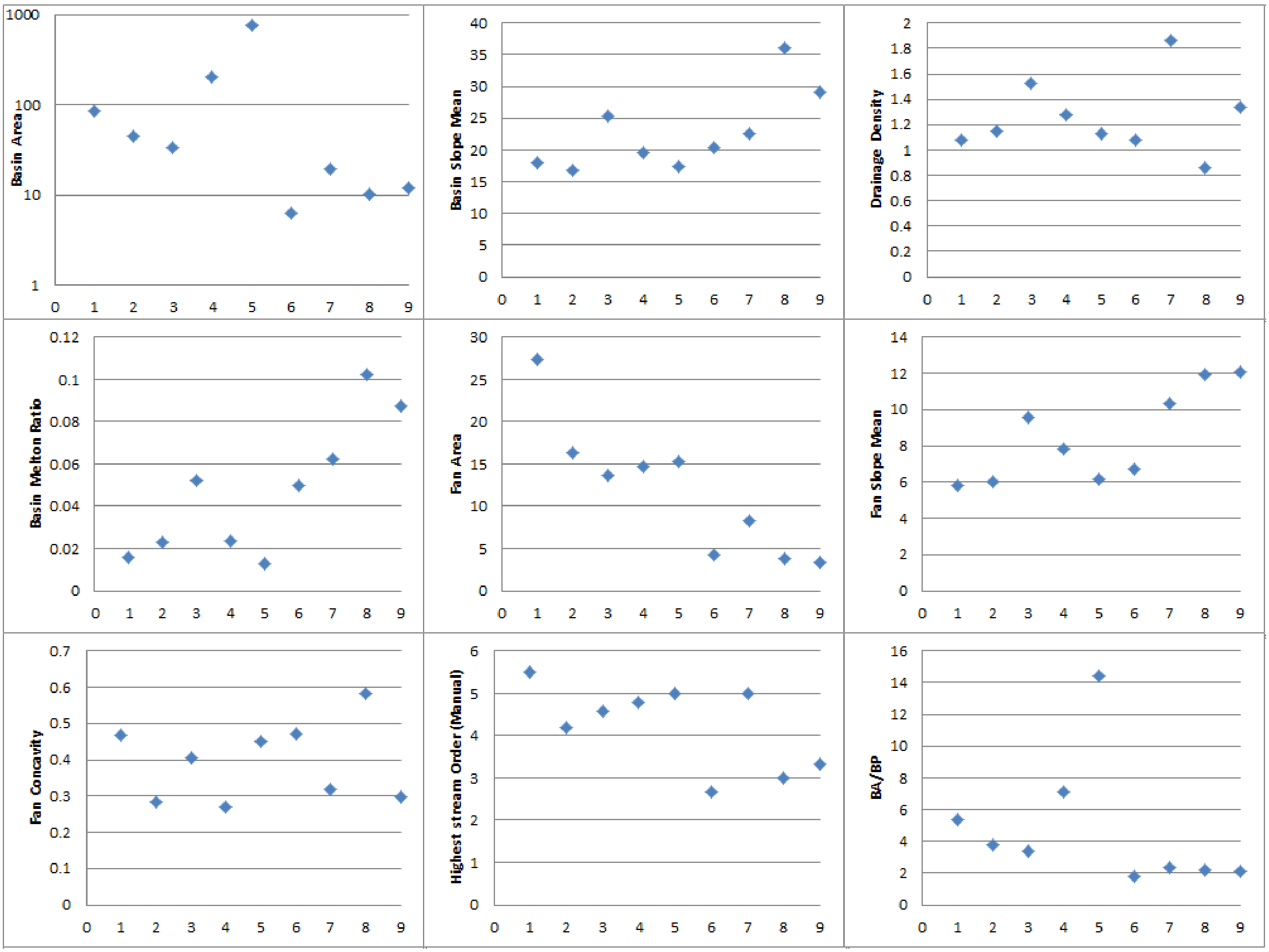

Figure 25: Averages of important geomorphological variables of all 47 fans. All parameters are set up against type of surface. 1 =type 1. 2 =type 2. 3=type 3. 4 = type 4. 5 = type 5. 6 = type 2/4. 7 = type 3/4. 8 = type 3/5. 9 = Colluvial.

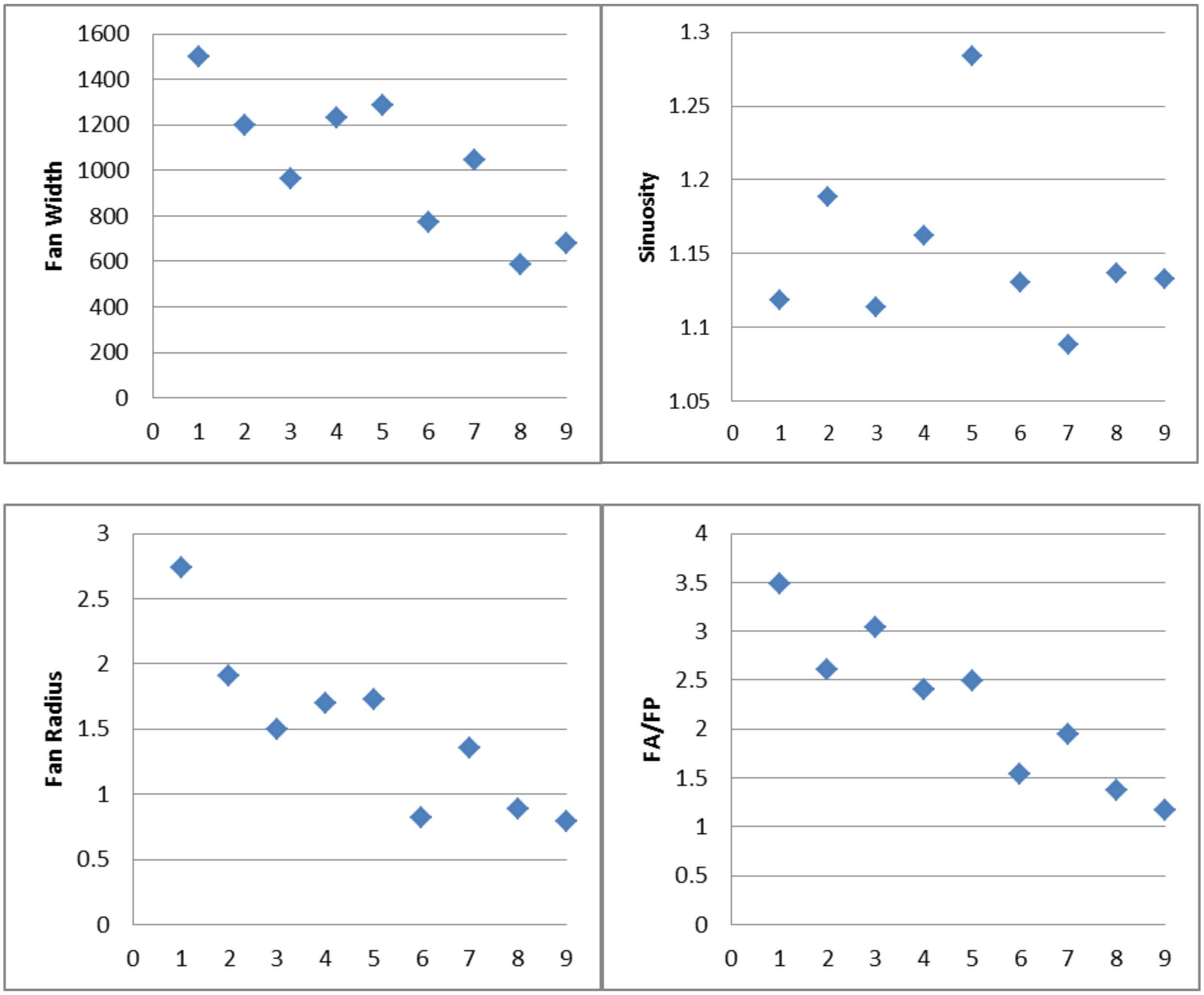

Figure 26: Averages of important geomorphological variables of all 47 fans. All parameters are set up against type of surface. 1 =type 1. 2 =type 2. 3=type 3. 4 = type 4. 5 = type 5. 6 = type 2/4. 7 = type 3/4. 8 = type 3/5. 9 = Colluvial.

Type-4 fan-surface morphologies have: a large basin area, a high basin slope, and intermediate drainage density, an intermediate basin Melton-ratio, an intermediate fan area, a large fan slope, an intermediate highest-order channel, an intermediate to high BA/BP-ratio, an intermediate fan width, a high sinuosity and an intermediate fan radius. Type-4 is not distinctive and has most similarities with type-5 and type-2. It has zero variables of the greatest magnitude and two variables of the lowest:

- Lowest: Fan concavity and the FA/FP-ratio (i.e. very rectangular shape).

Type-5 fans have: an intermediate basin slope, an intermediate drainage density, one of the lowest basin Melton-ratios, an intermediate fan slope, a high fan concavity, a great highest-order channel, a large fan width and an intermediate fan radius. Type-4 is most related to type-5, although similarities are not as strong as between type-1 and type-2. This is because type-5 has some very distinctive variables:

- Greatest: basin area, sinuosity, BA/BP-ratio (i.e. very round shape).
- Lowest: basin Melton-ratio.

Although the composite types have similarities in surface pattern with the other 5 types of fan-surface morphology, there are fewer similarities in geomorphological variables. Fan 44, 45 and 47 have a combination of surfaces from type-2 and type-4, but only fan concavity and fan slope have values between values of type-2 and type-4. Comparing to all the other types, the composite type 2/4 has the lowest basin area, the lowest highest-order channel and the lowest BA/BP-ratio (i.e. the most squared shape). Fan 33 is a composite fan with a surface of type-3 and type-4. Transitional values are again only found for two variables: basin slope and fan concavity. With a small basin area, the largest drainage density, a large Melton-ratio, a small fan area, a large fan slope, a small fan radius and the smallest sinuosity it closely resembles the variables of type-3 fans. Fan 21, another compositional fan, but with surfaces of type-3 and type-5, has no transitional values. Except on fan-concavity, all the other geomorphological variables closely resemble colluvial fans. Therefore it should be questioned whether this fan is an alluvial fan. Colluvial fans are very distinctive with small basin areas, extremely large basin slopes, high Melton-ratios, small fan areas, large fan slopes, low fan concavity, small highest-order channel, low BA/BP-ratio, small fan width, extremely small fan radius, and the smallest FA/FP-ratio. They can easily be separated from the other five types of fan-surface morphology.

Statistical analysis

One-way ANOVA

Due to their low amount of fans and their scatter of values for each variable, the composite fan-surface morphology types and colluvial fans are not taken into account in the statistical analysis. Besides, it is more important to find the differences between type-1 up to and including type-5. The first analysis that is done is the one-way ANOVA test (Table 1 and figure 27). As a reminder: The values of *F* closest to one will proof the null hypothesis, indicating there is no difference between the types of fan-surface morphology for a specific variable. *F* is linked to *P*, which is shown in figure 28. The values of *P* will indicate the significance of the *F* values. *P* values closer to zero, will show that difference between each type of fan-surface morphologies is significant for each geomorphologic variable. Thus, one-way ANOVA indicates that the following variables are most significant for determining variance between each type of fan-surface morphology in decreasing order of importance: fan slope, BA/BP-ratio, basin Melton-ratio, basin slope, drainage density, basin area, fan radius, fan area and fan width. Based on the one-way ANOVA test, the other variables do not show significant difference between each type of fan-surface morphology.

One-way ANOVA	F	P
FA/FP	0,392013	0,812831
Fan Concavity	0,734969	0,574749
Highest stream Order (Manual)	0,961531	0,441525
Sinuosity	1,410664	0,252085
Fan Width	1,522437	0,21836
Fan Area	1,578703	0,203061
Fan Radius	2,76078	0,043874
Basin Area	3,269978	0,023023
Drainage Density	3,293607	0,022352
Basin Slope Mean	3,565974	0,015937
Basin Melton Ratio	3,739614	0,012877
BA/BP	4,445021	0,005528
Fan Slope Mean	8,373428	8,88E-05

Table 1: Results of the One-way ANOVA test, of all five types of surface morphology.

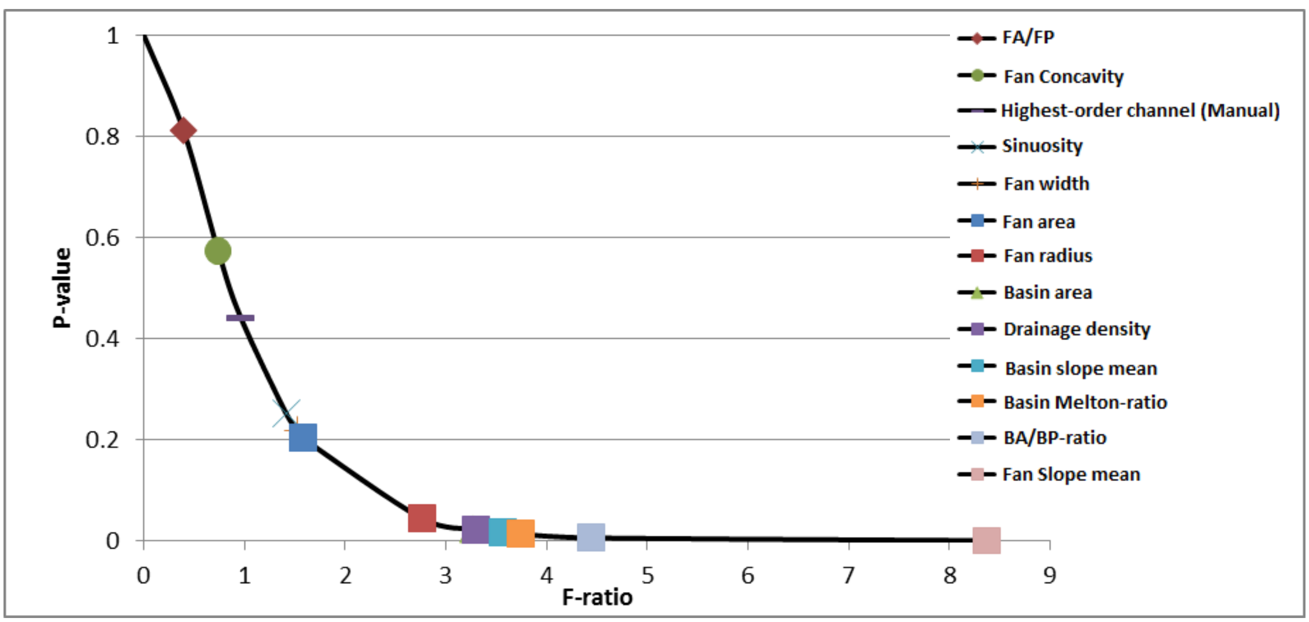

Figure 27: Overview of ANOVA of all five types of surface morphology.

