Gravity-based mass balance of an alluvial fan giant: the Arcas Fan, Pampa del Tamarugal, Northern Chile

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ABSTRACT

Alluvial fans and their catchments provide joint erosion and sedimentation regions, where exogenic mass transfer can be handled as a finite volume problem. The Arcas Fan in the Andean forearc of Northern Chile, one of the world 's largest alluvial fans, has been mapped by a high -resolution gravity survey to calculate sedimentary mass by means of interactive 3D modeling. Erosive mass is estimated by a digital 3D volume model of the catchment. The fan volume of 110 km^3 ($\Delta V = \pm 6$ %) with a mean sediment density of 1.80 g cm^{-3} ($\Delta\rho = \pm 2\%$) yields a mass of 198x10^9 ton ($\Delta m = \pm 8$ %). The catchment loss of 115 km^3 ($\Delta V = \pm 6$ %) of rock with a mean density of 2,36 g cm^{-3} ($\Delta\rho = \pm 2$ %) points to a total erosion of 271x10^9 ton ($\Delta m = \pm 8\%$), about 73x10^9 ton ($\Delta m = \pm 8\%$) more than calculated in the fan. The mass difference of 27% is related to subsurface dissolution, wind deflation, and surface denudation post-dating deposition. K-Ar ages of ignimbrites topping a peneplain (7.3±0.2 Ma), which covered parts of the catchment, an ignimbrite intercalated in the oldest fan sediments (7.2±0.2 Ma) and tuff layers near the distal fan surface (6.8±0.2 Ma) suggest a short duration (0.5 my) of the exogenic mass transfer. The erosion rate of 0.318 m ka^{-1} and the sedimentation rate of 0.296 m ka^{-1} are interpreted as a climatic signal for more humid conditions in Late Miocene times. The erosion rate is nearly equal to the erosion rates of about 0.300 m ka^{-1} proposed for the Bolivian Andes in the Late Miocene. Area and extent of the mass turnover were too insignificant to cause catchment uplift due to erosion and fan area deflection due to sedimentation.

Key words: Gravity modeling, Alluvial fans, Sedimentation and erosion rates, Late Miocene, Northern Chile.

RESUMEN

Balance de masas por medio de la gravimetría de un abanico aluvial gigante: el Abanico de Arcas, Pampa del Tamarugal, norte de Chile. Los abanicos aluviales y su zona de alimentación, se encuentran en regiones erosionadas y de sedimentación, donde la masa transferida por procesos exógenos puede ser considerada como un problema de volumen finito. El Abanico de Arcas en el antearco andino del norte de Chile, uno de los abanicos aluviales más grandes del mundo ha sido mapeado por medio de mediciones gravimétricas de alta resolución para calcular la masa sedimentaria, por medio del modelamiento interactivo tridimensional (3D). La masa erosionada fue estimada mediante un modelo de volumen tridimensional de la zona de proveniencia. El volumen del Abanico de Arcas de 110 km^3 con un promedio de densidad del sedimento de 1.80 g cm^{-3} tiene una masa de 198x10^9 ($\Delta m = \pm 8\%$) toneladas. La pérdida de la zona de proveniencia es de 115 km³ (ΔV = ±6%) de roca con una densidad promedio de 2,36 g cm⁻³ (Δρ = ±2%), indicando una erosión total de 271x10⁹ toneladas (Δ*m* = ±8%), alrededor de 73x10⁹ toneladas (Δ*m* = ±8%) más de las que se comprueban en el abanico. La diferencia de masa del 27% está relacionada con la disolución en la superficie, deflación eólica y denudación de la superficie después de la deposición. La edad K-Ar de las ignimbritas es de 7,3±0,2 Ma, que cubren parte de la zona de proveniencia, una ignimbrita intercalada en los sedimentos más antiguos de abanico (7,2±0,2 Ma) y de los estratos de tobas cerca de la superficie del abanico (6,8±0,2 Ma) hacen pensar en un evento de corta duración, sólo 0,5 Ma para la transferencia de masa exogénica. La tasa de erosión de 0,316 m ka⁻¹ y la tasa de sedimentación de 0,296 m ka⁻¹ son interpretadas como una señal climática, indicativa de condiciones de más humedad en el Mioceno Superior. La tasa de erosión es casi igual a aquélla de *ca.* 0,300 m ka⁻¹, propuesta para los Andes bolivianos en el Mioceno Superior.

Palabras claves: Modelo de gravedad, Abanicos aluviales, Tasas de sedimentación y erosión, Mioceno tardío, Norte de Chile.

INTRODUCTION

Alluvial fans are the first links in the chain of depositional systems, which accompany the exogenic turnover of erosional debris from uplifted source areas to the sites of final deposition. Their buildup is characterized by gravity-controlled mass movements and water flow processes, which form a cone-shaped sedimentary body at the base of a distinct catchment following discontinuous precipitation and depositional events. Fan construction is favoured at positions where flow expands out of a mountain front -usually with high topographic relief. Relative to the understanding of fan sedimentology and facies geometry (Nilsen, 1985; Blair and McPherson, 1994a, b), the relationship of the spatial and temporal development of large alluvial fans and their catchments is less well known. The present study yields improved insight into the evolutionary dynamics of large fans by examining the mass balance between erosion in the catchment and deposition within the fan, using a new technique.

The development of alluvial fans is favoured by an arid climate with event-like flashfloods. Calculating erosion and sedimentation rates and developing mass balances under these conditions is complicated, because fans are subject to post-depositional processes. Generally, there is little knowledge about sediment gain and loss on fossil fan surfaces due to processes post-dating fan buildup, such as wind deflation and water-flow winnowing. Although volume calculation of a fan catchment can be handled by computer-based 3D modeling tools (Ibbeken and Schleyer, 1991), reconstruction of the fan body is far more difficult. The fan surface is confined by the recent fan topography and the outline of the sedimentary cone. But the base, where progradation began, is difficult to restore due to the burial by the fan sediments. In a few cases, the fan base has been reconstructed by estimating a simple basement geometry like a basinward dipping plain (Hooke, 1972; Hooke and Dorn, 1992) or an antithetically dipping floor of an extensional graben. In these cases, an alluvial fan volume can be approximated mathematically by intersecting a simple cone by a plain. In the future, advanced exploration techniques (*e.g.,* reflection seismics, geoelectrics, gravimetry, soil radar) have to be tested to monitor interior or basal features of near surface alluvial fans in such cases where well control is lacking.

The gravity-based mass calculation of an alluvial fan requires data about the fan sediment densities not only near the surface, but also throughout the entire fan body. Extrapolation of the near surface densities would not consider loss of pore space and increase of density due to compaction. Additionally, calculation of erosion and sedimentation rates or the frequency of depositional events requires a good knowledge of the timing of the fan progradation. Dating of alluvial fan beds is a problem. A major drawback is the lack of fossils in most desert environments. Biostratigraphy in fringing lacustrine systems is often limited due to the endemism of the faunas. Radiometrically datable igneous intercalations are rarely observed. Due to the lack of stratigraphic control within the fan, the minimum requirements for determining the time of fan sedimentation are datable marker beds at the basal and top disconformities of the fan. Volcanic beds serve this purpose in the authors' study.

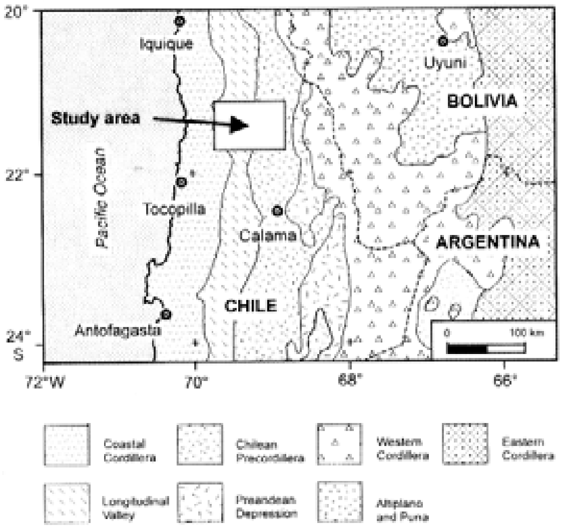


FIG. 1. Geologic and morphologic setting. Northern Chile is characterized by north-south trending morphological units. They are remnants of former volcanic arcs, which formed the Andean system since the Jurassic. The Recent magmatic arc, hosting prominent active volcanoes, is located in the Western Cordillera. A close-up of the Arcas Fan in the Longitudinal Valley and its catchment in the Precordillera (study area box) is presented in figure 2.