Canonical Variates Analysis

The canonical variates analysis (CVA) indicates which variable is most important for determining types of fan-surface morphology. The CVA test plots 70.81% of the variance on the first axis and 16.72% of the variance on the second axis. This means that 87.53% of the variance is explained by these two axes. The Pillai trace gives a probability of 0.1091 that the specified surface types are the same, which is a statistically significant result (Hammer et al., 2001). On the axes in figure 28, all five different types of fan-surface morphologies are plotted. These plots are based on linear combinations of the original values of geomorphological variables. The main results are: (1) type-1 and type-2 surfaces are most closely related; (2) type-4 and type-5 are most closely related; (3) type-3 is very distinctive and is not related with any of the other types and; (4) even though there is some overlap between different types of surfaces, all are linked to a unique kind of fan-surface morphology with its own set of geomorphological variables.

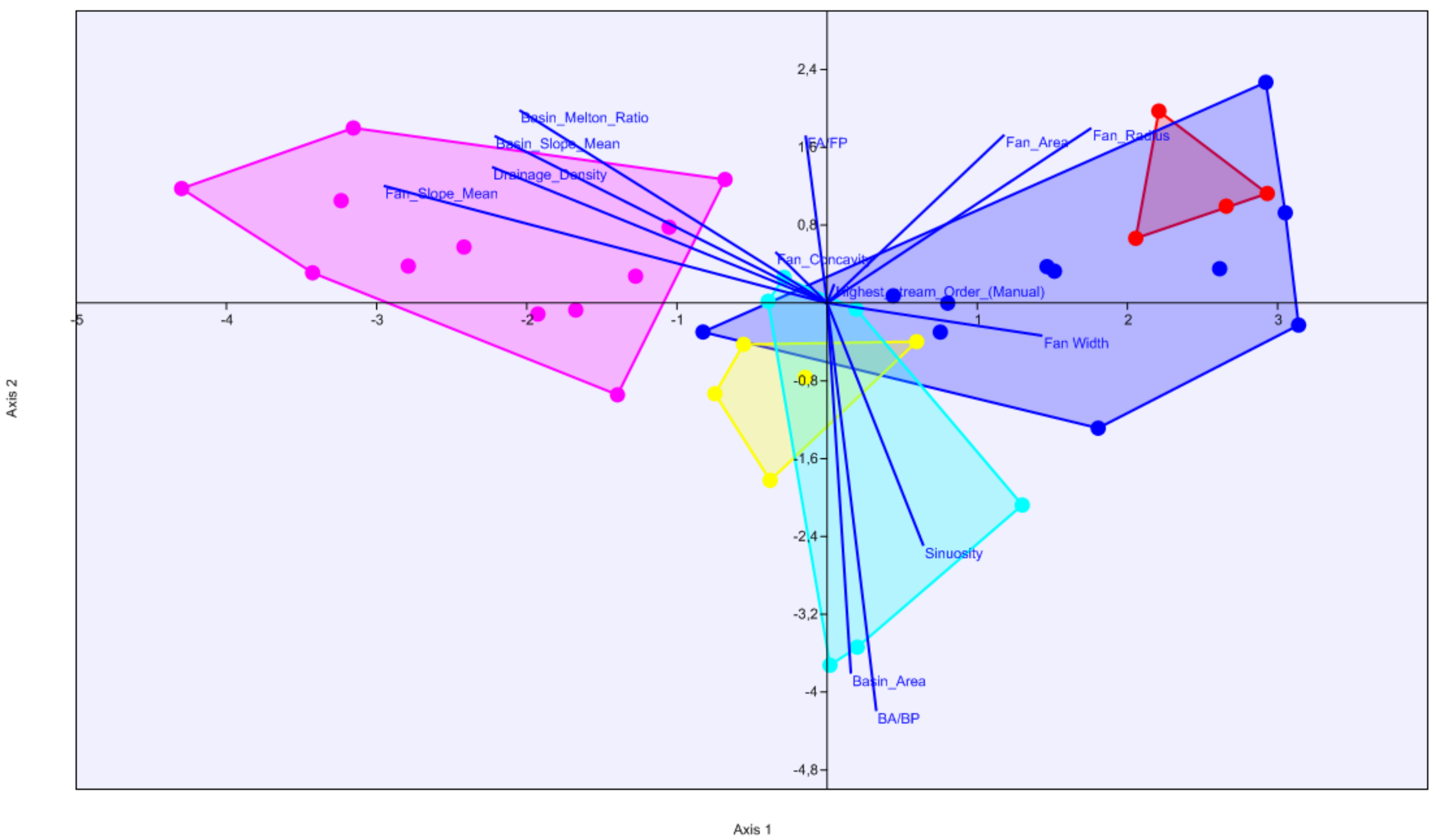

Figure 28: Results of the canonical variates analysis of all five surface types. Red = type-1 fans. Blue = type-2 fans. Purple =type-3 fans. Yellow = type-4 fans. Aqua = type-5 fans. The blue lines indicate in which direction the geomorphological variables have the greatest values. Geomorphological variables are written next to the blue lines.

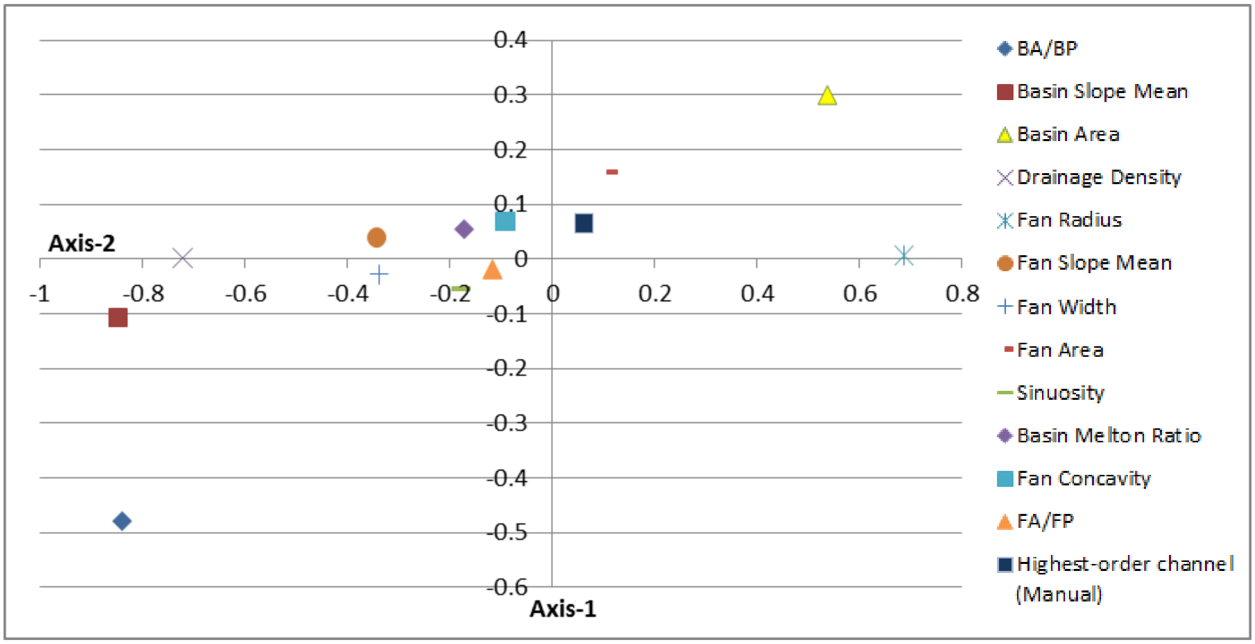

Figure 29: Canonical loadings from the canonical variates analysis of all five surface types.

The CVA-test confirms the comparisons that are done between the different types of fan-surface morphologies. According to the CVA test, type-3 fans have the greatest basin slope, fan slope, drainage density and basin Melton-ratio, indicated by the blue lines in figure 28. These values correspond to the greatest ones found in previous comparisons, shown in the results. Figure 29 shows the canonical loadings of the data. These loadings provide a large amount of information. The geomorphological variables that have the greatest loadings on an axis will explain the most variance on this axis. Thus, variance on the first axis is mostly caused by the BA/BP-ratio and variance on the second axis is mostly caused by the basin slope. This means that the difference between type-1, type-2, type-4 and type-5 fans is mostly caused by the BA/BP-ratio and the variance between type-3 fans and the other types is mostly caused by the catchment slope. The most important variables linked to the variance between each type of surface morphology (loadings of both the first- and second-axis) are, in decreasing order: the BA/BP-ratio, the catchment slope, the catchment area, the drainage density, the fan radius, the fan slope, the fan width, the fan area, sinuosity, the catchment Melton-ratio, the fan concavity, the FA/FP-ratio and the highest stream-order. Information that is also derived from the canonical loadings is that the geomorphological variables which are close together on both axes are most closely linked to each other. Geomorphological relationships that the canonical loadings reveal are: (1) catchment slope and drainage density, (2) fan and catchment area, (3) catchment Melton-ratio and fan concavity, (4) sinuosity and FA/FP-ratio, (5) highest-order channel and fan concavity, (6) fan width and fan slope, (7) fan radius and catchment area, (8) catchment slope and the BA/BP-ratio. The last information provided by the canonical loadings is that the location of the variable on both axes is most related to the type of fan-surface morphology plotted in the same area on both axes. In other words, type-5 is most related to BA/BP-ratio, catchment slope, drainage density, fan width, sinuosity and the FA/FP-ratio. This is not related to the greatest values, but related to which variables define that type of fan-surface morphology. For example, catchment slopes are not the greatest for type-5 fans, but do define each fan of this type (largest differences in value for each fan of type-5 for this geomorphological variable). To summarize, according to the CVA method, together with the one-way ANOVA, the BA/BP-ratio is the most influential parameter, followed in decreasing order by catchment slope, catchment area, drainage density, fan radius, fan slope, fan width and fan area. The other parameters either have a low significance (one-way ANOVA), or a low importance in defining different type of surface morphology (CVA).

Discussion

Fans and processes

Most geomorphological studies have recognized two main types of alluvial fans in terms of sedimentary processes, controlled either by sediment-gravity flows or by fluid-gravity flows. Surface morphology of alluvial fans is indeed mainly controlled by these two different categories of processes, but that does not imply that only two types of surface morphologies exist. For example, the type-1 fans recognized in this study clearly have a braided pattern over their surface; there are no levees and boulders are present only in the proximal part. The process linked to the development of a braided surface pattern is probably a secondary one; all its effects are surficial and formed either through slight rilling during waning flood stages or through later surficial winnowing and remoulding of primary deposits (Blair and McPherson, 2009). Braided patterns are not formed on alluvial fans during primary depositional events, due to their high angled slopes. The boulders found in the proximal part are transported by rockfall from slopes directly adjacent to fan surface and are probably not transported through the feeder channel of the drainage basin, unless they're embedded in debris-flow deposits.

It is questionable whether colour patterns from the satellite imagery can tell us anything about the actual surface of the fans. However, recent studies indicate that desert varnish might be a good reason for the darker colours that are present (Dorn, 2009; Dickerson, 2011). Desert varnish is formed by the oxidation of manganese and iron in clay by bacteria. This clay is generally an aeolian deposit from a distant source, and not an alteration product of surface deposits. Thicknesses of only 0.020mm can cause light-toned rocks to be darkened. Desert varnish will take thousands of years to form and is a good indication of lack of erosion on the rock-surface. Therefore, the brighter colours at the toe of most fans of type 1 correspond to a secondary process that is more recently active in the proximal part of the fan. The fans of type 1 are dominated by relatively large, gentle sloping fans, which are generally related to fluvial dominated processes (Kostaschuk et al., 1986; Scally and Owens, 2004).

As the results indicate, type-2 fans are similar to type-1 fans. Therefore, their braided surface pattern can also be linked to a secondary reworking. However, the surface morphology of type-2 includes boulders found on the distal part of the fans, and fan areas and slopes tend to be slightly larger. This means that the primary processes of type-2 fans are less related to runoff than for type-1 fans. The surfaces of type-2 also vary from colours, which could mean that at different stages in time reworking has taken place or deposition has occurred, since desert varnish will take time to form.

Type-3 fan surfaces are related to a primary process; the results of this study suggest this to be debris flows. Since debris flow moves as a viscous mass in a non-Newtonian, laminar manner, flows will be non-erosive even though they can transport clasts weighing several tons. The generation of a debris flow is promoted where colluvium contains mud. This causes hydrostatic pore pressure to increase and overcome shear strength, leading to the rapid downslope movement of a mud-bearing sediment-water mixture. Halting of debris flows primarily results from thinning to the point where the plastic yield strength equals the shear strength, a process promoted by expansion and aided by dewatering and a lessening of slope (Blair and McPherson, 2009). The corresponding deposits on alluvial fans are extremely poorly sorted and massive with matrix supported clasts. The depositional topography can present levees and lobes (Harvey, 2011). These deposits correspond to the ones observed on type-3 fan surfaces, and it also explains the presence of massive boulders over proximal, central and distal parts of the fans. The channels that radially incise through the fan are not related to constructive depositional event on this type of fans, but to erosion by flash floods issued from the feeder channel across the fan. If present, the channel walls can prevent flooding on the surface, which will cause an increase in depth and competency of the channel. These channels can bring coarse clasts either derived from the catchment or eroded from the walls of the channels up to proximal parts of the fans. Where incised fans do not reach the coast, incised channels serve as conduits for discharge of debris flows across the fan. Type-3 fans are linked to small fan areas and steep slopes, which are typical for landforms related to dominant debris-flows (Kostaschuk et al., 1986; Scally and Owens, 2004).