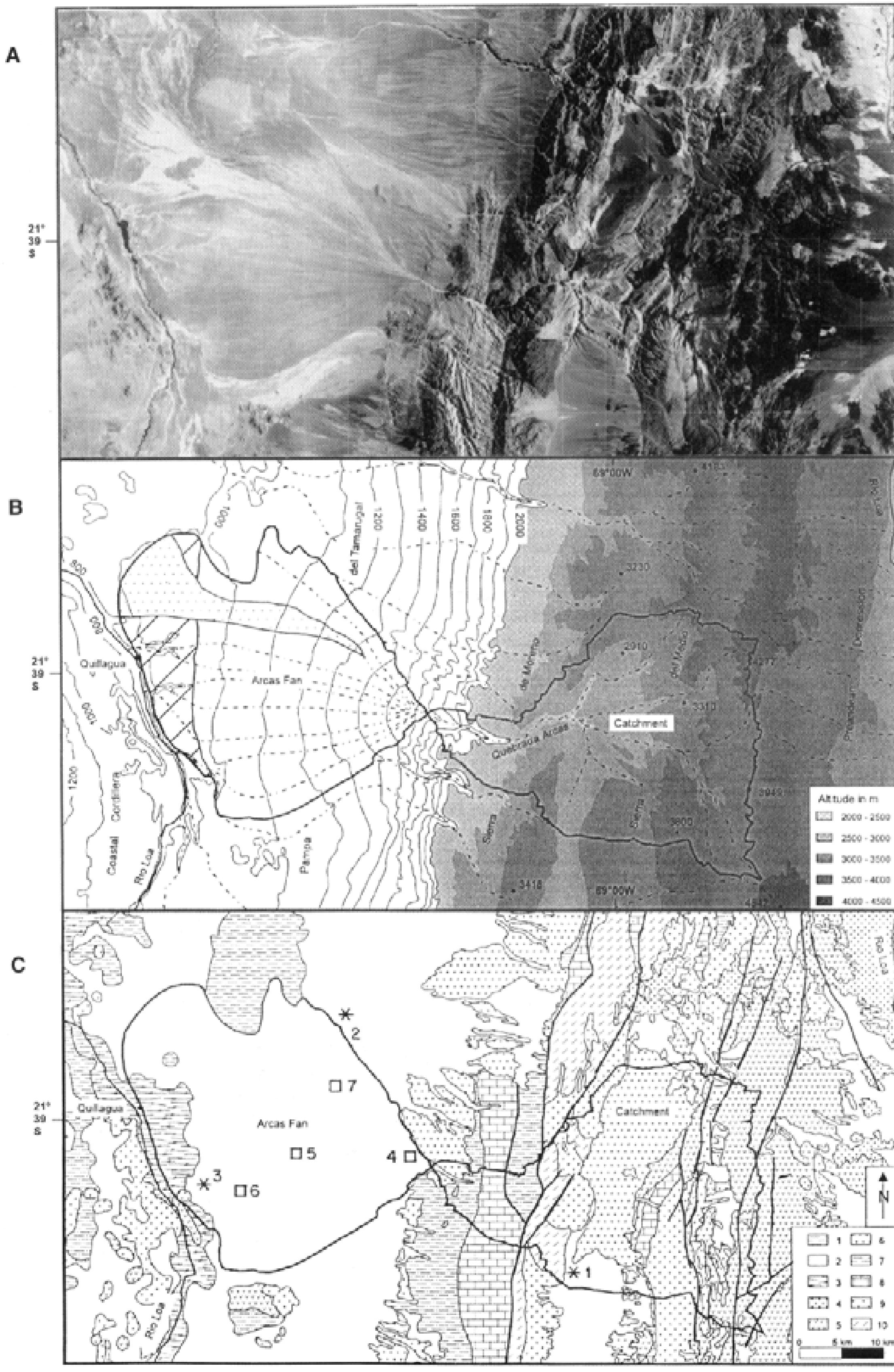
The Arcas Fan in the Atacama Desert of northern Chile (Figs. 1, 2), one of the world 's largest alluvial fans, offers an opportunity to carry out a high resolution volume calculation and mass balance of a large fan and its catchment. The purpose of our study is to establish an interdisciplinary geoscientific approach, which combines morphometrical, geophysical and geological techniques for exogenic mass balancing of large alluvial fans and their catchment. Morphometry consists of volume calculations and mass balance, handled as a finite volume problem. Catchment and fan areas are delineated by topography and satellite based remote sensing. Geophysical techniques consist of in the field gravity and density measurements, and 3D gravity modeling to construct a 3D volume-density model of the fan. The Arcas Fan is a low-density mass accumulation, which causes a local negative gravity anomaly within the regional residual field. Volumes and masses of catchment and fan can be compared directly, and allow for detection of mass loss during erosion and sedimentation. Geologic techniques consist of radiometric dating to constrain fan stratigraphy. The Arcas Fan spans the time from the Late Miocene to the Recent. However, data presented here suggest that the only important interval of fan progradation was during the Late Miocene. During the Late Miocene uplift of the Andean Altiplano fan development was accompanied by increased volcanic activity. Because ignimbrite and tuff layers are underlying and topping the fan, radiometric dating of the volcanic rocks provide a temporal framework for the calculation of erosion and sedimentation rates.

By means of these advanced techniques of exogenic mass balancing, the authors are able to predict crustal unloading in orogenic erosional areas and crustal loading due to sedimentation. The finite volume concept presented in this paper, allows extrapolation of local mass movements to the regional scales of sedimentary basins and source areas in magmatic arcs. The evolution of the Arcas Fan provides a climatic signal and gives more information about the paleoclimatic evolution of the Andean region during the Neogene.

GEOLOGICAL SETTING

The Arcas Fan and its catchment are located east of the village of Quillagua, 250 km northeast of Antofagasta in northern Chile (Figs. 1, 2). The erosion-deposition system straddles the structural border and morphologic escarpment between the Andean Precordillera in the east and the basin of the Longitudinal Valley in the west (Skarmeta and Marinovic, 1981; Skarmeta, 1983; Bogdanic, 1990; Jensen, 1992; Sáez, 1995a, b). In the framework of the modern plate configuration, the study area is located in a forearc position.

The active continental margin of the southern central Andes (Fig. 1) between 21°30 and 22°00'S is characterized by north-south trending morphostructural units (Reutter *et al.*, 1988). They are expressions of more or less continuous plate convergence since the Jurassic: The Peru-Chile Trench to the west is controlled by the east-dipping subduction zone between the oceanic Nazca Plate and the overthrusting South American Plate. The Coastal Cordillera along the Chilean Pacific coast is the uplifted basement of the initial, Jurassic to Early


A
21°
39
S
B
Quillagua
Arcas Fan
Catchment
Quebrada Arcas
Coastal Cordillera
Rio Loa
Pampa
del Tamarugal
Sierra de Moreno
Sierra del Medio
69°00W
Altitude in m
2000 - 2500
2500 - 3000
3000 - 3500
3500 - 4000
4000 - 4500
C
Quillagua
Arcas Fan
Catchment
Rio Loa
N
0 5 km 10 km

Cretaceous magmatic arc of the Andean system (Scheuber *et al.*, 1994) and reaches altitudes up to 2,500 m. To the east, the range is flanked by the Andean Longitudinal Valley (Rieu, 1975; Mortimer and Saric, 1975; Paskoff, 1977; Mortimer, 1981; Naranjo and Paskoff, 1982, 1983, 1985), a graben-shaped basin about 45 km wide, filled with Oligocene to Recent continental clastics and evaporites (Jensen, 1992). The Precordillera at the eastern margin of the Longitudinal Valley is characterized by Preandean basement-cored anticlines, with cores of Early Proterozoic to Paleozoic low- to medium-grade metamorphic and magmatic rocks (Skarmeta, 1983; Bogdanic, 1990). They are unconformably overlain by Mesozoic to Recent sediments and volcanic rocks. Locally, the Preandean Depression separates the Precordillera from the Western Cordillera (Reutter *et al.*, 1988). The front of the Miocene-Holocene volcanic arc is situated in the Western Cordillera, and is topped locally by active volcanoes with altitudes of up to 6,700 m. The Altiplano and Puna represent the plateau of the Andean orogen. The Eastern Cordillera and Subandean ranges are characterized by the Andean fold and thrust belt thrust over the foreland basin of the Brazilian Shield. The western morphostructural units are cut by north-south trending transform faults, the Atacama Fault Zone in the Coastal Cordillera and the West Fissure (Maksaev, 1990) in the Precordillera, which locally branch into complex zones of transpression and transtension.

As a consequence of plate convergence and tectonic erosion of the continental margin, the Andean magmatic arc migrated *ca.* 200 km to the east since the Jurassic. In the Late Miocene the subduction of the Nazca Plate beneath the South American continental lithosphere caused a rapid crustal thickening and uplift of the central Andean plateau (Altiplano) to mean altitudes of more than 4,500 m. The mechanisms of crustal thickening and uplift are discussed controversial (Whitman *et al.*, 1992). Thorpe *et al.* (1981) emphasized the growth of the continental crust by accretion of mantle-generated, new magmas beneath the active volcanic arc. Tectonic stacking (Jordan *et al.*, 1983; Lyon-Caen *et al.*, 1985; Roeder, 1988; Sheffels, 1990) is favoured by the foreland fold and thrust belt of the Eastern Cordillera. A combination of compressional crustal shortening and thickening, and lithospheric thinning by thermal expansion due to the intruding magmas

FIG. 2. Satellite image, morphology and geology of the Arcas Fan and its catchment: **A-** in the right part of the LANDSAT TM scene, the mountaineous region of the Precordillera is flanked to the east by the Preandean Depression. The most prominent feature within the Longitudinal Valley (left part of the satellite image) is the Upper Miocene Arcas Fan. It crosses the Pampa del Tamarugal from its apex at the end of the Quebrada Arcas, the solitary feeder channel crosscutting the Sierra de Moreno, to its toe at the Río Loa, where it interfingers with lacustrine deposits of the Late Miocene to Pliocene Quillagua Formation (hatched area in b). Almost the entire fan surface has a medium grey color representing areas of Late Miocene clast-rich debris flow deposits. In the northwestern part of the fan, Miocene deposits are covered by thin sub-Recent to Recent mudflow deposits (light grey and white areas, stippled area in b). The Arcas Fan prograded onto an Oligocene to Early Miocene, west-dipping alluvial wedge, which is characterized by medium to dark grey colors and crops out directly north of the fan apex. The Río Loa is located at the eastern foothills of the Coastal Cordillera. Grid spacing in the satellite image is 5 km; **B-** morphology of the Arcas Fan and its catchment. The catchment is limited by the Recent main divide to the east. The summits of the Sierra del Medio reach heights up to 4,300 m. The Sierra del Medio is deeply eroded by numerous tributary channels (broken lines), which all join into the 5th-order feeder channel, the Quebrada Arcas at an altitude of 2,200 m. The 15 km long Quebrada Arcas cuts through the Sierra de Moreno and reaches the fan apex at 1,650 m. The Arcas Fan emerges from the catchment with a flow expansion angle of 105°. The radial slope decreases from 1.2 to 2° in the proximal and medial areas to less than 1°, where the distal alluvial sediments interfinger with lacustrine sediments of the Quillagua Formation (hatched area). At Quillagua, the distal toes of the fan are located at an altitude of 850 m a.s.l. The arc-shaped contours in the proximal and medial part of the fan clearly contrast to the straight, north-south-trending contours of the alluvial wedge north and south of the Arcas Fan. The fan surface reveals a backstepping system of sub-Recent canyons (broken lines), which begin along the Río Loa, and are found all the way to the apex region, without reaching the most recently active mudflow channel; **C-** geology of the Arcas Fan area and the catchment: **1-** evaporites (Quaternary); **2-** alluvial sediments (Late Miocene to Pliocene); **3-** lacustrine sediments of the Quillagua Formation (Late Miocene to Pliocene); **4-** ignimbrites (Late Miocene); **5-** volcanic rocks (Permian-Triassic, Eocene and Late Paleocene to Early Oligocene); **6-** conglomerates and sandstones (Late Cretaceous to Paleocene and Oligocene to Early Miocene); **7-** sandstones and siltstones (Devonian to Carboniferous and Late Jurassic to Early Cretaceous); **8-** limestones and marls (Jurassic); **9-** plutonic rocks (Late Carboniferous to Permian and Late Cretaceous); **10-** metamorphic rocks (Proterozoic to Lower Paleozoic). Stars indicate approximate locations of the dated volcanic rocks (sample 1: ignimbrite, 7.3 Ma; sample 2: ignimbrite, 7.2 Ma; sample 3: tuff, 6.8 Ma). Boxes indicate approximate gravel analyses sample sites (sample 4: fan apex; sample 5: medial fan; sample 6: distal fan; sample 7: Recent mudflow). For exact coordinates, see tables 1 and 2.

is discussed by Froidevaux and Isacks (1984); Isacks (1988), and Francis and Hawkesworth (1994).