Type-4 fans have a smooth surface, most likely caused by prolonged weathering (Frankel and Dolan, 2007) and a specific reworking process. According to Scally and Owens (2004) less concave fans are generally debris-flow-controlled fans. The fact that boulders are found in the proximal, central and distal parts of the fan would also imply debris-flows. Moreover, due to its fine-grained texture, a more solid and smooth mass is also to be expected with debris-flow activities. Another argument in favour of sediment-gravity flows is that fluid-gravity flows would create more incised channels on the fan surface. If fluid-gravity flows had been the main process, even minor runoff events would have reworked the surface producing incised channels. Less incision by fluid-gravity flow would also correspond with the relative low fan concavity. The high fan slope and relative low fan area would also suggest sediment-gravity flows as the dominant process.

Fans of type-5 have shallow channels with a meandering pattern on their surface. No debris-flow deposits are recognized from the satellite images. Fluid-gravity flows are characterized by a lack of shear strength and by the maintenance of sediment and water in separate phases during transport. Most of the surface of type-5 is characterised by shallow incised channels that have meandering and braided patterns. Meandering channel patterns are commonly associated with less fluvial networks of lesser power. However, the relatively higher slopes compared to type-1 and type-2 fans would imply the runoff power to be relatively higher. It seems that the absences of walls will cause the channels to flood, which will cause a washout or a sheetflood, as reflected by the less developed braiding pattern. It also explains the coarse boulders found in the proximal part. The floods take place at different times on different fan areas, explaining the differences in surface colours and in the density of the channels. The results reported above indicate that, compared to the main five types, the composite types show outlying values for most geomorphological variables. Their values have extremes implying either sediment-gravity flows or fluid-gravity flows. However if these composite fans should be classified than type-3/4 fans can be interpreted as sediment-gravity controlled, and the type-2/4 fan as fluid-gravity controlled. After analysing the geomorphological variables, the type 3/5 fan is a colluvial fan, which is also possible based on its fan-surface morphology.

Drainage basins and processes

Fans with different surface morphologies are related to drainage basins with different properties. Important variables of the drainage basins define the sedimentary processes that occur on the surface of an alluvial fan. Slopes, along with bedrock type, may determine whether the dominant processes have been for example rockfalls, rock avalanches, debris flows or flash floods. This is related to the accommodation space of the drainage basin. Relief and basin area will determine the volume of available sediment, but the amount of sediment actually reaching the fan will depend on the properties of the drainage network. In general, larger catchments in combination with shallow slopes produce higher flood discharges and therefore more runoff-dominated fans. Smaller catchments with steep slopes produce higher sediment concentrations, coarser sediments and sediment-gravity flow dominated fans (Blair and McPherson, 2009; Harvey, 2011). Type-1 catchments are linked to drainage basins with relatively more active tectonics (most faults, as observed from the geological map) and primarily dominated by extrusive igneous rocks, which can easily be weathered. Therefore enough sediment should be available for sediment-gravity flows. According to many studies, bedrock lithology can be the most important factor for controlling fan depositional processes (Blair, 1999; Blair, 2003; Nichols and Thompson, 2005; Ventra, 2011). However this is only the case when other geomorphic variables are similar between fans (Crosta and Frattini, 2004). In general, catchments dominated by debris flows have a small basin area, higher slopes, a lower relief (but relatively higher, since catchment area is much smaller) and higher Melton-ratio (Scally and Owens, 2004; Rowbotham et al., 2005). Catchments of type-1 fans have intermediate area, a low slope, intermediate relief and low Melton-ratio, which would be in favour of runoff processes. On the contrary, the low sinuosity of the feeder channel (the highest-order channel) indicates the opposite, a mass-flow-controlled basin. Since debris flow moves as a viscous mass in a non-Newtonian, laminar manner, debris flows will not have the ability to move through a feeder channel with a high sinuosity, because the plastic yield strength will not overcome the shear strength. Thus, conditions where a low sinuosity feeder channel is present will be fitting for debris flows. However, a fluid-gravity flow will also continue to flow within a low-sinuosity feeder channel. The great highest-order channel for type-1 catchments, would also not suggest debris-flows to reach the feeder channel. Moreover, drainage density is low for type-1 fans, which would indicate lower sediment supply, another factor in favour of fluid-gravity flows. Apparently runoff-controlled systems will have a more round shape drainage basins (high BA/BP-ratio); if indeed type-1 catchments create fluid-gravity controlled flows, further explained in the geomorphological variables section of the discussion. The hypsometric curves do not give any indication of large accommodation space or steep slopes for catchments of type-1 fans, and thus excluding the production of a large amount of fines in these catchments. Thus, hypsometric curves together with the other geomorphological variables make it more plausible that type-1 catchments are dominated by fluid-gravity flows. According to Strahler (1952), Ohmori (1993) and Perez-Pena (2009), the hypsometric curves describe the stages of geomorphological development of a drainage basin (Figure 30). Convex hypsometric curves characterize young slightly eroded regions; S shaped curves characterize moderately eroded regions; concave curves point to old, highly eroded regions. This may imply that all the drainage basins of all surface morphology types are in a young stage, but this does not match with the fact that the surface of the alluvial fans are dated at 80 to 40 Ka (Hartley et al., 2005). On the other hand, the low amount of fan-surface activity in the Coastal Cordillera could be a good reason for this relatively youthful stage.

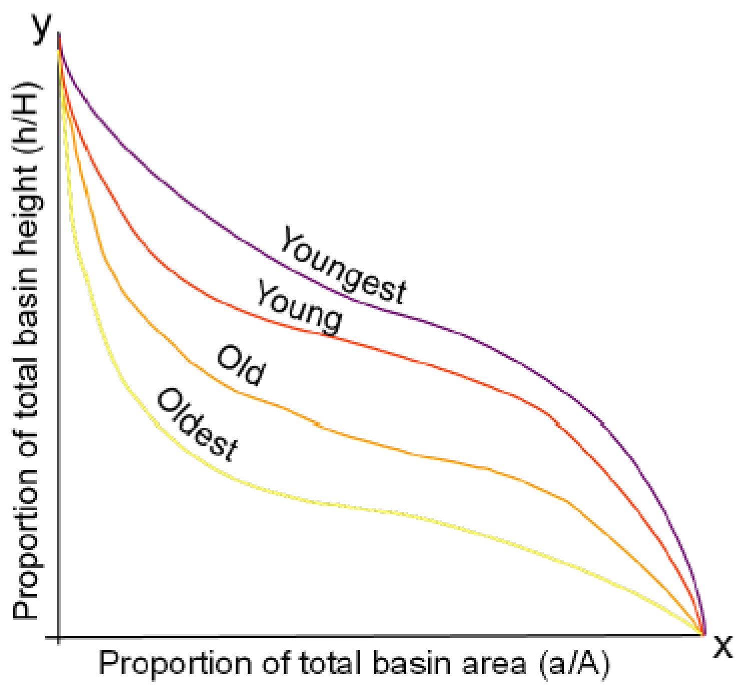

Figure 30: Interpretation of the hypsometric curves according to Strahler (1952), Ohmori (1993) and Perez-Pena (2009).

Type-2 drainage basins are linked to catchments of small area, lowest slopes, a low relief and a low Melton-ratio. This morphology would again be more favourable to fluid-gravity flows, except for the small area. The lowest highest-order channel would indicate less control of fluid-gravity flows. Despite this, sinuosity of the feeder channel is so high that fluid-gravity flows will be the only one that can reach the fan apex. However, type-2 catchments are less fluid-gravity controlled than drainage basins of type-1. This is also confirmed by the hypsometric curves of type-2 catchments, where steeper slopes, flat areas and thus accommodation are more abundant than for type-1 catchments. Type-2 drainage basins also have a lot more intrusive igneous rocks, such as granites and andesites. These rocks should provide a lot less sediment, since they are less sensitive to weathering processes. Nevertheless, this is not an argument that can be taken into account for a catchment controlled by fluid-gravity flows, due to the climate along the Coastal Cordillera. On the coastal fans of the Coastal Cordillera salt weathering is caused by salts released by the coastal fog. This will result in the production of fine sediments (Kwaad, 1970; Hartley et al., 2005). Granites will weather to quartz grains and clay-sized particles; basalts will weather to clay and iron oxide. This will be in favour of the production of debris-flow deposits.

The catchments of type-3 fans seem to possess characteristics favourable to sediment-gravity flows: small areas, great slopes, high relief, high Melton-ratios, low highest-order channel, low BA/BP ratios, a low sinuosity and stepped hypsometric curves. But as already mentioned, this applies probably only in the presence of salt weathering, since the bedrock lithology of type-3 catchments is more dominated by granites then for the other fan types. Perhaps lithology and amount of faults do not influence the system. Though many studies (Blair, 1999; Blair, 2003; Nichols and Thompson, 2005; Ventra, 2011) have shown that lithology can be more important than climate and tectonics in determining the depositional controls (sediment-gravity or fluid-gravity) on alluvial fans, the alluvial fans on the Coastal Cordillera seem not affected by lithology, since climate is more important in generating fine sediments than bedrock lithology. Faults in catchments could be important in controlling processes on alluvial fans, since uplift in the Coastal Cordillera creates the Coastal Scarp and causes a lot of active faults. It could also cause granitic bedrock to be crushed into finer particles within fault zones (Blair, 2003). However faults do not seem to influence the type of fan or the production of finer sediments, since the differences in amount of faults between different catchments are minor. After analysing the first four fans (Appendix 1 and 3), faultlines seem to coincide with the steep slopes at the end of most drainage basins. Despite this, steep slopes at the end of drainage basins are also present without fault zones. The overall uplift seems to be the main reason for the steep Coastal Scarp, and not the regional faulting. Thus lithology or faults are not affecting the types of different types of surface morphology, climate and tectonics are important but similar to all types of fans, and catchment geomorphology is likely the dominant factor for the type of depositional processes. Perhaps in earlier stages of development of the Coastal Cordillera geomorphology was less important, but this analysis considers alluvial fans and drainage basins in their present state.

Continuing with the catchments of type-4 fans, it is clear that they are less dominated by variables favourable to sediment-gravity flows. Especially their large drainage basin areas and the high sinuosities for the feeder channel are not in favour of debris-flows. Hypsometric curves are similar to type-2 catchments. However, their large catchment area creates more changes of parts with steep slopes and flat areas and therefore offers more accommodation space. Catchment slopes are also steeper than for type-2 drainage basins, making it more plausible that sediment will be supplied to the feeder channel.

Type-5 catchments have variables pointing to well-developed runoff-controlled fans. Especially the large basin areas, high sinuosities and large flat areas within the catchments can be more logically linked to effective runoff processes. Outcropping bedrock lithology of type-5 catchments contains more fine-grained sediments then drainage basins of other fan-surface morphology. This could indicate a higher concentration within flows that reach the fan apex. However, it is only 6% more and the absence of steep slopes and thus reduced shear strengths during sediment transport imply that depositional processes from these catchments will be mainly fluidal. Smooth Hypsometric curves do not imply a lot more fine-grained particle production. This supports the previously mentioned inference that geomorphology is the most important control. Another argument for this is revealed by the catchments of fans with composite surfaces, which possess much differentiated values of geomorphic variables compared to other fan types, especially when considering catchment area and Melton-ratio. It is therefore possible that different processes occur on individual fans due to the wide spread of geomorphological variables in their drainage basins.

Geomorphological variables

Statistical analysis can be very sensitive, especially when the amount of samples is very low. This is the case for type-1, type-4 and type-5 fan-surface morphologies. With only four samples for type-1 fans, the statistical significance is potentially low. Especially the one-way ANOVA test is hard to implement on a low sample numbers, since it is based on the assumption of a normal sample distribution. This means that if there is one outlier, the analysis will be disturbed. An alternative approach could have been represented by the Kolmogorov-Smirnov test (Hammer et al., 2001), which is a nonparametric test for overall equal distribution of two univariate samples; in other words, it does not test specifically for equality of mean, variance or any other parameter. A problem with this test is that it requires larger amount of alluvial fans studied and it better applied if only two dominant types of alluvial fans were present, instead of five. The one-way ANOVA test is the best choice for this kind of analysis and can be considered as a good first-order approximation. The results of the one-way ANOVA test do seem to be very logical, since it reaches assumptions such as a normal distribution and an equal variance for most of the variables. The CVA-test confirms the comparisons between the different types of fan surfaces. Type-3 is a very distinctive type of fan-surface morphology and its geomorphological variables are in favour of sediment-gravity flows. Other geomorphological studies, such as Rowbotham et al. (2005), Wilford et al. (2004), Scally and Owens (2004), Kostaschuk et al. (1986) and Crosta and Frattini (2003), chose different statistical methods. However, the aim of these studies was to make distinctions between only two types of fans. The main depositional processes that occur are indeed only two, but that does not result into only two types of alluvial-fan surfaces. As shown by the results of the CVA, it is clear that there are two main depositional processes, but the dynamics between alluvial fans and their drainage basins simply cannot be defined by just two models. The results of previous studies were very different: Rowbotham et al. (2005) concluded that the standard deviation of slope and the standard deviation of aspect are the strongest predictors for differentiating between debris-flow catchments and fluvial catchments; Scally and Owens (2004) mentioned that catchment area and fan slope would be the best indicators to discriminate between debris-flow and runoff catchments; Wilford et al. (2004) consider catchment Melton-ratio and watershed length to be the most appropriate discriminants; Kostaschuk et al. (1986) found that fan slope and catchment Melton-ratio will determine the different fan types; Crosta and Frattini (2003) indicate that catchment area and average slope are most important to differentiate between debris flows and fluid-gravity flows. They do mention that amount of runoff and non-erodibility of bedrock is also very important. Heavy rainfall can cause landslides and will change a geomorphically controlled fluid-gravity flow into a sediment-gravity flow, due to the sudden availability of loose sediment. Non-erodibility of bedrock can change a potential debris-flow fan into a fluid-gravity flow fan. Since rainfall and lithology seem to be similar for all types of fans on the Coastal Cordillera, this has no effect. It is important to mention that the studies done by Rowbotham et al. (2005), Scally and Owens (2004), Wilford et al. (2004), Kostaschuk et al. (1986) and Crosta and Frattini (2003) show contradictory results in what can be considered the best discriminants. In this study about the alluvial fans in the Coastal Cordillera, other variables, the BA/BP-ratio and the basin slope are determined as the most important differentiators. Aspect has not been taken into account in this study because in the research of Rowbotham et al. (2005) all debris-flow fans happen to be on one side of the Cascade Mountains of south-western British Columbia (Canada) and runoff-controlled fans on the other side. That was not the case in this study, since most fans examined were on the coastal side of the Coastal Cordillera, and there was no difference in aspect between the types of fan-surface morphologies. All other variables of importance in the studies done by Rowbotham et al. (2005), Scally and Owens (2004), Wilford et al. (2004), Kostaschuk et al. (1986) and Crosta and Frattini (2003), such as catchment area and fan slope, resulted to be also important in the this study, except for basin Melton-ratio and especially watershed-length. A reason that the BA/BP-ratio is not found to be important the studies done by Rowbotham et al. (2005), Scally and Owens (2004), Wilford et al. (2004), Kostaschuk et al. (1986) and Crosta and Frattini (2003) could be that it was simply not taken into account. The most important aspect of the present study is that many more variables have been taken into account compared to previous studies, which is a good reason for explaining these differences between this present study and the previously done. In this study, more rounded catchment shapes (large BA/BP-ratios) coincides with larger basin areas, low

Melton-ratios and higher sinuosities for the feeder channel. This could mean that mass-flow catchments develop laterally in one direction and fluid-gravity flow catchments develop laterally in all directions. Again this can be explained by the behaviour of a mass-flow. As mentioned a debris-flow is not able to continue along a channel with a high sinuosity. Therefore a more rectangular shaped catchment (low BA/BP-ratio) will make it easier for the plastic yield strength to overcome the shear strength. So, a fluid-gravity controlled catchment will have fewer problems creating a more complex network of channels developing laterally in all directions causing a more rounded catchment shape. This round shape coincides with a larger catchment area, which usually means that we are dealing with more developed catchments. Unfortunately, this cannot be proven for fan-catchment dynamics in other regions of the world, since other studies have not implemented the BA/BP-ratio. Nevertheless for the alluvial fans in the Coastal Cordillera (Atacama Desert, Chile), the BA/BP-ratio seems to be a very important indicator.

Important geomorphic relationships were also established in this study. The most important ones are (Bull 1977; Harvey 1997; Scally and Owens, 2004; Harvey, 2011): (1) $F = {}_pA^q$ and (2) $G = -{}_aA^b$, based on the fact that sediment discharge will increase when drainage area increases, resulting in higher flow velocity and bed shear stress. Thus, the flow is capable of transporting on a lower slope the same material transported by smaller discharges on a higher slope. These relationships are also found in the results of comparisons of the geomorphological variables between the different types of fan-surface morphologies. It is for sure that type-3 fans are debris-flow fans and have small areas, small catchments areas and steep fan slopes, while the opposite holds for runoff-dominated fans. According to the one-way ANOVA test, it is also statistically significant. However, according to the CVA there is only a tenuous relationship between fan area and catchment area, and none at all between catchment area and fan slope. This can be explained by the fact that most alluvial fan surfaces are limited distally by the coastal erosion or by land use, such as road construction and mining, causing a disturbance in the natural causal relations. An important relationship observed in this study occurs between catchment slope and drainage density. These two variables are strong in defining different types of fan-surface morphology. They show a good statistical value in the one-way ANOVA test and they have large canonical loadings in the CVA-test. These two variables are also logical for predicting the occurrence of debris-flows. An increase in drainage density together with an increase in catchment slope will cause more capacity for sediment to be supplied to the alluvial fan, and therefore a sediment-gravity controlled alluvial fan will be expected when these two geomorphological variables are relatively high.

Conclusions

The alluvial fans along the Coastal Cordillera of the Atacama Desert (northern Chile) have five different main types of fan-surface morphologies. There are various geomorphological and geological causes for the occurrence of different primary and secondary processes on fan surfaces. The main causes are tectonics, bedrock lithology, climate and geomorphology. Since alluvial fans in the Coastal Cordillera (Atacama Desert, Chile) have equal conditions for tectonics, lithology and climate, it must be concluded that geomorphology is the main control for causing different types of depositional processes to occur on alluvial fans, eventually causing different types of fan-surface morphologies. Type-3 fan-surface morphologies is controlled by sediment-gravity flows and is linked to specific geomorphological values: small fan areas, steep fan slopes, small basin areas, great basin slopes, high relief, high basin Melton-ratio, low highest-order channel, low BA/BP ratio, a low sinuosity for the feeder channel and stepped hypsometric curves. It is concluded that these characteristics can be used to determine a sediment-gravity controlled alluvial fan. Not only the geomorphological variables, but also visual inspection of satellite imagery can detect sediment-gravity controlled deposits on the surface of alluvial fans. These are levees, lobes and boulders found in proximal, central and distal parts of the fan. For the fluid-gravity controlled alluvial fans, the geomorphological values are opposite to the sediment-gravity controlled alluvial fans. However there is not one type of fan-surface morphology linked to exactly the opposite values as type-3 fans. This is the main reason that causes the diversity in types of fan-surface morphology. Type-4 fans tending to be more sediment-gravity controlled alluvial fans. Type-1, type-2 and type-5 fans tend to be more fluid-gravity controlled. However, based on geomorphological variables and on fan-surface morphology, type-5 fans are quite different compared to type-1 and type-2 fans. A challenge is that the surfaces of fluid-gravity controlled alluvial fans are more reworked by secondary processes and therefore a visual inspection of deposits cannot be done on satellite imagery. Based on statistical analysis, the main differentiators between different types of surface morphology are in decreasing order: the BA/BP-ratio, basin slope, basin area, drainage density, fan radius, fan slope, fan width and fan area. Previous studies found different differentiators. This is because the influence of each geomorphological variable changes for each specific location, due to the complex dynamics between alluvial fans and drainage basins. For the alluvial fans in the Coastal Cordillera (Atacama Desert, Chile) the BA/BP-ratio is the most important differentiator between different types of fan-surface morphology. From this I conclude that the shape and amount of development of catchments are very important features in this region for determining depositional processes on alluvial fans. Larger well developed basins have a more pronounced round shape and are fluid-gravity controlled. Smaller undeveloped basins match with a rectangular shape and are linked to sediment-gravity controlled processes. The most important geomorphological relationship is between basin slope and drainage density. These two variables are also important indicators for sediment-gravity controlled flow on alluvial fans. In retrospect, a visual and analysing inspection on the geomorphological and geological aspects of alluvial fans prooved to be usefull. Although, next time more samples should be used to make statistical analysis more significant and a DEM and geological map with a higher resolution would give more detail. To solve problems such as a lack of visual inspection on reworked surfaces and information on the type of deposits, a future field-work should be done.

Guidelines for future fieldwork

Future fieldwork might be possibly organized on the alluvial fans of the Coastal Cordillera (Atacama Desert, Chile). The most important goal should be a large-scale investigation of the types of deposits present on the fans. Especially for reworked surfaces, it is very important to recognize what kinds of deposits are buried underneath the exposed surface. Bear in mind that the deposits can solely reflect the local flow conditions and sediment availability, not the entire environmental setting of the drainage basin of alluvial fans. Therefore the exact locations for fieldwork should be set appropriate. It should be possible to test whether the geomorphological variables here considered determinant for sediment-gravity flows and fluid-gravity flows are correct and whether the fan types have been correctly categorized. If possible, samples of the surface should be taken on different parts of the alluvial fan for dating; the desert varnish would be particularly useful to this aim (Dorn, 2009; Dickerson, 2011). With the available information, it should be possible to predict the types of geomorphic activity characterizing each fan (Bovis and Jakob, 1999). For drainage basins, bedrock lithology and fault density should be investigated at a smaller scale than on the geological map of Chile, in order to ascertain whether catchment lithology has any influence on the dominant processes occurring on alluvial fans.