Steep relief of the rising Andes triggered erosion and an exogenic mass exportation toward the Pacific Ocean in the west and toward the Amazon Basin in the east. In northern Chile huge volumes of terrigenous clastics were transported from the uplifted source areas in the Western Cordillera and the Precordillera preferentially to the west into the Longitudinal Valley basin and the Preandean Depression. The arid climate (Alpers and Brimhall, 1988; Abele, 1989) favoured development and preservation of alluvial fans and bajadas, which fringe the basins. Along the Longitudinal Valley locally lacustrine systems developed, which host the economic evaporite deposits of northern Chile (Sáez, 1995a, b).

MORPHOLOGY AND GEOLOGY OF THE ARCAS FAN AND ITS CATCHMENT

The Arcas alluvial fan is located at the piedmont of the western range front of the Precordillera and spreads westerly into the Longitudinal Valley (Skarmeta and Marinovic, 1981; Skarmeta, 1983). In the vicinity of the Arcas Fan three morphologic components can be clearly outlined in LANDSAT TM scenes (Fig. 2A). The catchment in the Precordillera, a feeder channel crosscutting the narrow range of the Sierra de Moreno and the Arcas Fan in the Longitudinal Valley (Pampa del Tamarugal) in the west.

CATCHMENT AND FEEDER CHANNEL: MORPHOLOGY

The catchment of 723 km^2 is located in the Precordillera. It extends from altitudes of 4,300 m to 1,650 m and is bounded by the Recent drainage divide (Fig. 2B). The eastern part, the Sierra del Medio, is deeply eroded and dissected by branching canyons. They join into the Quebrada Arcas valley, 5th-order-feeder channel to the Arcas Fan (Fig. 3A).The Quebrada Arcas transects the Sierra de Moreno, the narrow frontier range of the Precordillera with altitudes up to 3,400 m. The canyon is 15 km long and up to 500 m deep. The junction of the 4th-order channels into the single 5th-order channel is located at the eastern flank of the Sierra de Moreno at an altitude of 2,200 m. Along its length in the Sierra de Moreno, the Quebrada Arcas valley is fed by short tributaries which are incised in the steep valley walls and small alluvial cones, which locally merge into abandoned terraces. The feeder valley reaches the Arcas Fan at an altitude of 1,650 m. Locally, the valley flanks are covered by remnants of gravel terraces. The main terrace merges in the Arcas Fan surface in the apex area. Two levels about 5 m and 40 m above may represent periods of deceleration of the valley cut. The lowermost and youngest terrace is episodically charged by Recent, gravel-poor mud flows. At the fan apex, the youngest terrace sediments merge with Recent and sub-Recent mudflow deposits, which spread as white, thin veneers over the northern flank of the Arcas Fan (Fig. 2A). Between altitudes of 2,800 and 3,700 m, parts of the catchment reveal remnants of a Miocene peneplain (Galli-Olivier, 1967).

CATCHMENT AND FEEDER CHANNEL: GEOLOGY

Volcanic, plutonic and metamorphic rocks as well as marine and continental sedimentary rocks of Precambrian to Recent age occur in the catchment (Skarmeta, 1983; Bogdanic, 1990). Volcanic rocks of rhyolithic to andesitic composition of Permian to Triassic, Eocene, and Late Paleocene to Early Oligocene age are restricted to the Sierra del Medio (Fig. 2C). Upper Carboniferous to Permian granites and granodiorites crop out in the eastern part of the Sierra de Moreno and the center of the Sierra del Medio. Jurassic limestones and marls are found throughout the catchment. Devonian to Carboniferous and Upper Jurassic to Lower Cretaceous sand- and siltstones crop out in the center and the western part of the Sierra de Moreno. Conglomerates of Late Cretaceous to Paleocene and Oligocene to Early Miocene age in the center of the catchment dominate among all rock units. The metamorphic rocks (migmatites, gneisses, micaschists and amphibolites) are restricted to the Sierra de Moreno and represent one of the few outcrops of Preandean basement in the Precordillera. The entire rock suite is strongly deformed by north-south trending folds, and cut by approximately northeast trending strike-slip faults. The Precambrian to Cenozoic sequences are unconformably overlain by Late Miocene ignimbrites and tuff layers, released from volcanic eruptions in the Western Cordillera.

ARCAS FAN: MORPHOLOGY

The Arcas Fan is characterized by a saddle-shaped surface with a concave radial and convex cross profile. It covers an area of 742 km^2. In the upper and middle sections of the fan, arc-shaped contours of the Arcas Fan contrast with the straight, north-south trending contour lines of the west-dipping, alluvial wedge north and south of the fan and allows a clear delimitation of the Late Miocene fan body (Fig. 2B). At the apex, a strong contrast between the light fan sediments and the dark, desert varnish-covered gravels of the precursor wedge evident in the LANDSAT TM scene (Fig. 2A), matches the kinks of the contour lines. On the lower fan, where it interfingers with horizontal lacustrine beds, contours tend to run north-south. The fan cone has a flow expansion angle of 105° and a minimum radial length of 30 km. The fan apex is situated at an altitude of about 1,650 m, and the fan toe is at an altitude of 850 m at the course of the north-flowing Río Loa. The mean slope of 1.2° to 2° in the upper to medial fan contrasts with the mean slope of less than 1° at the fan toe. These morphologic characteristics clearly separate the Arcas Fan from a fluvial system (Blair and McPherson, 1994a).

ARCAS FAN: GEOLOGY

Arcas Fan sediments are characterized by clast-rich debris flow deposits (Fig. 3B), composed of all rock types present in the catchment. Sediment transport from the catchment to the fan extends over distances of more than 60 km and is accompanied by total mixing of weathered rock types. Production of fine-grained particles is supported by recycling of the Cenozoic clastics, which are, likewise, composed of immature mixtures of most catchment rocks. The high amounts of silt and clay in the coarse-grained Arcas Fan debris flow deposits and the feeder channel terraces, are thought to be relicts of the widespread Cenozoic volcanic rocks, which experienced rapid decay due to weathering,and recycling of Mesozoic to Cenozoic sedimentary rocks. Primary production of erosional debris from crystalline rocks is responsible for the coarse-grained fractions of the sediment.

The fan surface has been erosively cut by a back-stepping system of Recent to sub-Recent canyons. They begin at the Río Loa and extend upfan to the near-apex region without joining the recently active mudflow channel. The Recent canyons dissect the radial debris flow pattern, which is preferably exposed at the more deeply denuded southern edge of the fan. To the north, these Late Miocene fan deposits are covered by veneers of Recent eolian sand dunes and mudflow deposits (bright areas in Fig. 2A, Fig. 3C). The occurrence of Recent mudflows is restricted to the northern part of the fan, where a solitary sinuous channel, 2 m wide and 5 m deep, cuts into the Miocene debris flow deposits. The channel intersects the fan surface in the northwestern distal region, where the mudflows merge into a mudflat. The mudflat extends far away from the fan toe, but never reaches the Río Loa. During flash floods muds mobilized in the catchment, flow down the single channel, leaving small levee and crevasse deposits of mud around areas fringing the channel.

At the fan toe, fan sediments interfinger with carbonate-dominated lacustrine beds of the Late Miocene to Pliocene Quillagua Formation (Jensen, 1992). According to biostratigraphical data and radiometric dating of tuffs, the Miocene-Pliocene lake transgressed over the distal portion of the fan, depositing carbonates and evaporites at the northwestern fan margin.

Abandoned erosional channels, desert varnish-covered gravels, and excavated boulders (Fig. 3D) suggest a shift of the post-fan drainage system on the fan surface from south to north through time. The erosional character of the Recent drainage, which dissects the Late Miocene debris flow deposits, the terraces of the Quebrada Arcas valley, and the Miocene to Pliocene lacustrine sediments interfingering with the fan toe proves that the Arcas Fan *s. str.* is a fossil fan. All processes recently modifying the surface clearly contrast with the constructive depositional events, which formed the fan body in the Late Miocene.

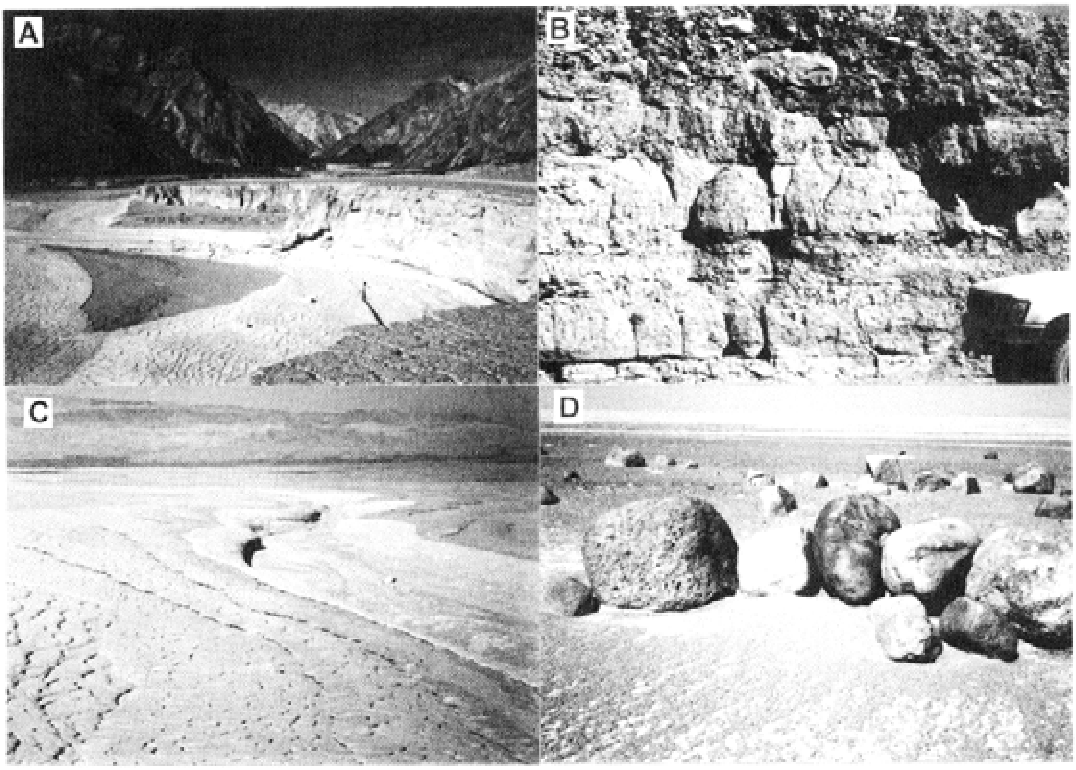


FIG. 3. **A-** The Quebrada Arcas, the 5th-order feeder channel to the Arcas Fan, cuts the mountain front of the Sierra de Moreno in east-west-direction (range in the background). The canyon, which is locally 500 m deep, contains remnants of 4 terraces, the most prominent one in the foreground merges into the fan sedimentary succession in the apex region. The uppermost and oldest terrace is about 40 m above the canyon base. The lowermost terrace (foreground) is composed of mud-dominated debris flow deposits. The recent mudflow channel (far left) represents the current base level and is covered by mudflow deposits of a 1994 flood. The surface of the deposits is strongly mud-cracked.