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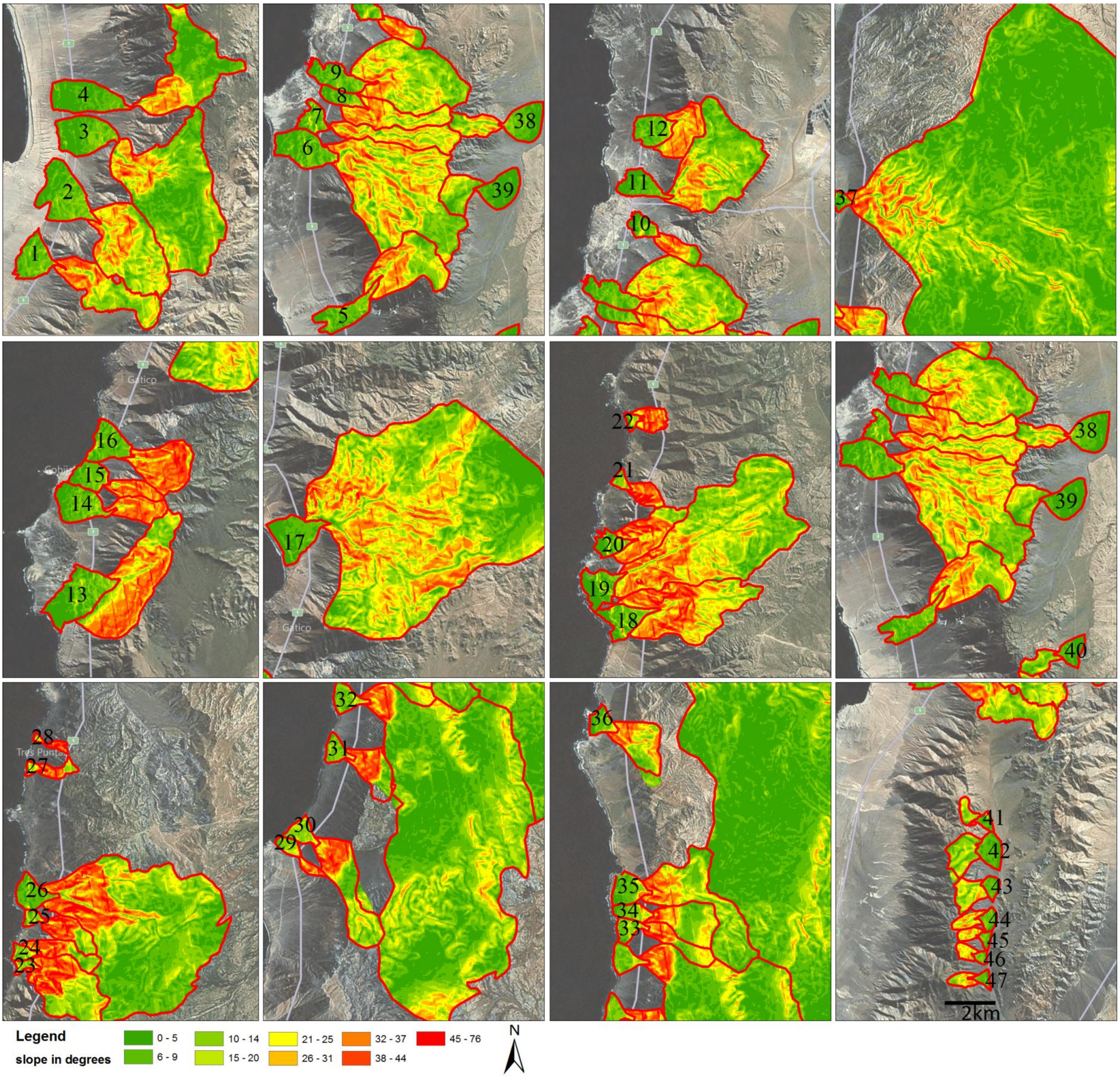
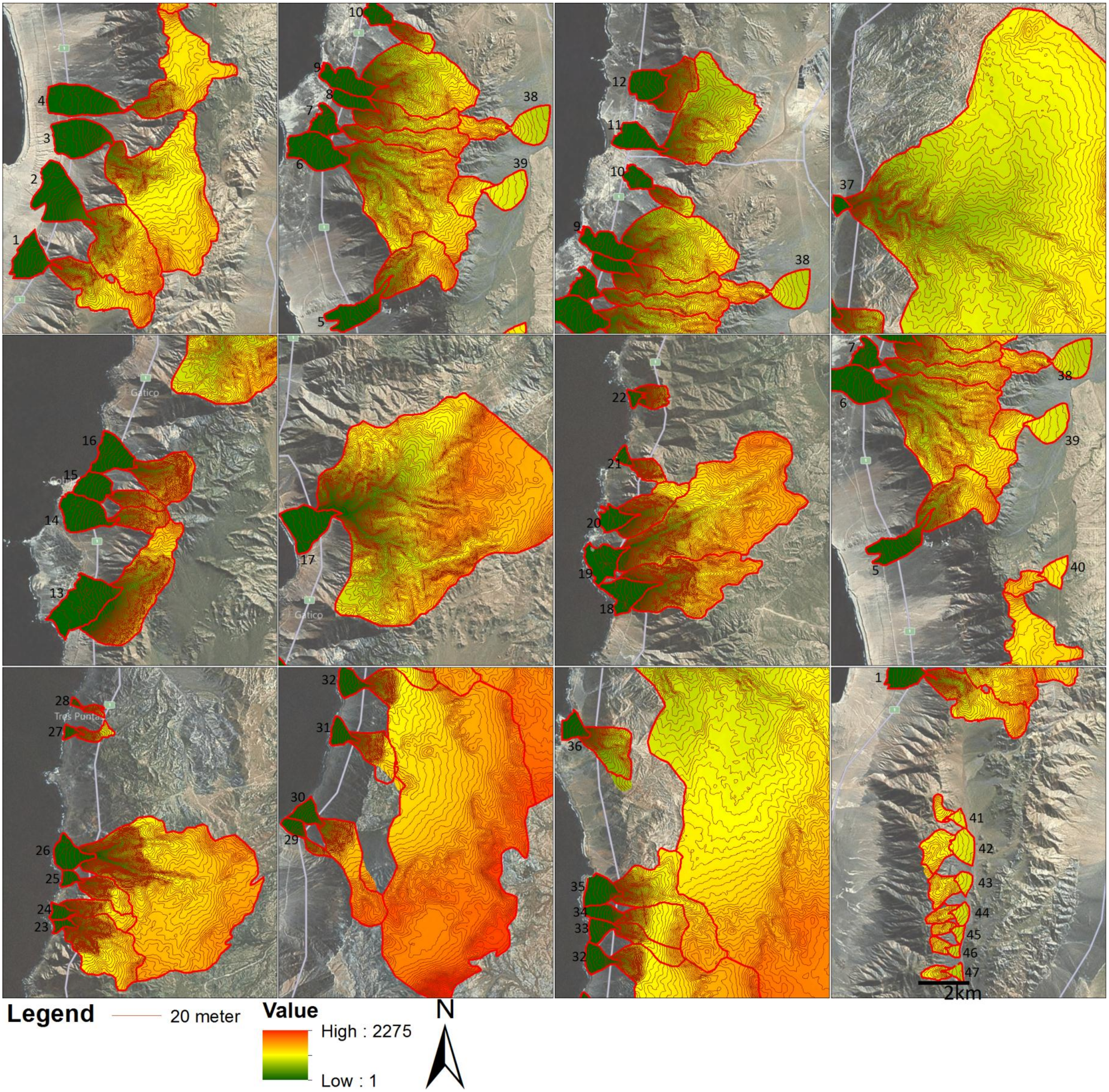
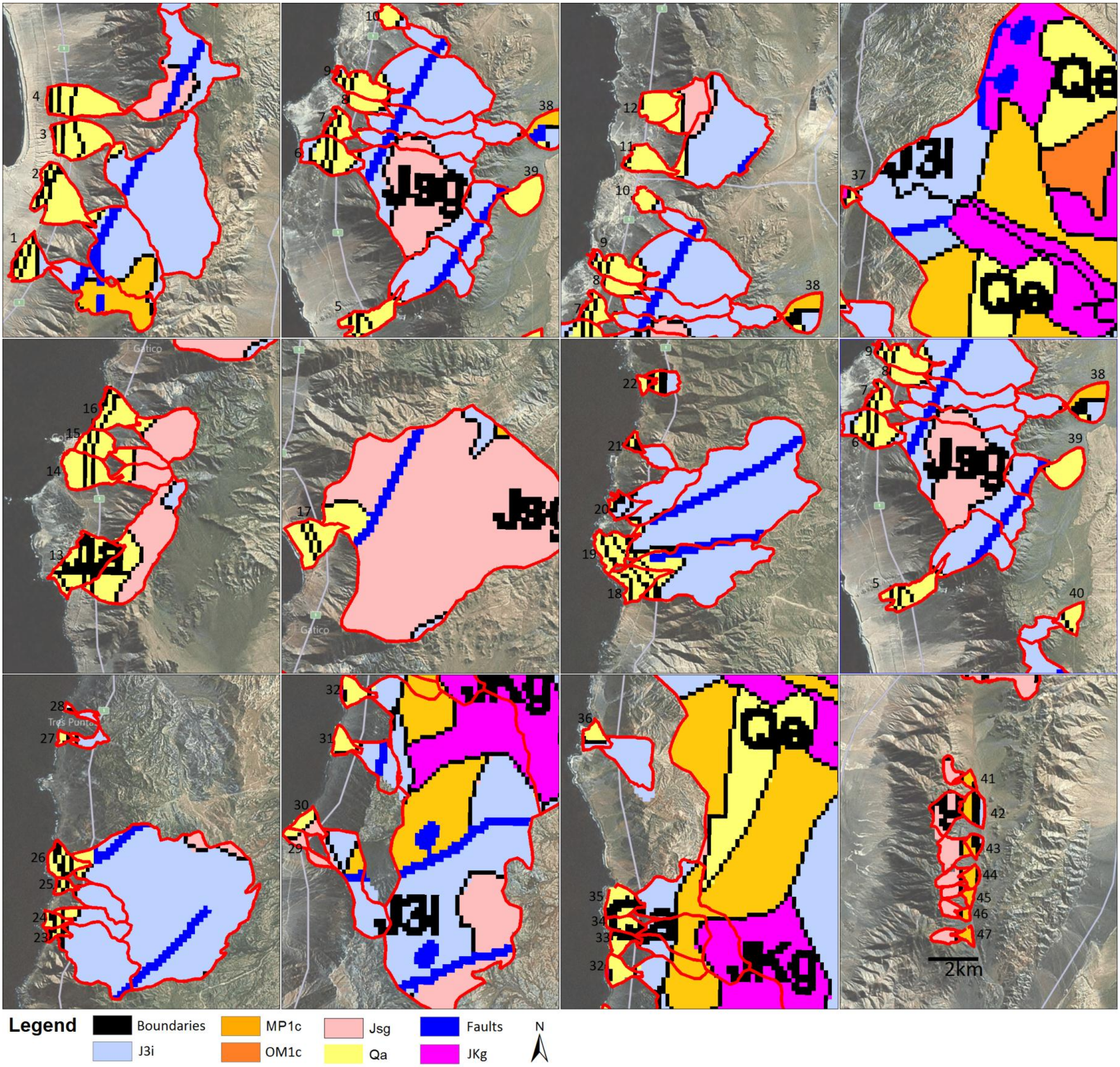
Appendix 1: Slope.



Appendix 2: DEM and Contour.



Appendix 3: Geological map of alluvial fans and drainage basins.



Appendix 4: Variables: Basin area, Basin Height, Basin Slope, Basin Aspect.

	Basin Area	Basin Height Mean	Basin Height St.Dev	Basin Slope Mean	Basin Slope St.Dev	Basin Aspect Mean	Basin Aspect St.Dev
Fan 1	53.14	1004.28	278.74	20.15	10.36	238.69	91.59
Fan 2	84.15	1040.73	270.96	20.51	8.81	255.9	87.24
Fan 3	175.7	1073.26	201.73	12.14	8.99	218.54	117.24
Fan 4	84.55	1091.12	204.05	12.56	10.68	227.82	80.32
Fan 5	54.69	1000.46	282.38	21.24	10.16	242.37	64.76
Fan 6	170.85	952.8	255.76	20.22	9.4	219.55	109.17
Fan 7	37.62	910.75	289.33	21.11	8.21	250.05	87.24
Fan 8	35	762.09	299.02	23.47	8.89	257.57	90
Fan 9	100.2	844.17	250.13	17.36	8.47	249.18	87.78
Fan 10	13.1	686.92	224.55	24.73	11.87	259.46	103.47
Fan 11	106.22	781.92	168.78	15.18	9.5	239.14	87.03
Fan 12	25.74	486.19	188.3	28.81	8.38	271.69	41.73
Fan 13	88.89	751.7	361.26	26.36	11.04	254.9	59.74
Fan 14	18.66	850.31	302.09	31.09	7.98	274.26	44.93
Fan 15	13.26	697.19	293.74	31.2	8.27	280.4	62.23
Fan 16	39.44	882.55	342.04	33.87	8.77	274.36	76.3
Fan 17	655.39	1108.8	325	17.41	9.96	212.16	94.57
Fan 18	91.72	932.03	394.41	27.38	10.92	251.42	70.55
Fan 19	229.81	1153.21	335.11	17.63	9.88	232.88	83.63
Fan 20	34.23	639.05	329.26	27.94	12.17	239.61	54.84
Fan 21	10.17	704.43	270.11	36.11	11.18	300.66	42.23
Fan 22	10.53	474.67	227.77	33.52	10.83	271.89	32.97
Fan 23	63.63	1004.58	310.93	23.68	13.48	255	89.65
Fan 24	18.71	843.01	358.12	24.13	13.46	257.28	70.53
Fan 25	19.19	857.44	295.13	27.95	13.98	272.69	79.09
Fan 26	319.79	1197.19	291.48	14.42	11.57	218.69	110.71
Fan 27	6.78	675.21	242.55	25.8	11.9	267.91	36.19
Fan 28	2.61	646.98	205.01	36.22	9.17	293.85	14.63
Fan 29	5.77	683.94	183.33	30.93	7.58	276.24	89.65
Fan 30	51.62	1283.19	374.44	20.36	12.64	228.95	121.08
Fan 31	24.96	928.36	306.09	24.24	14.54	247.69	103.07
Fan 32	688.51	1483.37	241.28	10.59	7.5	238.91	99.91
Fan 33	19.22	941.63	291.96	22.48	11.78	269.97	57.04
Fan 34	34.26	941.63	291.96	22.48	11.78	269.97	57.04
Fan 35	84.53	1101.57	302.77	15.79	10.19	225.95	98.37
Fan 36	30.6	663.46	176	21.58	10.3	255.26	75.05
Fan 37	2722.24	1209.22	269.2	6.91	5.6	209.97	109.44
Fan 38	15.68	1255.57	73.05	16.48	8.45	119.9	116.58
Fan 39	18.89	1177.9	70.57	12.43	6.71	162.79	88.52
Fan 40	10.19	1330.18	50.35	10.08	4.44	128.31	95.77
Fan 41	5.42	1125.29	77.7	13.06	5.13	146.98	49.49
Fan 42	16.11	1109.33	47.24	11.19	4.88	157	117.3
Fan 43	12.45	1123.37	70.43	16.62	6.69	139.39	107.96
Fan 44	6.89	1129.9	88.66	22.15	7.82	98.71	62.4
Fan 45	6.89	1114.03	91.95	21.13	7.29	99.75	33.27
Fan 46	4.42	1087.47	88.03	20.22	6.35	107.61	24.56
Fan 47	5.38	1026.11	67.6	17.66	8.17	110.64	81.09

Appendix 5: Variables: Highest-order Length, Sinuoisity, Basin Perimeter.

	Highest order Length	As the Crow Flies	Sinuosity	Highest order Length 25%	As the Crow Flies 25%	Sinuosity 25%	Basin Perimeter
Fan 1	2777.187916	1818.66	1.527052	694.296979	441.71	1.571838942	14.71
Fan 2	3622.815328	2707.6	1.338017	905.703832	764.2	1.185165967	13.64
Fan 3	2207.581773	1667.05	1.324244	551.895443	490.61	1.124916824	20.76
Fan 4	2087.516043	1871.84	1.115221	521.879011	515.24	1.012885279	16.85
Fan 5	1612.618907	1487.29	1.084267	403.154727	399.9	1.008138852	12.8
Fan 6	5746.686137	4435.43	1.295632	1436.671534	1012.8	1.418514548	21.48
Fan 7	5735.379951	4271.35	1.342756	1433.844988	1194.07	1.2008048	12.77
Fan 8	3904.786403	3016.96	1.294278	976.196603	783.15	1.246500163	12.41
Fan 9	361.404176	322.8	1.119592	90.351044	83.97	1.07599195	14.59
Fan 10	1563.157661	1392.19	1.122805	390.789415	387.1	1.009530909	5.29
Fan 11	2663.500248	2335.57	1.140407	665.875062	642.83	1.035849388	15.58
Fan 12	207.097699	204.8	1.011219	51.774425	51.68	1.001827109	8.07
Fan 13	1874.644941	1772.68	1.05752	468.661235	460.17	1.018452387	16.18
Fan 14	1598.294789	1490.08	1.072623	399.573697	380.38	1.05045927	6.99
Fan 15	1622.948316	1535.31	1.057082	405.737079	399.95	1.014469506	5.95
Fan 16	644.238523	589.43	1.092986	161.059631	151.61	1.062328547	8.96
Fan 17							35.46
Fan 18	2790.052672	2590.96	1.076841	697.513168	640.98	1.088198022	17.85
Fan 19	4827.564671	4298.3	1.123133	1206.891168	1137.1	1.061376456	24.59
Fan 20	908.474875	893.46	1.016805	227.118719	226.46	1.002908765	10.28
Fan 21	1358.906944	1195.17	1.136999	339.726736	327.41	1.037618692	4.6
Fan 22	804.024509	780.822263	1.029715	201.006127	199.98	1.005131148	5.18
Fan 23	1005.441333	948.39	1.060156	251.64718	216.49	1.162396323	12.16
Fan 24	2491.401985	1878.96	1.325947	622.850496	619.58	1.005278569	9.11
Fan 25	1941.467788	1598.71	1.214396	485.366947	481.82	1.00736156	6.75
Fan 26							28.77
Fan 27	1058.535488	917.82	1.153315	264.633872	261.85	1.010631552	5.04
Fan 28	428.281043	414.73	1.032674	107.070261	106.83	1.002249003	2.79
Fan 29	755.490233	719.84	1.049525	188.872558	188.21	1.003520312	3.11
Fan 30	4848.115055	4313.77	1.12387	1212.028739	1158.64	1.046078798	13.04
Fan 31	1204.301953	1166.98	1.031982	301.075488	294.56	1.022119392	7.91
Fan 32							43.28
Fan 33	1753.788033	1612.16	1.08785	438.447008	433.56	1.011271815	8.3
Fan 34	251.164208	248.24	1.01178	62.791052	62.75	1.000654215	8.65
Fan 35	1262.405851	1081.33	1.167457	315.601463	314.03	1.005004181	18.7
Fan 36	2534.944472	2035.5	1.245367	633.736118	566.12	1.119437784	8.06
Fan 37							75.98
Fan 38	668.645181	662.03	1.009992	167.161295	166.62	1.00324868	6.24
Fan 39	80.191032	79.51	1.008565	20.047758	20.01	1.001886957	6.08
Fan 40	1322.971212	1180.42	1.120763	330.742803	235.26	1.405860763	5.3
Fan 41	920.56056	702.09	1.311172	230.14014	223.35	1.030401343	4
Fan 42	1454.850335	963.15	1.510513	362.962584	355.78	1.020188274	5.87
Fan 43	873.398828	790.64	1.104673	218.349707	218.35	0.999998658	5.06
Fan 44	779.225999	720.61	1.081342	194.8065	177.41	1.09805817	4.41
Fan 45	657.316889	601.72	1.092397	164.329222	156.74	1.048419178	2.9
Fan 46	571.6615	559.01	1.022632	142.915375	142.43	1.003407814	3.14
Fan 47	539.723955	443.52	1.21691	134.930989	133.72	1.009056155	3.92

Appendix 6: Variables: Basin Length, Basin Crest, Basin End, First-order channel length, Amount of first-order channels, Total channel length, Drainage Density.