B- debris flow deposits of the Arcas Fan. The Late Miocene Arcas Fan is mainly composed of clast-rich debris flow deposits. In canyons of the sub-Recent to Recent drainage system, they occur as distinct beds, which wedge out at lateral distances of less than 1 km. Hanging beds often erosively cut into the underlying beds. This vertical section is characterized by alternating clast-poor, mud-dominated beds (lowermost beds) and mud-poor gravels with boulders up to several meters in diameter (uppermost bed), implying that the debris flows belong to stacked fan lobes of different ages and lateral extension. Thin mud layers, which are interbedded with the debris flow successions, are the result of a grading within sediment gravity flow and muds (bed below the large boulder).

C- Recent mudflow channel. The Arcas Fan surface is cut by sub-Recent to Recent channels. One system is near the Río Loa in the west and dissects the distal and medial parts of the fan. The currently active erosive channel connects to the Quebrada Arcas and cuts into the northern flank of the Arcas Fan (Figure 2A, bright channel). These two channel systems are not linked. The intersection point of the active channel is located about 25 km northwest of the apex. During rare precipitation events, such as the March 1994, low viscosity, gravel-poor muds are mobilized in the catchment (mountain range in the background) and swept down through the meandering channel. During flooding levee and crevasse deposits form along the channel banks. Within hours after flooding deep mud cracks develop within the rapidly drying beds. The photo documents five successive mudflow beds, with a maximum thickness of 0.05 m (channel width is 2 m). Below the intersection point, the mud is deposited on a vast mudflat, which expands beyond the northwestern edge of the Arcas Fan (Fig. 2A).

D- boulder field. On the Recent Arcas Fan surface, large boulder fields are common. Up to two hundred boulders between 0.5 and 5 m in diameter are scattered over a lenticular shaped area of about 100 m in length and some 50 m in width. They are composed of the crystalline rocks of the catchment, mainly granodiorite, granite and volcanic rocks, and rarely sedimentary rocks. The volcanic and sedimentary components experience rapid physical weathering. Because most of the boulders are still embedded in the fan surface (boulders in background), the boulder fields are interpreted as the relicts of a post-Late Miocene erosive lowering of the fan surface due to wind deflation and winnowing during flash floods. Occasionally, up to ten boulders line up to form a boulder train (boulder in the left has a diameter of 1.2 m).

ARCAS FAN SEDIMENTOLOGY

As evidenced in canyon sections, the Arcas Fan sedimentary succession is characterized by prograding beds between 0.2 and 1 m thick (Fig. 3B). Beds are separated by erosive bedding planes, which are locally truncated by flat channels or narrow gullies. Vertical profiles near the fan apex are dominated by coarse-grained, mud-supported gravel beds with large amounts of boulders, and few mud intercalations. Typical for medial and distal sections are successions of gravel-bearing, mud-dominated layers interbedded with thin gravel beds. Occasionally gravel-sized components at the base of beds are imbricated. Fluvial channels are small and rare. Strong vertical contrasts of the mean grain size between beds are common. Normal or inverse grading within beds is rare. The beds wedge out over lateral distances of few hundreds of meters to about one kilometer and belong to a distinct fan lobe deposited during a single debris flow event. The contrasting mean grain size of the single beds points to the fact that the liquefied debris flows experienced a gravitative differentiation during flow on the fan surface. While the gravel-dominated bedload was deposited in more proximal areas, the supporting matrix was squeezed out by compactional flow and deposited in marginal areas and the top of the lobe. Gravel dikes, which initiate at the fan surface and cut the beds vertically are interpreted as filled desiccation cracks post-dating debris flow sedimentation.

Though the remote sensing and topographic data point to the true alluvial fan character of the Arcas Fan, further sedimentological analyses were needed to confirm this interpretation and to understand the dominant sediment transport mechanism. Because there is no obvious internal facies differentiation and stratigraphic control within the fan, gravel analyses of locally representative beds helped to reveal transportation hydraulics and sedimentation processes (for coordinates, see Table 1). Gravel analyses (Ibbeken and Schleyer, 1991), based on some 200 kg of sediment from a single debris flow bed at a steep canyon wall, were performed at the apex, and at medial and distal sites of the fan (Fig. 4).

Fan apex sediments are characterized by a Rosin-like distribution (Ibbeken, 1983) with a pronounced mode between -5 and -7 Phi, corresponding to a grain size between 32 and 128 mm. The range between -4 to 4 Phi shows a nearly linear decrease from coarse to fine particles. In the medial section, fan sediments have a bimodal grain size distribution with modes at -5 Phi (=32 mm) and <4 Phi, the latter corresponding to the silt and clay fractions. The distal Arcas Fan sediments have a unimodal grain size distribution with a pronounced fine gravel mode at -2 Phi (= 4 mm). While the apex sediments show proximity to jointed and weathered source rocks, the medial grain-size distribution indicates textural maturation during transport from the Quebrada Arcas to mid-fan deposition sites. The shift of the gravel mode and occurrence of a silt/clay mode in medial sediments can be attributed to young volcanic rock components, which suffer intense mechanical decay and attrition producing high amounts of silt and clay particles. Grain size distribution of the distal sediments is interpreted as an effect of fluviatile reworking, possibly post-dating the fan development.

TABLE 1. GRAVEL ANALYSES SAMPLING SITES ON THE ARCAS FAN.

	Sample 4	Sample 5	Sample 6	Sample 7
Lithology	Debris flow	Debris flow	Debris flow	Mudflow
Position	Fan apex	Medial fan	Distal fan	Channel
Long.	69°09'30"W	69°15'10"W	69°27'40"W	69°19'20"W
Lat.	21°43'10"S	21°41'03"W	21°44'42"S	21°35'50"S
Age	Late Mioc.	Late Mioc.	Late Mioc.	Recent

Typically gravel-sized particles are well rounded, while the fine-gravel and sand modes are not. About 51.5 % of the gravel components are composed of volcanic rocks, 25.2 % are granites. The amounts of metamorphic and sedimentary rocks are 17.0 and 6.3%, respectively. Volcanic clast sizes mainly range between 80 and 50 mm, while the typical range for granitoid clasts is 63 to 32 mm. Metamorphic and sedimentary clasts range between 32 and 25 mm. The sand mode is dominated by volcanic and metamorphic rock fragments. Silt is dominated by solitary quartz and feldspar grains.

A special feature of the Arcas Fan is large

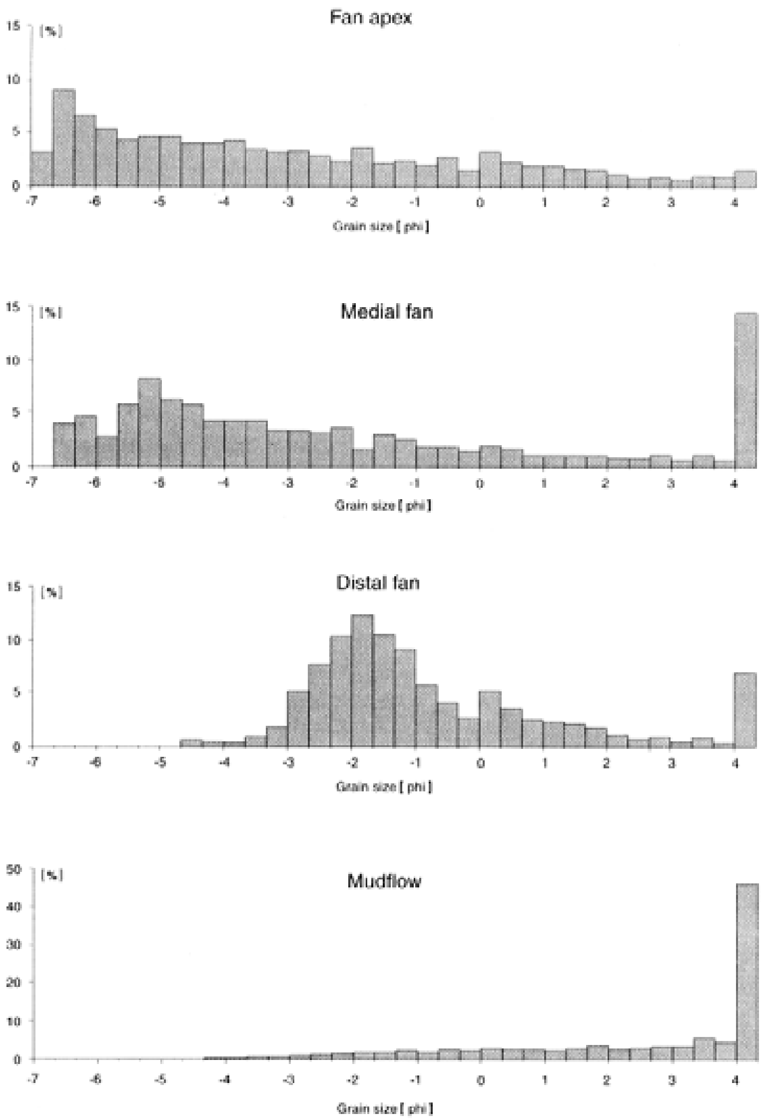


FIG. 4. Arcas Fan grain size distributions. The Rosin-like grain size distribution (upper histogram) of the fan apex sediments emphasizes the relation to the jointed and weathered rocks of the source area. Medium gravel and silt/clay modes in medial fan histogram point to textural maturation during transport of the rock debris from the feeder channel to mid-fan depositional sites. This distribution of components is typical for the Arcas Fan debris flow deposits, which are characterized by mud-supported gravels and boulders. The shift of the fine gravel in distal fan sediments (lower middle histogram) is a signal of fluviatile reworking of debris flow sediments possibly post-dating the fan development. Contrasting to theLate Miocene debris flows, the grain size distribution of the sub-Recent to Recent mudflow (lower histogram) is characterized by smaller maximum grain size, a plateau distribution in gravel and sand fractions and high silt and clay amounts of up to 50%. It is a clast-poor debris flow (for sample locations see Table 1).

boulder fields (Fig. 3D). About 100 to 200 boulders with sizes between 0.5 and 5 m are spread over lenticular-shaped areas 100 m long and 20 to 50 m wide. The boulder fields are present across the surface of the whole fan. Most of the blocks are one-third embedded into fan surface sediments. While the largest blocks are composed of granodiorite, the medium-sized ones are mainly composed of granite and volcanic rocks. Sedimentary rocks like limestone, sandstone and shale are rare and have the smallest clast size. Granitoid boulders are well rounded. Volcanic rocks experience fast decay producing silt and clay-sized particles. Since boulders of similar size are common components of debris flow deposits in subsurface sections, their scattered occurrence across the fan surface indicates erosive winnowing of the fan surface.