	Basin Length	Basin Crest	Basin End	First-order channel length	Amount of first-order channels	Total channel length	Drainage Density
Fan 1	1.78	1508	297	40.53	552	67.52	1.270605947
Fan 2	3.87	1562	364	36.86	381	70.63	0.839334522
Fan 3	6.46	1511	326	120.54	1262	223.87	1.274160501
Fan 4	6	1389	360	95.77	923	153.38	1.814074512
Fan 5	2.76	1501	337	41.91	363	64.57	1.180654599
Fan 6	6.64	1459	171	161.73	1638	236.95	1.386889084
Fan 7	5.29	1404	204	32.06	263	45.77	1.216640085
Fan 8	3.5	1296	143	32.82	285	44.74	1.278285714
Fan 9	3.77	1289	191	73.41	826	121.49	1.21247505
Fan 10	1.9	982	199	12.03	106	18.7	1.427480916
Fan 11	4.74	1047	188	103.94	1204	167.43	1.576256825
Fan 12	1.13	831	73	22.08	131	29.44	1.143745144
Fan 13	3.69	1476	39	46.35	128	60.76	0.683541456
Fan 14	2.11	1427	248	16.78	117	23.85	1.278135048
Fan 15	2.33	1386	189	12.16	113	17.59	1.326546003
Fan 16	2.44	1557	170	30.96	208	46.57	1.180780933
Fan 17	10.63	1695	111				
Fan 18	4.32	1471	52	68.45	411	95.85	1.045028347
Fan 19	7.86	1618	64	259.8	2802	386.07	1.679953005
Fan 20	2.44	1204	74	24.38	164	33.52	0.979257961
Fan 21	1.48	1181	139	5.95	29	8.73	0.85840708
Fan 22	1.14	888	44	5.95	18	6.61	0.627730294
Fan 23	3.33	1465	105	72.57	808	105.78	1.662423385
Fan 24	2.55	1297	63	20.72	168	27.71	1.481026189
Fan 25	2.42	1257	195	25.01	210	34.64	1.805106826
Fan 26	7.69	1589	116				
Fan 27	1.28	1009	156	7.32	72	10.75	1.585545723
Fan 28	0.91	999	232	3.32	52	4.96	1.900383142
Fan 29	1.4	1115	324	6.96	36	8.51	1.474870017
Fan 30	4.8	1750	270	44.94	425	75.23	1.45738086
Fan 31	2.21	1278	154	28.62	340	45.51	1.823317308
Fan 32	14.94	2275	221				
Fan 33	3.05	1419	222	23.72	167	35.88	1.866805411
Fan 34	2.76	1419	222	50.82	580	78.39	2.288091068
Fan 35	6	1493	209	84.8	1087	132.22	1.564178398
Fan 36	2.5	974	121	26.18	196	40.68	1.329411765
Fan 37	23.75	1827	28				
Fan 38	2.08	1407	1043	6.8	29	9.63	0.614158163
Fan 39	1.49	1390	1031	14.5	76	22.12	1.170989942
Fan 40	1.59	1442	1194	10.2	98	14.58	1.430814524
Fan 41	1.18	1300	999	2.17	11	3.1	0.57195572
Fan 42	1.53	1243	1007	11.03	69	14.95	0.927995034
Fan 43	1.52	1254	938	10.73	84	15.05	1.208835341
Fan 44	0.99	1287	939	8.01	63	10.01	1.452830189
Fan 45	0.77	1261	914	3.33	20	4.27	0.619738752
Fan 46	0.72	1245	909	3.73	25	4.68	1.058823529
Fan 47	0.84	1126	865	5.21	33	6.31	1.172862454

Appendix 7: Variables: Basin Relief, Basin Melton-ratio, Basin Relief-ratio, Basin Elevation/Relief-ratio, Fan Area, Fan Height, Fan Slope.

	Basin Relief	Basin Melton Ratio	Basin Relief Ratio	Basin Elevation-Relief Ratio	Fan Area	Fan Height Mean	Fan Height St.Dev	Fan Slope Mean
Fan 1	1.211	0.02278886	0.680337079	584.0462428	20.3	165.15	51.28	7.18
Fan 2	1.198	0.014236482	0.309560724	564.8831386	37.78	163.42	80.57	6.66
Fan 3	1.185	0.006744451	0.183436533	630.5991561	31.02	137.75	63.89	5.92
Fan 4	1.029	0.012170313	0.1715	710.5150632	32.7	135.15	62.93	4.63
Fan 5	1.164	0.021283598	0.42173913	569.9828179	20.94	164.35	101.93	7.37
Fan 6	1.288	0.007538777	0.193975904	606.9875776	27.67	104.67	64.03	6.34
Fan 7	1.2	0.031897927	0.2268431	588.9583333	10.94	98.09	36.48	7.59
Fan 8	1.153	0.032942857	0.329428571	536.9384215	9.87	142.41	65.37	7.24
Fan 9	1.098	0.010958084	0.291246684	594.8724954	18.78	114.13	77.93	6.75
Fan 10	0.783	0.059770992	0.412105263	623.1417625	8.86	102.84	44.07	7.23
Fan 11	0.859	0.008086989	0.181223629	691.4086147	15.7	61.62	51.15	5.12
Fan 12	0.758	0.029448329	0.67079646	545.1055409	17.13	113.98	51.89	7.93
Fan 13	1.437	0.016166048	0.389430894	495.9638135	39.33	83.06	66.3	5.93
Fan 14	1.179	0.06318328	0.558767773	510.8651399	24.97	86.5	69.92	6.5
Fan 15	1.197	0.090271493	0.513733906	424.5530493	14.67	71.67	47.15	7.19
Fan 16	1.387	0.035167343	0.568442623	513.7346792	20	90.12	55.19	7.47
Fan 17	1.584	0.002416882	0.14901223	629.9242424	26.97	61.87	46.38	5.05
Fan 18	1.419	0.015470999	0.328472222	620.1761804	18.67	87.87	69.44	8
Fan 19	1.554	0.006762108	0.197709924	700.9073359	18.26	43.03	41.2	5.62
Fan 20	1.13	0.033011978	0.463114754	500.0442478	10.39	58.05	50.29	6.8
Fan 21	1.042	0.10245821	0.704054054	542.6391555	3.83	60.38	51.22	11.96
Fan 22	0.844	0.080151947	0.740350877	510.2725118	3.26	54.27	45.71	10.51
Fan 23	1.36	0.021373566	0.408408408	661.4558824	36.62	104.88	55.94	12.03
Fan 24	1.234	0.065954035	0.483921569	632.0988655	5.19	97.62	65.24	11.54
Fan 25	1.062	0.055341324	0.438842975	623.7664783	4.23	79.68	49.96	10.94
Fan 26	1.473	0.004606148	0.191547464	734.0054311	14.38	69.64	47.34	6.7
Fan 27	0.853	0.125811209	0.66640625	608.6869871	2.65	79.96	67.37	14.86
Fan 28	0.767	0.293869732	0.842857143	541.0430248	1.28	67.41	54.72	15.4
Fan 29	0.791	0.137088388	0.565	455.0442478	3.9	105.33	67.86	12.54
Fan 30	1.48	0.028671058	0.308333333	684.5878378	9.31	130.39	78.81	12.57
Fan 31	1.124	0.045032051	0.508597285	688.9323843	8.11	94.41	62.42	10.47
Fan 32	2.054	0.002983254	0.137483266	614.5910419	10.58	94.38	64.7	10.5
Fan 33	1.197	0.062278876	0.392459016	601.1946533	8.23	93.29	66.4	10.32
Fan 34	1.197	0.034938704	0.433695652	601.1946533	9.12	93.29	66.4	10.32
Fan 35	1.284	0.015189873	0.214	695.1479751	14.67	90.48	59.34	8.99
Fan 36	0.853	0.027875817	0.3412	635.943728	9	54.35	49.09	7.9
Fan 37	1.799	0.000660853	0.075747368	656.5981101	4.29	29.54	12.64	5.15
Fan 38	0.364	0.023214286	0.175	583.9835165	19.75	896.79	50.08	6.09
Fan 39	0.359	0.019004764	0.240939597	409.1922006	18.43	980.13	30.62	4
Fan 40	0.248	0.024337586	0.155974843	549.1129032	8.92	1150.1	25.07	4.54
Fan 41	0.301	0.055535055	0.255084746	419.5681063	3.4	985.82	18.95	5.69
Fan 42	0.236	0.014649286	0.154248366	433.6016949	11.02	974.97	25.95	5.34
Fan 43	0.316	0.025381526	0.207894737	586.6139241	4.79	948.84	22.62	6.36
Fan 44	0.348	0.050507983	0.351515152	548.5632184	4.72	919.77	26.69	7.07
Fan 45	0.347	0.050362845	0.450649351	576.4553314	4.72	890.11	22.85	6.52
Fan 46	0.336	0.0760181	0.466666667	531.1607143	2.35	887.39	27.53	8.83
Fan 47	0.261	0.048513011	0.310714286	617.2796935	3.12	845.03	28.19	6.54

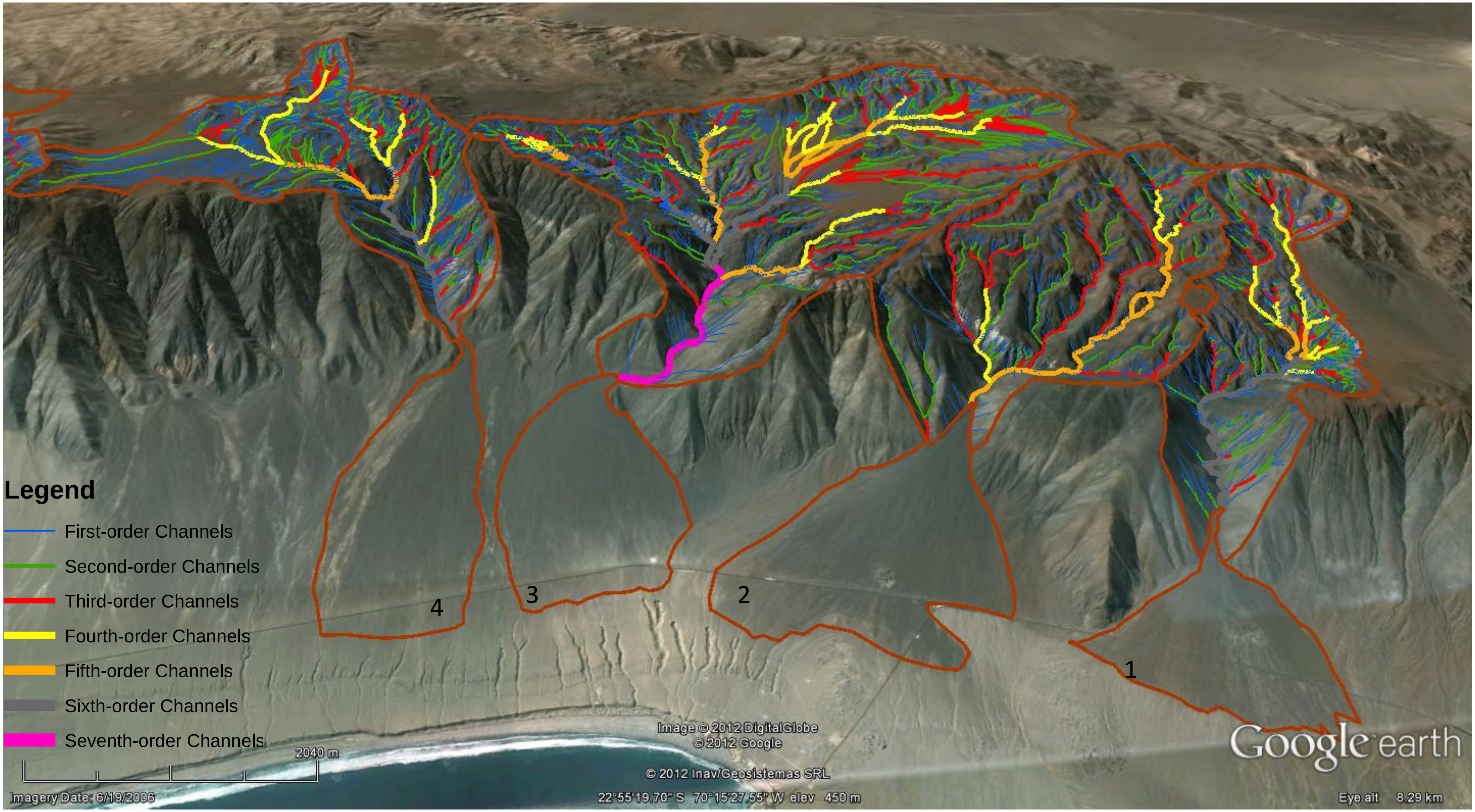
Appendix 8: Variables: Fan Aspect, Fan Perimeter, Fan Apex, Fan Toe, Fan Concavity, Fan Relief, Fan Melton-ratio, Fan Elevation/Relief-ratio.

	Fan Slope St.Dev	Fan Aspect Mean	Fan Aspect St.Dev	Fan Perimeter	Fan Apex	Fan Toe	Fan Concavity	Fan Relief	Fan Melton Ratio	Fan Elevation-Relief Ratio
Fan 1	3	266.34	64.88	7.39	401	84	0.219138057	0.317	0.015615764	255.9936909
Fan 2	3.24	280.04	73.35	9.66	453	55	0.224089636	0.398	0.010534674	272.4120603
Fan 3	3.4	252.02	62.2	7.24	338	53	0.348017621	0.285	0.009187621	297.3684211
Fan 4	2.3	268.83	57.88	8.38	362	45	0.325102881	0.317	0.00969419	284.384858
Fan 5	3.58	224	46.97	9.04	551	43	0.177072671	0.508	0.02425979	238.8779528
Fan 6	3.43	264.8	58.95	7.21	301	8	0.248447205	0.293	0.010589086	329.9317406
Fan 7	4.46	240.2	96.72	5.51	228	49	0.287958115	0.179	0.016361974	274.2458101
Fan 8	3.81	275.32	45.9	4.97	356	47	0.581027668	0.309	0.031306991	308.7702265
Fan 9	3.25	265.78	56.06	8.68	384	7	0.506706408	0.377	0.020074547	284.1644562
Fan 10	4.92	256.88	92.73	4.28	242	56	0.418539326	0.186	0.020993228	251.827957
Fan 11	2.84	275.88	64.27	6.17	271	5	0.555555556	0.266	0.016942675	212.8571429
Fan 12	3.56	253.89	36.74	5.36	282	32	0.175925926	0.25	0.014594279	327.92
Fan 13	3.97	235.98	63.27	9.66	334	1	1.164294955	0.333	0.008466819	246.4264264
Fan 14	3.65	277.14	62.5	7.42	369	7	0.39184953	0.362	0.014497397	219.6132597
Fan 15	3.67	286.02	58.43	5.05	227	6	0.412121212	0.221	0.015064758	297.1493213
Fan 16	3.31	285.03	46.41	6.51	262	4	0.007905138	0.258	0.0129	333.7984496
Fan 17	2.32	236.46	49.45	7.49	211	1	0.181378476	0.21	0.007786429	289.8571429
Fan 18	5.21	244.69	53.06	7.2	323	1	0.09603073	0.322	0.01724692	269.7826087
Fan 19	4.7	222.14	72.41	6.92	202	1	0.231707317	0.201	0.011007667	209.1044776
Fan 20	5.02	261.9	42.39	5.55	247	1	0.64507772	0.246	0.023676612	231.9105691
Fan 21	6.54	302.14	33.67	2.78	234	1	0.583220568	0.233	0.060835509	254.8497854
Fan 22	6.63	250.32	50.78	3	214	2	0.160771704	0.212	0.065030675	246.5566038
Fan 23	4.86	267.81	31.1	3.31	260	18	0.127226463	0.242	0.006608411	359.0082645
Fan 24	4.99	275.61	20.11	3.39	331	9	0.438596491	0.322	0.062042389	275.2173913
Fan 25	4.94	280.04	22.32	2.98	243	10	0.113960114	0.233	0.055082742	299.055794
Fan 26	2.89	265.38	49.57	5.33	213	4	0.101317123	0.209	0.014534075	314.0669856
Fan 27	7.49	274.98	15.26	2.61	329	8	0.621004566	0.321	0.121132075	224.1744548
Fan 28	7.97	287.27	14.67	1.71	231	3	0.204708291	0.228	0.178125	282.5
Fan 29	5.8	312.29	14.59	3.07	321	9	0.60483871	0.312	0.08	308.75
Fan 30	4.09	312.29	14.59	4.63	376	14	0.164041995	0.362	0.038882922	321.519337
Fan 31	4.17	284.21	30.16	4.21	334	14	0.299145299	0.32	0.03945746	251.28125
Fan 32	5.07	284.21	30.16	4.63	355	17	0.546341463	0.338	0.03194707	228.9349112
Fan 33	4.39	262.94	21.45	4.22	337	13	0.318416523	0.324	0.039368165	247.808642
Fan 34	4.39	262.94	21.45	4.14	337	13	0.501367366	0.324	0.035526316	247.808642
Fan 35	6.75	273.59	33.4	5.1	327	16	0.624349636	0.311	0.021199727	239.4855305
Fan 36	5.46	278.8	61.57	4.17	230	6	0.878594249	0.224	0.024888889	215.8482143
Fan 37	2.98	224.41	90.82	2.72	82	9	1.105527638	0.073	0.017016317	281.369863
Fan 38	2.88	82.15	34.62	5.68	1077	815	0.347666972	0.262	0.013265823	312.1755725
Fan 39	1.58	94.12	46.33	5.59	1072	929	0.181818182	0.143	0.007759088	357.5524476
Fan 40	1.96	84.77	38.84	4.23	1236	1106	0.202492212	0.13	0.014573991	339.2307692
Fan 41	3.52	97.77	38.87	3	1047	948	0.174081238	0.099	0.029117647	382.020202
Fan 42	2.16	97.84	34.56	4.29	1043	931	-0.071813285	0.112	0.010163339	392.5892857
Fan 43	2.28	106.89	27.04	2.84	1005	910	0.085653105	0.095	0.019832985	408.8421053
Fan 44	2.8	108.4	30.14	2.97	1017	884	0.25	0.133	0.028177966	268.9473684
Fan 45	3.73	121.76	41.37	2.44	988	862	0.724637681	0.126	0.026694915	223.0952381
Fan 46	3.63	105.4	18.85	2.1	973	845	0.216666667	0.128	0.054468085	331.171875
Fan 47	3.07	105.4	18.85	2.9	954	806	0.438756856	0.148	0.047435897	263.7162162

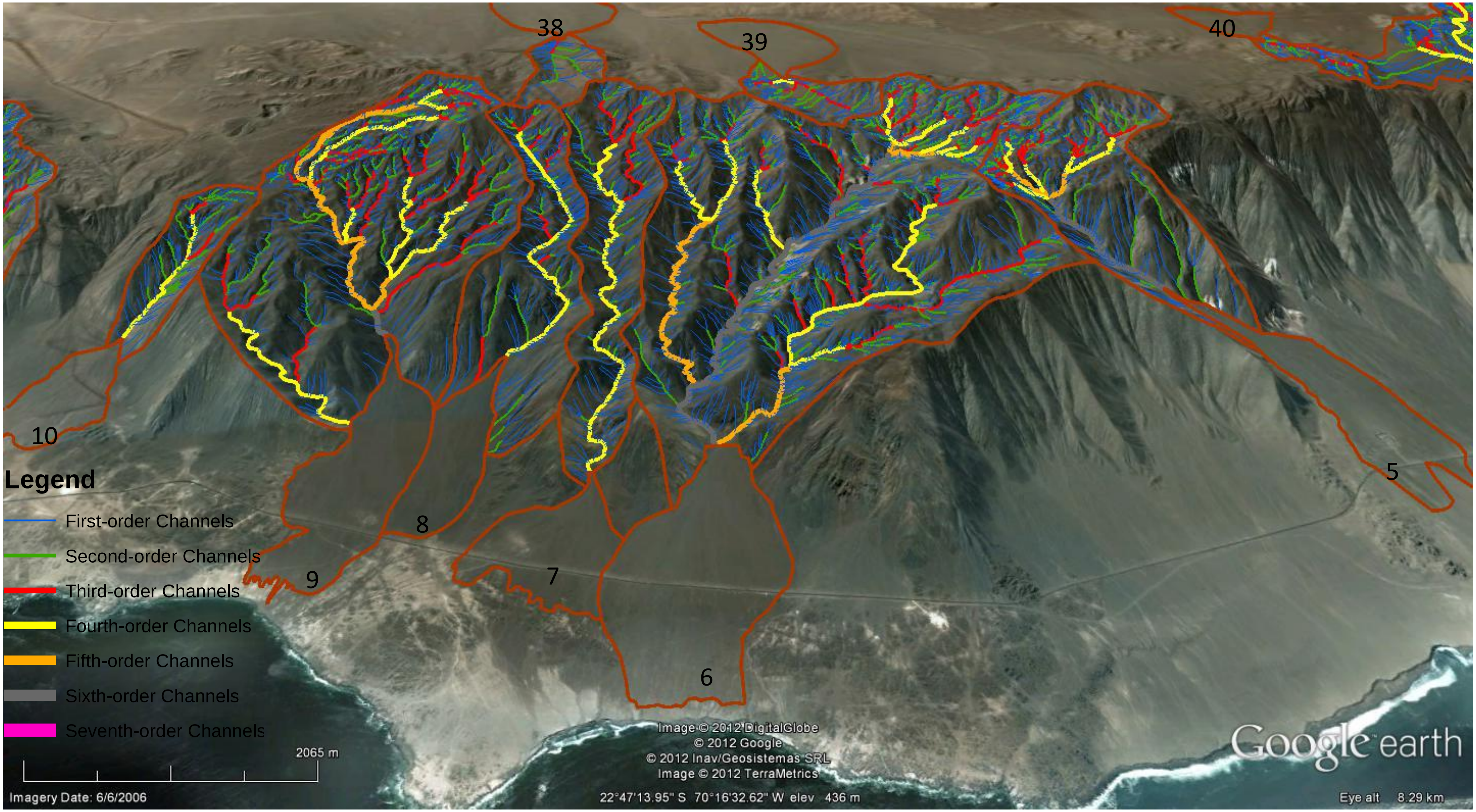
Appendix 9: Variables: Highest stream-order (Strahler), Maximum Flow Accumulation, Highest stream-order (Manual), Type of fan-surface morphology, Fan Radius, BA/BP, FA/FP, Fan Width.

	Highest Stream Order (strahler)	Maximum Flow Accumulation	Highest stream Order (Manual)	Type of surface	Type	Fan Radius	BA/BP	FA/FP	Fan Width
Fan 1	6	6360	6	5 (smooth channelized)	5	2.05	3.612508	2.746955	1779.36
Fan 2	6	8798	5	2 (braided + high-relief)	2	2.76	6.169355	3.910973	2165.43
Fan 3	7	13208	7	1 (braided +low-relief)	1	2.65	8.463391	4.28453	1625.3
Fan 4	6	6388	6	2 (braided + high-relief)	2	3.49	5.017804	3.902148	1309.14
Fan 5	6	6727	6	1 (braided +low-relief)	1	3.03	4.272656	2.316372	907.65
Fan 6	6	14794	6	4 (smooth)	4	2.62	7.953911	3.837725	1311.05
Fan 7	6	2879	4	4 (smooth)	4	1.39	2.945967	1.985481	1143.37
Fan 8	5	4432	4	2 (braided + high-relief)	2	2.13	2.820306	1.985915	609.62
Fan 9	6	8522	6	2 (braided + high-relief)	2	2.95	6.867718	2.163594	1001.2
Fan 10	5	1452	4	3(deeply channelized + smooth)	3	1.35	2.476371	2.070093	729.4
Fan 11	6	6496	6	2 (braided + high-relief)	2	2.12	6.817715	2.544571	1211.01
Fan 12	5	3580	4	2 (braided + high-relief)	2	1.82	3.189591	3.195896	1286.98
Fan 13	5	5792	4	1 (braided + low-relief)	1	3.41	5.49382	4.071429	2032.2
Fan 14	5	2139	4	3(deeply channelized + smooth)	3	2.56	2.669528	3.365229	1638.11
Fan 15	5	1696	4	3(deeply channelized + smooth)	3	1.6	2.228571	2.90495	1203.78
Fan 16	5	4667	5	3(deeply channelized + smooth)	3	1.89	4.401786	3.072197	888.78
Fan 17	8	46466		5 (smooth channelized)	5	2.13	18.48252	3.600801	1726.21
Fan 18	6	8256	5	4 (smooth)	4	2.09	5.138375	2.593056	1432.1
Fan 19	7	24780	7	4 (smooth)	4	1.91	9.345669	2.638728	1590.8
Fan 20	5	4625	4	5 (smooth channelized)	5	1.83	3.329767	1.872072	974.73
Fan 21	4	1239	3	5 (smooth channelized) / 3 (deeply channelized + smooth)	5 or 3	0.89	2.21087	1.377698	584.74
Fan 22	4	527	2	Colluvial Fan	0	0.56	2.032819	1.086667	802.69
Fan 23	5	6478	6	3(deeply channelized + smooth)	3	1.03	5.23273	11.06344	437.49
Fan 24	5	2133	4	3(deeply channelized + smooth)	3	1.12	2.053787	1.530973	645.49
Fan 25	5	1525	4	Colluvial Fan	0	0.97	2.842963	1.419463	676.31
Fan 26	7	33781		5 (smooth channelized)	5	1.79	11.1154	2.697936	1119.35
Fan 27	4	654	4	Colluvial Fan	0	0.84	1.345238	1.015326	550.42
Fan 28	4	368	3	Colluvial Fan	0	0.64	0.935484	0.748538	324.68
Fan 29	4	712	3	3(deeply channelized + smooth)	3	1.19	1.855305	1.270358	571.64
Fan 30	6	5624	4	3(deeply channelized + smooth)	3	1.36	3.958589	2.010799	1081.23
Fan 31	5	3149	5	1 (braided +low-relief)	1	1.28	3.155499	1.926366	1222.14
Fan 32	8	23299		4 (smooth)	4	1.51	15.90827	2.285097	1334.45
Fan 33	4	2029	5	4 (smooth)/ 3 (deeply channelized + smooth)	4 or 3	1.35	2.315663	1.950237	1044.42
Fan 34	6	3799	6	3(deeply channelized + smooth)	3	1.7	3.960694	2.202899	561.03
Fan 35	6	6527	6	3(deeply channelized + smooth)	3	1.58	4.520321	2.876471	1271.35
Fan 36	5	2326	4	3(deeply channelized + smooth)	3	1.3	3.796526	2.158273	1325.91
Fan 37	7	2326		5 (smooth channelized)	5	0.83	35.82838	1.577206	829.2
Fan 38	5	1327	3	2 (braided + high-relief)	2	1.79	2.512821	3.477113	1566.86
Fan 39	5	2723	5	1 (braided +low-relief)	1	1.87	3.106908	3.296959	1441.31
Fan 40	5	1226	3	2 (braided + high-relief)	2	1.12	1.922642	2.108747	1246.92
Fan 41	5	811	2	2 (braided + high-relief)	2	0.93	1.355	1.133333	674.6
Fan 42	5	1084	3	2 (braided + high-relief)	2	1.1	2.744463	2.568765	1400.53
Fan 43	5	1340	4	2 (braided + high-relief)	2	0.78	2.460474	1.68662	707.43
Fan 44	4	865	3	2 (braided + low-relief)/ 4 smooth	2 or 4	0.91	1.562358	1.589226	921.2
Fan 45	4	363	2	2 (braided + low-relief)/ 4 smooth	2 or 4	0.65	2.375862	1.934426	726.64
Fan 46	4	460	2	4 (smooth)	4	0.65	1.407643	1.119048	576.61
Fan 47	5	888	3	2 (braided + high-relief)/ 4 smooth	2 or 8	0.91	1.372449	1.075862	663.83