The Recent mudflows (Fig. 3C) reveal a significantly different grain size distribution from the Late Miocene debris flows. Maximum grain size is 4 1/3 Phi (= 20 mm) with a plateau distribution in the gravel and sand fractions; silt and clay may amount to 50 %. The thickness of the most recent mudflow, in March 1994, was ≤0.05 m (Ibbeken, 1995). As observed along collapsed channel walls, the cumulative thickness of all Recent mud flow deposits is less than 1 m, and they are restricted to the currently active channel. Because of the local occurrence at the northwestern margin of the fan and the minor thickness, compared to the clast-rich debris flow deposits, these mudflow deposits contribute only negligible amounts to the sediment volume of the Arcas Fan and are thus, insignificant for the mass balance.

At the distal toes, the alluvial sediments interfinger with lacustrine facies consisting of carbonates and evaporites. In outcrops along the Río Loa, underlying alluvial fan red beds vertically grade into white, calcareous beds of the Late Miocene to the Pliocene Quillagua Formation. The younger part of the Quillagua Formation disconformably overlaps the distal Arcas Fan beds in a transgressive relationship. Thin-bedded successions of fine-grained detrital, calcareous and evaporitic beds point to the fact that the transgressing lake experienced high-frequency changes of transgression, regression and total dessication. The lacustrine facies are lacking in fluvial components. Onlapping lake deposits and fan abandonment in Late Miocene precluded both further progradation of the Arcas Fan and the development of a fluvial system at the fan toe.

It can be concluded that the Arcas Fan is a relatively uniform sedimentary body with weak internal facies differentiations. Characteristic sedimentary features are prograding, mud-supported gravel bodies, which have been identified as typical debris flow deposits. The uniform distribution of these clast-rich debris flows all over the fan suggests mass movements of viscous sediment as the major transportation mechanism. The well-developed roundness of gravel mode particles are thought to be a result of multi-phase deposition and reworking of sediment within the catchment and along the transportation route from the Quebrada Arcas to the distal toes of the fan. The debris flows forming the Arcas Fan body must have been of great volumes and initial high viscosity to carry boulders as large as 5 m over distances of more than 30 km. Prerequisites of debris flows are accumulations of rock debris in the catchment and high intensity and high volume precipitation (or glacial melting) events. The Recent mudflows are clast-poor debris flows (Blair and McPherson, 1994a). The lack of clasts >20 mm indicates that, recently, the amount and intensity of precipitation are insufficient to produce clast- and boulder-rich debris flows, like those that built the Miocene sedimentary body of the Arcas Fan.

GRAVITY FIELD OF THE ARCAS FAN

Apart from a poor-quality well log penetrating 936 m into the northwestern portion of the fan (Rieu, 1975), gravity data provide the only subsurface data concerning the thickness, shape, and internal architecture of the Arcas Fan. Knowledge of the fan body volume and sediment density is necessary for a mass balance calculation by 3D gravity modeling. Because low density fan sediments contrast with the compacted, denser sedimentary, magmatic and metamorphic rocks of the basement, the fan body generates a local negative gravity anomaly, which can be detected by a high-resolution gravity survey.

Gravity measurements were made at 80 stations, spaced approximately 2 km apart along three survey lines in the Arcas fan area, and along a fourth line 5 km off the fan (Fig. 5). The survey is a subset in a file of about 12,000 gravity sites for the whole central Andes. All measurements are tied to the IGSN71 gravity datum in Iquique/Chile (IGSN71 40400K). Tidal corrections of gravity measurements were calculated using the tables of the 'Annual Earth-Tides-Corrections', published yearly by Geophysical Prospecting. The drift of the LaCoste and Romberg instruments (models G and D) is estimated to be less than 0.1 mGal per day (1 mGal $=10^{-5}$ m s^{-2}). Longitude and latitude were determined by GPS; altitude was determined by high-precision barometry linked to the base station at Quillagua. To improve the quality of the barometric measurements, time-dependent drift corrections were calculated, using as many benchmarks and repeated measurements as possible. The normal gravity was calculated according to IGSN71, using the International Gravity Formula of 1967. For the topographic reduction, a method developed for gravity investigations in the Alps was used (Ehrismann *et al.*, 1966), after

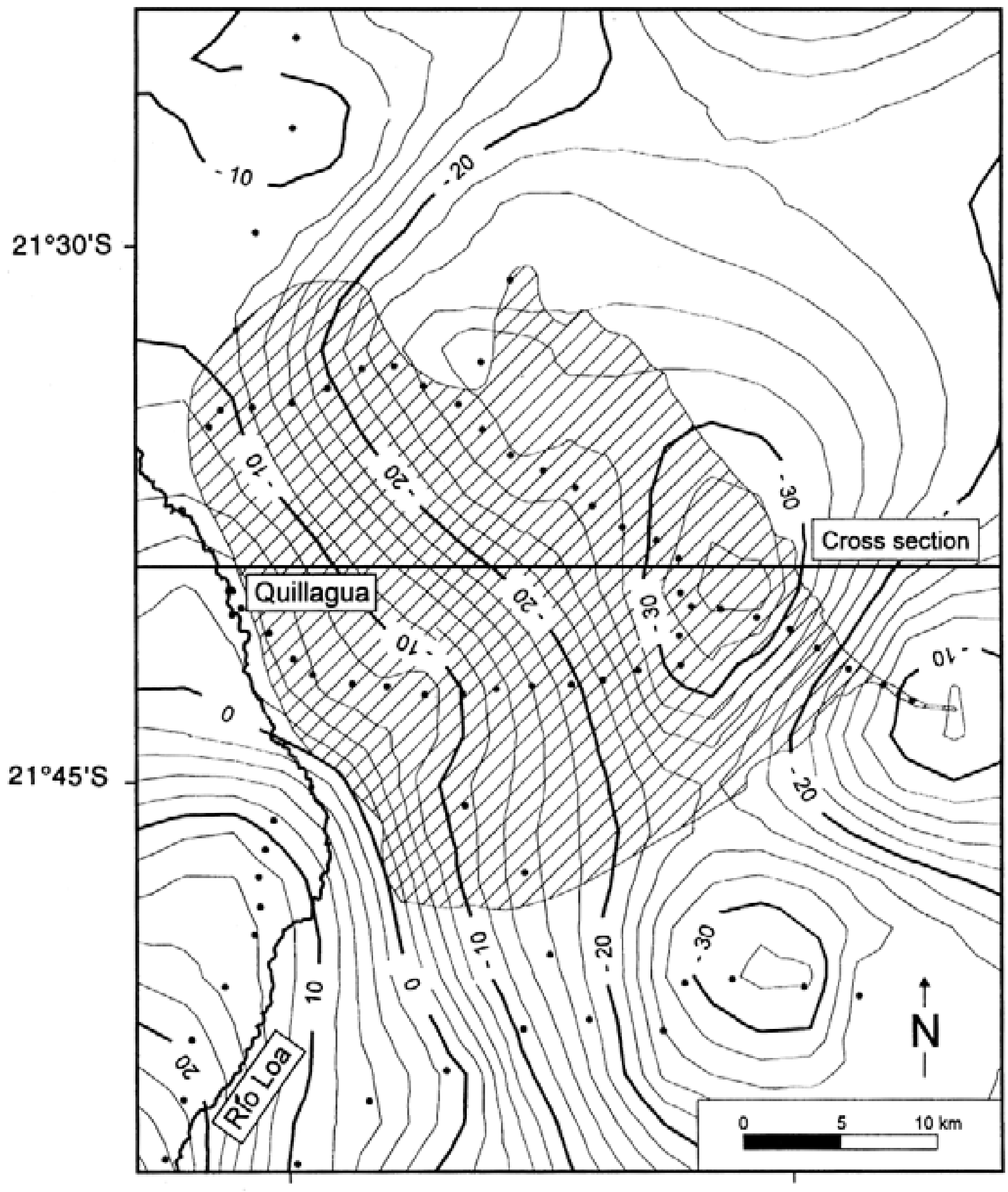


FIG. 5. Arcas Fan residual gravity field. The residual gravity is calculated from the Bouguer gravity field by elimination of long wavelengths by numerical filtering. Gravity contour interval is 2 mGal. Black dots indicate gravity sites along three profiles crossing the Arcas Fan (hatched area) in east-west- and northwest-southeast direction. A local minimum of -35 mGal indicates the maximum thickness of the Arcas Fan about 13 km northwest of the apex. Cross section shown in figure 6. The origin of the -32 mGal minimum southeast of the fan is not yet known. Geological evidence from the Río Loa canyon points to a regional basement uplift along a fault striking northwest-southeast from the village of Quillagua along the course of Río Loa up to the river bent to proceed in a southeastern direction. It can be assumed that the gravity minimum reflects a strong density contrast between light alluvial sediments on the downthrown, northeastern block and uplifted, high-density basement units southwest of the fault.

adapting it to the special situation in the Central Andes.

The residual gravity anomaly map (Fig. 5) was calculated from the Bouguer anomaly field by applying a bi-polynomial field of degree k=5. The Bouguer gravity field covers the western South American continental margin from the coast in the west to the lowlands of the NW Argentinian Chaco from latitudes 20°S to 30°S (Araneda *et al.*, 1994; Götze *et al.*, 1994; Götze *et al.*, 1990). The amplitude of the residual field of the Arcas Fan amounts to about -35 mGal, which is interpreted to reflect the density contrast between the fan sediments and the underlying denser rocks.