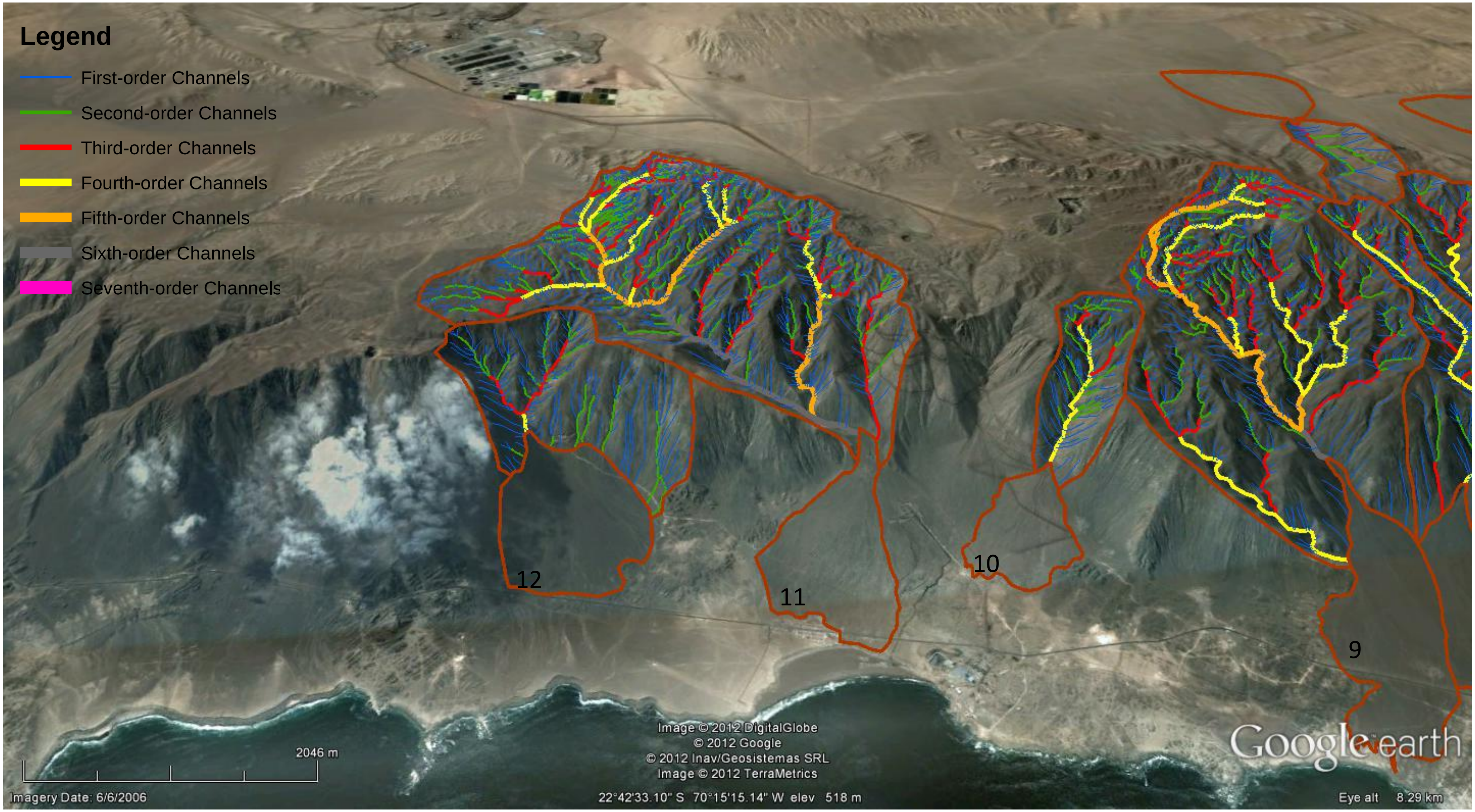
Appendix 10: Channel-network of Alluvial Fan 1, 2, 3 and 4.



Appendix 11: Channel-network of Alluvial Fan 5, 6, 7, 8, 9, 10, 38, 39 and 40.

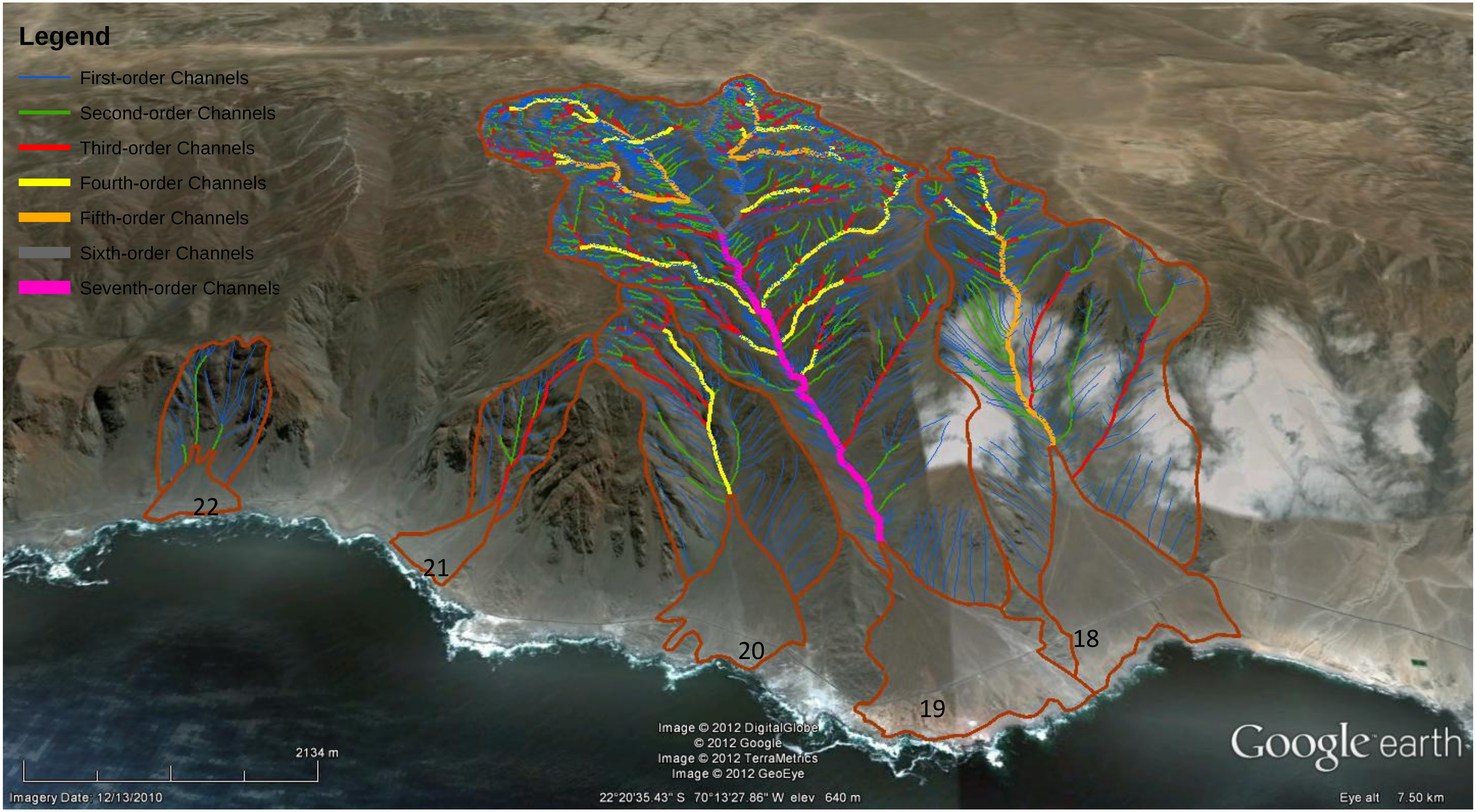


Appendix 12: Channel-network of Alluvial Fan 11 and 12.



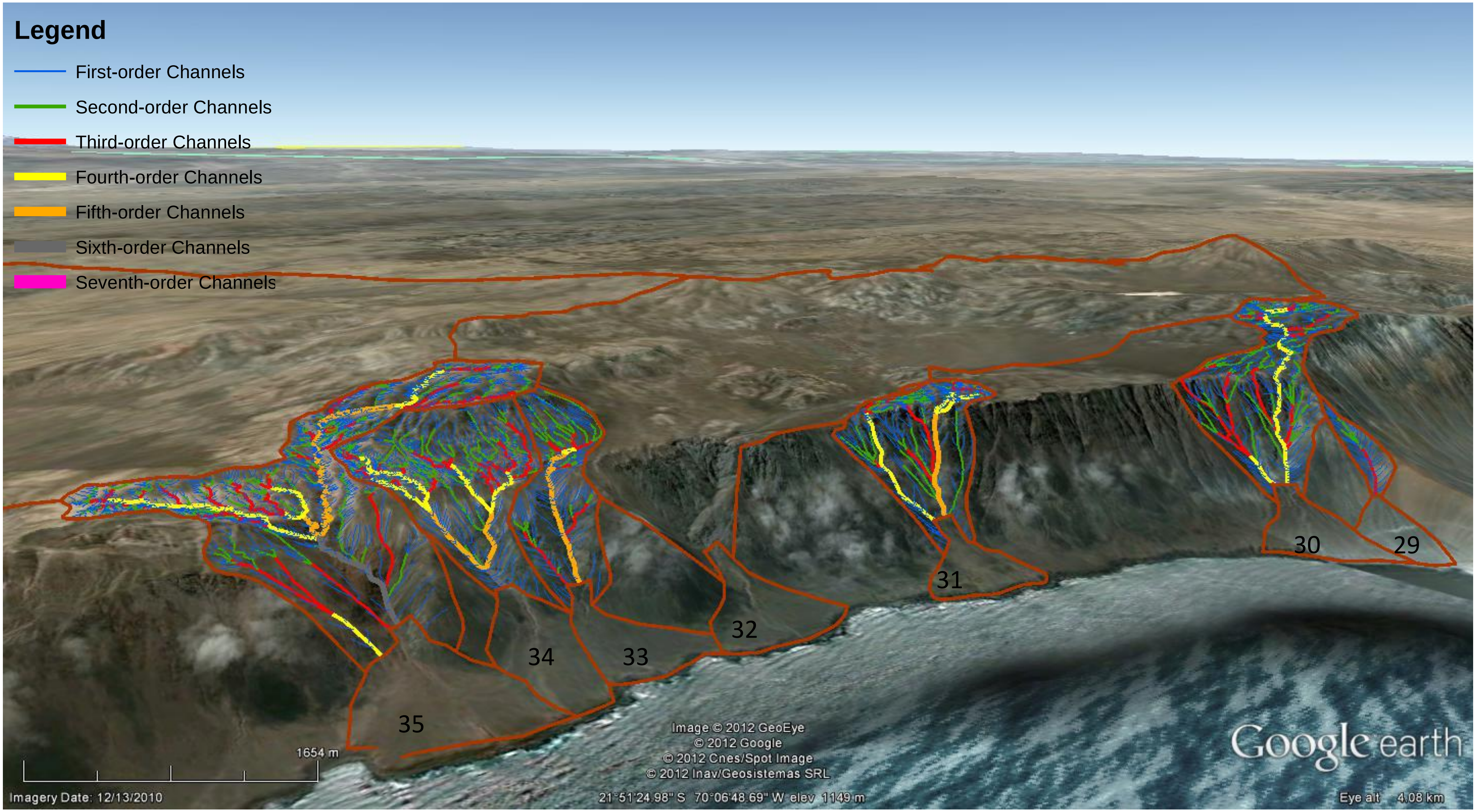
Appendix 13: Channel-network of Alluvial Fan 13, 14, 15, 16 and 17.

Appendix 14: Channel-network of Alluvial Fan 18, 19, 20, 21 and 22.



Appendix 15: Channel-network of Alluvial Fan 23, 24, 25, 26, 27 and 28.

Appendix 16: Channel-network of Alluvial Fan 29, 30, 31, 32, 33, 34 and 35



Appendix 17: Channel-network of Alluvial Fan 36 and 37.

Appendix 18: Channel-network of Alluvial Fan 41, 42, 43, 44, 45, 46 and 47.

Appendix 19: Image of the geological map of Chile.