Interpretation of the residual field is based on interactive 3D forward modeling using the IGMAS-program (Götze, 1984; Götze and Lahmeyer, 1988; Schmidt, 1993). 3D modeling of the Arcas Fan is divided into two steps:

1- utilizing the stratigraphic and tectonic field data, six east-west geological cross sections of the Arcas Fan area with a spacing between 2 and 8 km were constructed. Six cross sections are the minimum prerequisite to construct a 3D model of the Arcas Fan parallel to the general eastwest direction of the mass movement. The geometric outlines of the geological bodies were digitized and filed as polygons in the IGMAS program. The geological model cross sections separate the Arcas Fan, the Sichal Formation, the Precordillera and the basement of the Longitudinal Valley, the Quillagua Formation, and the Coastal Cordillera (Fig. 6). Mean rock densities are assigned to each geological body and are determined in two ways: in the first method, the fan sediment density is calculated in the field by *in situ* density determinations. About 0.5 m^3 of sediment was excavated and weighed with a field scale. The excavated hole was filled by a mold of loose sand, and the mold volume was determined with a measuring jug for liquids. A mean fan sediment density of 1.80 g cm^{-3} ($\Delta\rho$ = ±2%) was calculated applying Athy 's law (Athy, 1930) of exponential

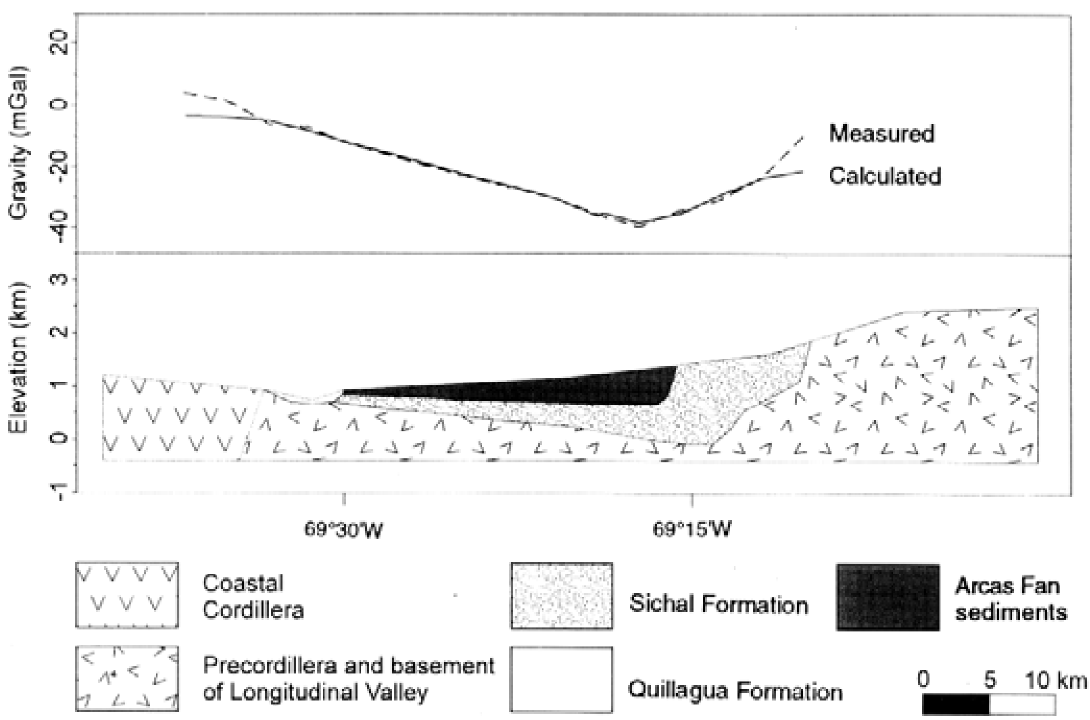


FIG. 6. 2D-density model cross section of the Arcas Fan at 21°39'S. The section contains the model bodies, which contribute to the gravity effect of the 3D model; **a-** dashed line: residual gravity; solid line: gravity calculated by interactive modeling; **b-** rock types and densities: Coastal Cordillera, Jurassic to Neogene sediments, plutonic and volcanic rocks; ρ = 2.76 g cm^{-3}; Precordillera and basement of the Longitudinal Valley (Paleozoic to Paleogene); ρ = 2.64 g cm^{-3}, Sichal Formation, Oligocene to Miocene terrestrial conglomerates; ρ = 2.07 g cm^{-3}; Quillagua Formation, Late Miocene lacustrine carbonates; ρ = 1.87 g cm^{-3}; Arcas Fan, Late Miocene clast-rich debris flow deposits, ρ = 180 g cm^{-3}. Vertical exaggeration is 4.

increase of density due to compaction, using a measured surface density of 1.76 g cm^{-3} ($\Delta\rho = \pm 2$ %), a compaction coefficient of 0.34 km^{-1} for coarse clastic deposits, and an average fan thickness of 150 m. All other rock densities were determined by using actual measurement;

2- polygons in the geological cross sections are linked to closed 3D bodies by triangulation and are combined to form a 3D subsurface model of the Arcas Fan area. The synthetic residual gravity field caused by the geological model is calculated, and modeled and observed field data are compared. To match the modeled and observed residual gravity fields, the polygon vertices and specific densities of the geological bodies are adapted by interactive computer graphics. A close fit of measured to modeled residual gravity fields shows the high quality of the 3D model (Fig. 6).

VOLUME AND MASS CALCULATION OF THE ARCAS FAN AND CATCHMENT

The main requirement of the mass balance calculation is the reconstruction of rock volumes eroded from the catchment and accumulated in the fan. The central problem is the reconstruction of geological bodies with different boundary shapes (Fig. 7).

CATCHMENT

For volume calculation, the catchment has to be subdivided into two areas, the area of the Quebrada Arcas drainage system below and the area of the topographic elevation above the Miocene peneplain. The remnants of this peneplain served as construction points to model its topography. The peneplain covers 64% of the catchment and dips west 3° to 3.5°. It intersects the Sierra del Medio and Sierra de Moreno at altitudes of about 3,750 m and 2,900 m ($\Delta h = \pm 0.01$%), respectively. Because the peneplain is topped by a likewise incised ignimbrite with similar age and chemistry as the ignimbrite at the Arcas Fan base the authors assume, its remnants in the Sierra de Moreno were connected with the fan apex at 1,650 m. Additionally, the similar ages and stratigraphic positions of the ignimbrites in both areas suggest that the beginning of the erosion in the catchment is time-equivalent with the onset of fan sedimentation in the Longitudinal Valley (K-Ar dating of reference surfaces). The area below the

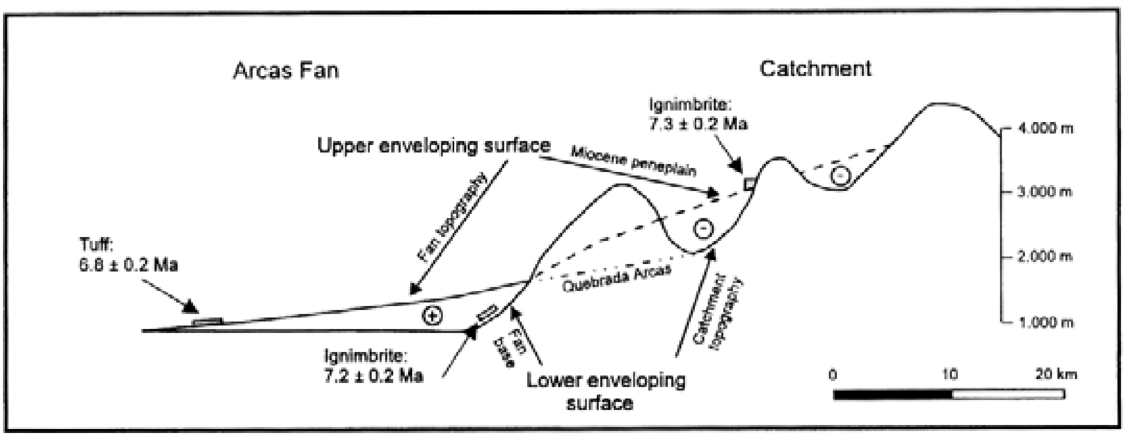


FIG. 7. Concept of volume calculations and timing of the exogenic mass transfer. The volume calculation in the catchment is based on a volumetric modeling of the negative geological body underneath the Miocene peneplain and extrapolation of the mean amount of erosion for the area above the peneplain. The fan bodv represents a positive geological body, limited by the fan topography and the fan base, according to the 3D gravity modeling. Ignimbrites covering remnants of the peneplain and intercalated in the old fan sediments and a tuff layer within the youngest fan sediments were dated by the K-Ar technique, providing the temporal framework of the mass transfer between catchment and fan (cross section is idealized, volcanic layers not to scale).

peneplain is a volumetrically negative body or open pit and is defined by two surfaces: the lower surface is the present day topography, the upper surface is defined by the former peneplain. For further calculations both surfaces were digitized and filed in the ENTEC 3D modeling software system. The volume calculation for the area below the peneplain yields 73.2 km^3, corresponding to an average erosion of 159 m. For the topographic elevations above the peneplain the authors assume the same average vertical erosion as in the area below because rock types and structural evolution are identical. Since the catchment area is relatively small and the relief above the peneplain is low, it is reasonable to assume that Late Miocene erosion throughout the entire catchment was controlled by equal climatic conditions. Based on these assumptions an eroded rock volume of 41.8 km^3 was calculated for the area above the peneplain. The eroded rock volume of both areas adds up to 115 km^3 ($\Delta V = \pm 6$ %) for the entire catchment. Taking into account a mean density of the catchment rocks of 2.36 g cm^{-3} ($\Delta\rho = \pm 2$ %), a total eroded mass of 271x10^9 ($\Delta m = \pm 8\%$) ton results.

THE ARCAS FAN

The Arcas Fan, a positive or filled geological body, is likewise bounded by an upper surface, the recent topography. The fan base, where sedimentation initiated, cannot be observed directly due to burial. By interactive 3D gravity modeling the fan base could be reconstructed, due to the density contrast between the Arcas Fan sediments and the denser basement rocks (Fig. 6). The topographic data sets of the actual morphology and the fan base were also combined in the ENTEC system and linked to form a closed geological body. The Arcas Fan volume of 110 km^3 ($\Delta V = \pm 6\%$) and a mean density of 1.80 g cm^{-3} ($\Delta\rho = \pm 2\%$) results in a total mass of 198x10^9 ton ($\Delta m = \pm 8\%$).

K-Ar DATING OF REFERENCE SURFACES

In order to balance the exogenic mass exchange between catchment and fan, the beginning and end of fan accumulation must be dated precisely. Miocene eruptions in the Western Cordillera produced ignimbrite and tuff layers covering areas in the catchment and interbedded in the basal fan (Fig. 7).

Radiometric ages from three locations constrain mass-exchange chronology (for coordinates, see Table 2). In the catchment, an ignimbrite overlies the peneplain. Consequently, this volcanic event represents a maximum age for peneplain dissection and initiation of mass export to the Arcas Fan. Another ignimbrite layer crops out at the northern flank of the Arcas Fan and is interbedded in the oldest beds, about 20 m above the fan base, which is defined by the unconformity with the underlying Sichal Formation. Tuffs are intercalated in the marginal lacustrine beds of the Quillagua Formation, which interfinger with the youngest and most distal beds of the Arcas Fan. The stratigraphic position of the tuff beds near the top of the fan represents a datum for the end of debris supply to the fan from the catchment, and thus the cessation of fan accumulation.

The andesitic ignimbrites are composed of a matrix of unaltered, welded glass shards with a mean grain size of 100 µm. Phenocrysts consist of quartz, plagioclase and biotite. K-Ar ages were obtained from biotite crystals with a grain size between 75 and 150 µm. Whole-rock potassium concentration varies between 5% and 8% which is sufficient for precise dating of volcanic rocks aged less than 10 Ma. The age obtained from the catchment ignimbrite is 7.3±0.2 Ma, the ignimbrite near the fan base yields an age of 7.2±0.2 Ma.

TABLE 2. SAMPLES DATED BY THE K-Ar METHOD.

	Sample 1	Sample 2	Sample 3
Lithology	Ignimbrite	Ignimbrite	Tuff
Position	Top peneplain	Fan base	Top fan
Longitude	69°01'42"W	69°04'38"W	69°29'52"W
Latitude	21°44'18"S	21°28'50"S	21°41'02"S
Age	7.3±0.2 Ma	7.2±0.2 Ma	6.8±0.2 Ma
Potassium	6.6%	6.6%	7.2%

Geochron Laboratories, Krueger Enterprises Inc., Cambridge, Massachussets, U.S.A.

Similar major and minor element spectra obtained by XRFA suggest an origin of the volcanic rocks from the same magma chamber. The fine-grained acidic tuffs, which overlie Arcas Fan sediments are not welded and occur as decimeter-thick multi-layered beds. Unaltered biotite crystals yield a K-Ar age of 6.8±0.2 Ma.

Erosion in the catchment began after 7.3±0.2 Ma; Arcas Fan sedimentation began at the same time. The age of the ignimbrite (7.2±0.2 Ma) intercalated in basal fan sediments supports this inference. Fan sedimentation ceased shortly after deposition of the 6.8±0.2 Ma tuffs. Based on the mean ages, fan sedimentation and erosion of the catchment lasted about 0.5±0.4 Ma. Considering the analytical errors of the age determinations, it is reasonable that the exogenic mass transfer had a duration between 0.1 and 0.9 Ma.

MASS BALANCE, EROSION AND SEDIMENTATION RATES

Volume calculations based on 3D gravity modeling revealed an Arcas Fan volume of 110 km^3 ($\Delta V = \pm 6$ %). Based on a mean sediment density of 1.80 g cm^{-3} ($\Delta\rho = \pm 2$ %), the fan contains a mass of 198 x 10^9 ton ($\Delta m = \pm 8$ %). Throughout the fan base area of 742 km^2 an average local crustal load of 0.267 x 10^9 ton km^{-2} results. Given a mean rock density of 2.36 g cm^{-3} ($\Delta\rho = \pm 2$ %), the volume of eroded material in the source area, 115 km^3 ($\Delta V = \pm 6$%), amounts to 271x10^9 ton ($\Delta m = \pm 8$%). Throughout the source area of 723 km^2 the average local crustal unloading was 0.375x10^9 ton km^{-2}. Isotopic dating of volcanic rocks suggests ages of 7.3±0.2 Ma and 6.8±0.2 Ma for the beginning and the end of the catchment erosion and Arcas sedimentation, respectively. Considering the most probable mean values of this timing, the Arcas Fan developed during an interval of 0.5 my. Averaging the fan volume of 110 km^3 throughout its base area of 742 km^2 results in a mean sediment accumulation rate of 0.296 m ka^{-1}. The erosional volume of 115 km^3 throughout the Arcas Fan source area of 723 km^2 results in a mean erosion rate of 0.318 m ka^{-1} Comparison of the fan and source rock masses reveals a deficiency of 73 x10^9 ton ($\Delta m = \pm 8$%) in the Arcas Fan. About 27% of the rock volume eroded in the source area is missing in the Arcas Fan. The mass deficiency of 27% is calculated independently of the analytical errors, because they are in the same order of magnitude in both the erosional and the depositional areas. Since calculation of the fan volume is based on a potential technique, a cumulative error of the mass deficiency is hard to estimate. The mean sedimentation rate based on the calculation of the Arcas Fan volume should have been about 0.407 m ka^{-1}. Post-sedimentary, erosive lowering of the fan surface is evidenced by canyon incisions and excavated boulders. Clast-rich debris flow sedimentation stopped at 6.8 Ma, and secondary processes began to alter the fan surface. The strategy of error estimation for this mass balance is discussed by Dörr (1996).

DISCUSSION

ORIGIN AND GEOLOGICAL SIGNIFICANCE OF THE MASS TURNOVER

According to the mass balance calculation, development of the Arcas system occurred over about 500 ka in which erosion and sedimentation rates were almost balanced. The comparison of the fan and source masses reveals a deficiency of about 27% in the Arcas Fan. This loss can be attributed to chemical dissolution of sediment in the fan subsurface by groundwater moving from the Precordillera down to the Río Loa, wind deflation of the fan surface and erosion by episodic rains. Nevertheless, the mean sediment accumulation rate of the Arcas Fan (0.296 m ka^{-1}) is similar to rates of 0.1 to 1.11 m ka^{-1} for alluvial fans in the Death Valley, California (Hooke, 1972; Hooke and Dorn, 1992) and 0.3 m ka^{-1} for Miocene alluvial fans in the Teruel-Ademuz Basin, Spain (Kiefer, 1993).

According to fission track data, Benjamin *et al.* (1987) proposed uplift rates of about 0.3 m ka^{-1} between 10 and 5 Ma for the Bolivian Eastern Cordillera. Masek et al. (1994) proposed to interpret the original data in terms of denudation rates (Jordan, personal communication, 1997). Data reevaluation provided denudation rates of 0.2 to 0.4 m ka^{-1} at altitudes between 4,000 m and 5,000 m and 0.3 to 0.9 m ka^{-1} at altitudes between 2,000 m and 3,000 m. Though the Bolivian Eastern Cordillera and the Arcas Fan source area are widely separated, the denudation rates of both regions seem to be in the same order of magnitude in the Late Miocene. Considering the Recent high altitudes of the Precordillera, the authors support the statement of Masek *et al.* (1994) concerning the Central Andes that even in the catchment area of the Arcas Fan the rate of uplift overwhelmed the rate of erosion. Within this context the authors have to interpret the Arcas Fan and its catchment as an intra-montane erosion sedimentation-system without mass exportation off the orogen.

Obviously the mass turnover, which created the Arcas Fan was not exclusively controlled by the Late Miocene uplift of the Precordillera: the short-termed fan progradation, characterized by a sudden initiation of debris flows and a dramatic decline in fan accumulation after 6.8 Ma may correspond to a temporal limited sediment supply from the catchment area. Since there is no evidence for an increase or a decrease of the uplift rates within the Andean orogen in Late Miocene (Masek *et al.*, 1994), the mass turnover must have been triggered by a climatic change. Other lines of evidence may support this assumption.

The Arcas Fan sediments distally interfinger with formations of the Quillagua-Llamara-Basin sedimentary system, which developed in the Longitudinal Valley from Oligocene to Quaternary (Jensen, 1992). The basin fill is characterized by a complex framework of alluvial, fluvial and lacustrine depositional systems. (Sáez, 1995b). It is assumed that the subsidence history of the basin is mainly controlled by the structural evolution of the Longitudinal Valley and the adjacent Precordillera. Nevertheless, alternating levels of fluvial, lacustrine and evaporitic beds suggest repeated changes of the climatic conditions. Due to the lack of radiometric and biostratigraphic data, the climatic history of the basin is difficult to record. Various investigations are in progress. A Middle Miocene climatic change to more arid conditions was proposed by Alpers and Brimhall (1988) according to geochemical data from secondary ores of the La Escondida mining district southeast of Antofagasta. Within this context, the progradation of the Arcas Fan is interpreted as a climatic signal. Because the tectonic uplift of the catchment was obviously not balanced by erosion prior to 7.3 Ma, a shift to more humid conditions between 7.3 and 6.8 Ma must have triggered erosion, mass turnover and fast accumulation in the fan area. Onlap of the Quillagua Formation carbonates, which grade into the Soledad Formation evaporites (Jensen, 1992; Sáez, 1995b) point to a reverse shift back to more arid conditions in the Latest Miocene. If tectonic uplift of the catchment and /or constant climatic conditions would have controlled sedimentation, the authors would expect a temporal and spacial stable facies association in the basin rather than a fast fan progradation followed by a lacustrine onlap and a final evaporation period.

The exogenic mass turnover within the Arcas Fan system should cause an isostatic uplift of the catchment in the Precordillera due to unload and a deflection of the fan area of the Longitudinal Valley due to loading. Based on the mass balance data, Dörr (1996) realized and discussed rough estimations of the amounts of vertical isostatic response of both areas. According to the Airy Model (Airy, 1855; Pratt, 1859) of isostatic compensation, the catchment area uplift should be about 114 m, the fan area deflection about 80 m. Application of the Vening-Meinesz model (Vening-Meinesz, 1928), which includes the flexural strength of the lithosphere, predicts a catchment uplift of about 30 m and a fan area deflection of about 20 m. According to the Vening-Meinesz model the catchment area would have elevated with a rate of 4.4 mm ka^{-1} and the fan area would have deflected with a rate of 3.4 mm ka^{-1}. Interference of horizontal forces due to the plate convergence of the South American and the Nazca plates have not been included because the deep crustal structure of the Andean forearc is still under discussion. Though the model calculations are just rough estimations, they seemed to be about 2 orders of magnitude less than uplift rates recently proposed by Muñoz and Charrier (1996) for the western Altiplano of northern Chile, Sebrier *et al.* (1979) for the Central Andes of Peru, and Tosdal *et al.* (1984) for the Precordillera of southern Peru.

Concerning this large difference, the authors conclude that the area of the exogenic mass turnover in the Arcas Fan system and the amount of rock debris were too insignificant to cause vertical movements in an order of magnitude to be detected in the context of the Andean uplift.

CONCLUSIONS

- Analysis of the Arcas Fan demonstrates the usefulness of high-resolution gravity 3D modeling as a tool for reconstructing near-surface sedimentary bodies. A low density sedimentary body of the size of the Arcas Fan may cause a local negative anomaly of up to -35 mGal, which can clearly be separated from the regional residual gravity field. In combination with 3D volumetric modeling of the eroded volume in the catchment, an exogenic mass balance of a large alluvial fan and its catchment can be established. The combination of both techniques links erosional and sedimentary systems and thus provides a new geological tool to quantify exogenic processes.
- Volume calculations based on gravity modeling and radiometric dating of volcanic rocks revealed a mean sedimentation rate of the Arcas Fan of 0.296 m ka^{-1}, which is in the same range of rates of alluvial fans in the Death Valley, California, and in the Teruel-Ademuz Basin, Spain. The mean erosion rate in the catchment of about 0.318 m ka^{-1} is in the same magnitude as the erosion of the Bolivian Andes of about 0.3 m ka^{-1} in the Late Miocene proposed by Benjamin *et al.* (1987) and Masek *et al.* (1994).
- The total exogenic mass transfer from the catchment to the Arcas Fan occurred in a short timespan of 0.5±0.4 my. Transport was characterized by clast-rich debris flows, which must have been mobilized by intense episodic precipitation. Consequently, the Arcas Fan can be interpreted as a climatic signal for wetter conditions between 7.3 Ma±0.2 Ma and 6.8 Ma±0.2 Ma. The hyperarid climate in the Atacama Desert, which has prevailed since then, is characterized by extremely low precipitation with a recurrence interval of several years. The low intensity, short-term precipitation events only trigger small-scaled, clast-poor debris flows, which locally form a thin veneer on the fan surface.
- Erosion of 271×10^9 ton (Δm = ±8%) in the catchment and sedimentation of 198×10^9 ton (Δm = ±8%) in the Arcas Fan are evidenced by a mass deficiency in the fan of about 27%, which is interpreted to be of post-sedimentary subsurface groundwater dissolution, wind deflation and surface erosion.
- Area and extent of the mass turnover was too insignificant to cause catchment uplift due to erosional unload and fan area deflection due to sedimentary load. Obviously, even larger erosion-deposition-system, probably in the dimension of the entire Andean forearc, have to be considered to evidence a feedback of the exogenic and endogenic forces controlling the Andean orogeny.

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REFERENCES

Abele, G. 1989. The interdependence of elevation, relief, and climate on the western slope of the central Andes. *Zentralblatt für Geologie und Paläontologie*, No. 5-6, p. 1127-1139.

Airy, G.B. 1855. On the computation of the effect of the attraction of mountain-masses, as disturbing the apparent astronomical latitude of stations in geodetic surveys. *Philosophical Transactions of the Royal Society of London*, Vol. 145, p. 101-104.

Alpers, C.N.; Brimhall, G.H. 1988. Middle Miocene climatic change in the Atacama desert, northern Chile: evidence from supergene mineralization at La Escondida. *Geological Society of America, Bulletin*, Vol. 100, No. 10, p. 1640-1656.

Araneda, M.; Götze, H.-J.; Schmidt, S.; Goltz, G.; Alvers, M.; Riquelme, R.; Ugalde, H.; Ibbeken, H.; Kiefer, E.; Doerr, M. 1994. A new update of the gravity database in Northern Chile. *In Congreso Geológico Chileno, No. 7, Actas*, Vol. 1, p. 566-570. Concepción.

Athy, L.F. 1930. Density, porosity and compaction of sedimentary rocks. *American Association of Petroleum Geologists, Bulletin*, Vol. 14, p. 1-24.

Benjamin, M.T.; Johnson, N.M.; Naeser, C.W. 1987. Recent rapid uplift in the Bolivian Andes: Evidence from fission-track dating. *Geology*, Vol. 15, p. 680-683.

Blair, T.C.; McPherson, J.G. 1994a. Alluvial fan processes and forms. *In* Geomorphology of Desert Environments (Abrahams, AD.; Parsons, A.J.; editors). *Champman & Hall*, p. 345-398.

Blair, T.C.; McPherson, J.G. 1994b. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes*, Vol. 64, No. 3, p. 450-489.

Bogdanic, T. 1990. Kontinentale Sedimentation der Kreide und des Alttertiars im Umfeld des subduktionsbedingten Magmatismus in der chilenischen Präkordillere. *Berliner Geowissenschaftliche Abhandlungen*, Vol. A 123, 117 p.

Dörr, M.J. 1996. Der Arcas Fächer und sein Erosionsgebiet in Nordchile: Bilanz einer exogenen Massenverlagerung. *Berliner Geowissenschaftliche Abhandlungen*, Vol. A 189, 121 p.

Ehrismann, W.; Müller, G.; Rosenbach, O.; Sperlich, N. 1966. Topographic reduction of gravity measurements by the aid of digital computers. *Bolletino de Geofisica teoretica ed applicata* Vol. 8, p. 118-128.

Francis, P.W.; Hawkesworth, C.J. 1994. Late Cenozoic rates of magmatic acitivity in the Central Andes and their relationshjps to continental crust deformation and thickening. *Journal of the Geological Society of London*, Vol. 151, Part 5, p. 845-854.

Froidevaux, C.; Isacks, B.L. 1984. The mechanical state of the lithosphere in the Altiplano-Puna segment of the Andes. *Earth and Planetary Science Letters*, Vol. 71, p. 305-314.

Galli-Olivier, C. 1967. Pediplane in northern Chile and Andean uplift. *Science*, Vol. 158, p. 653-655.

Götze, H.-J. 1984. Über den Einsatz interaktiver Computergrafik im Rahmen 3-dimensionaler Interpretationstechniken in Gravimetrie und Magnetik. Habilitation Thesis (Unpublished), *Technische Universität, Clausthal*, 234 p. Germany.

Götze, H.-J.; Lahmeyer, B. 1988. Application of three-dimensional interactive modeling in gravity and magnetics. *Geophysics*, Vol. 53, p. 1096-1108.

Götze, H.-J.; Araneda, M.; Chong, G.; Giese, P.; Heinsohn, W.-D.; Krüger, D.; Omarini, R.; Röwer, P.; Schmidt, S.; Schmitz, M.; Schwarz, G.; Wigger, P.; Viramonte, J. 1994. The Lithospheric Structures of the Central Andes (20°-26°S) as inferred from Interpretation of Geophysical Research. *In Congreso Geológico Chileno, No. 7, Actas*, Vol. 2, p. 1349-1353. Concepción.

Götze H.-J.; Lahmeyer, B.; Schmidt, S.; Strunk, S.; Araneda, M. 1990. A new gravity data base in the Central Andes (20°-26°S). *EOS Transactions, American Geophysical Union*, Vol. 71, p. 401, 406-407.

Hooke, R.LeB. 1972. Geomorphic evidence for the Late-Wisconsin and Holocene tectonic deformation, Death Valley, California. *Geological Society of America, Bulletin*, Vol. 83, p. 2073-2098.

Hooke, R.LeB.; Dorn, R.L. 1992. Segmentation of alluvial fans in Death Valley, California. New Insights from surface exposure dating and laboratory modeling. *Earth*

Surface Processes and Landforms, Vol. 17, p. 1-19.

Ibbeken, H. 1983. Jointed source rocks and fluvial gravels controlled by Rosin's law: A grain-size study in Calabria, south Italy. *Journal of Sedimentary Petrology*, Vol. 53, p. 1213-1231.

Ibbeken, H.; Schleyer, R. 1991. Source and Sediment: A case study for the Calabrian active margin. *Springer*, 300 p. Heidelberg.

Ibbeken, H. 1995. The Arcas Fan in the central Andes, signals of exogenic mass transfer, Movie 36 min, 16 mm or Video. Zentralein-richtung für Audiovisuelle Medien. *Freie Universität* Berlin.

Isacks, B.L. 1988. Uplift of the Central Andean plateau and bending of the Bolivian orocline. *Journal of Geophysical Research*, Vol. 93, p. 3211 -3231.

Jensen, A. 1992. Las cuencas aluvio-lacustres oligoceno-neogenas de la región de ante-arco de Chile septentrional, entre los 19° y 23° Sur. Ph.D. Thesis (Unpublished), *Universidad de Barcelona*, 217 p.

Jordan, T.E.; Isacks, B.L.; Brewer, J.A.; Ramos, V.A.; Ando, C.J. 1983. Andean tectonics related to geometry of subducted Nazca plate. *Geological Society of America, Bulletin*, Vol. 94, p. 341-361.

Kiefer, E. 1993. Modellierung von Sedimentationsraten. *Die Geowissenschaften*, Vol. 11, p. 231-245.

Lyon-Caen, H.; Molnar, P.; Suárez, G. 1985. Gravity anomalies and flexure of the Brazilian shield beneath the Bolivian Andes. *Earth and Planetary Science Letters*, Vol. 75, p. 81-92.

Maksaev, V. 1990. Metallogeny, geological evolution, and thermochronology of the Chilean Andes between latitudes 21° and 26° South, and the origin of major porphyry copper deposits. Ph.D. Thesis (Unpublished), *Dalhousie University*, 554 p. Halifax, Canada.

Masek, J.G.; Isacks, B.L.; Gubbels, T.L.; Fielding, E.J. 1994. Erosion and tectonics at the margins of continental plateaus. *Journal of Geophysical Research*, Vol. 99, p. 13941-13956.

Mortimer, C.; Saric, N. 1975. Cenozoic studies in northernmost Chile. *Geologische Rundschau*, Vol. 64, p. 395-420.

Mortimer, C. 1981. Drainage evolution in the Atacama desert of northernmost Chile. *Revista Geológica de Chile*, Vol. 11, p. 3-28.

Muñoz, N.; Charrier, R. 1996. Uplift of the western border of the Altiplano on a west-vergent thrust system, northern Chile. *Journal of South American Earth Sciences*, Vol. 9, p. 171-181.

Naranjo, J.A.; Paskoff, R.P. 1982. Estratigrafía de las unidades sedimentarias cenozoicas de la cuenca del Río Loa en la Pampa del Tamarugal, Región de Antofagasta, Chile. *Revista Geológica de Chile*, Vol. 15, p. 49-57.

Naranjo, J.A.; Paskoff, R.P. 1983. Formation et évolution du piemont andin dans le desert du Nord du Chili (18°-21° latitude Sud) pendant le Cénozoique supérieur. *Comptes Rendus de l' Académie de Sciences de Paris*, Serie II, p. 743-748.

Naranjo, J.A.; Paskoff, R.P. 1985. Evolution cenozoica del piedmonte Andino en la Pampa del Tamarugal, Norte de Chile (18°-21°S). *In Congreso Geológico Chileno, No. 4, Actas*, Vol. 4, p. 149-165. Antofagasta.

Nilsen, T.H. 1985. Modern and ancient alluvial fan deposits. *Van Nostrand Reinhold*, 372 p. New York.

Paskoff, R.P. 1977. Quaternary of Chile: State of research. *Quatemary Research*, Vol. 8, p. 2-31.

Reutter, K.-J.; Giese, P.; Götze, H.-J.; Scheuber, E.; Schwab, K.; Schwarz, G.; Wigger, P. 1988. Structures and Crustal Development of the Central Andes between 21° and 25°S. *In* The Southern Central Andes (Bahlburg, H.; Breitkreuz, C.; Giese, P.; editors). *Lecture Notes in Earth Sciences*, Vol. 17, p. 231-261.

Rieu, M. 1975. Les formations sédimentaires de la Pampa del Tamarugal et le Río Loa (Norte du Chili). *Cahiers ORSTOM, Série Géologique*, Vol. 7, p. 145-164.

Roeder, D. 1988. Andean-age structure of the Eastern Cordillera (province of La Paz, Bolivia). *Tectonics*, Vol. 7, p. 23-29.

Sáez, A. 1995a. Recent and ancient lacustrine systems in convergent margins. *GLOPALS-International Association of Sedimentologists, Abstracts*, 41 p.

Sáez, A. 1995b. Recent and ancient lacustrine systems in convergent margins. Excursion Book: Cenozoic and Quaternary lacustrine systems in northern Chile (Central Andes, Arc and Fore-Arc zones. *GLOPALS-International Association of Sedimentologists*, 77 p.

Scheuber, E.; Bogdanic, T.; Jensen, A.; Reutter, K.-J. 1994. Tectonic development of the North Chilean Andes in relation to plate convergence and magmatism since the Jurassic. *In* Tectonics of the Southern Central Andes (Reutter, K.-J.; Scheuber, E.; Wigger, P.; editors). *Springer-Verlag*, p. 121-140.

Schmidt, S. 1993. 3-D interactive modeling and the visualization in gravity and magnetics (Abstract). *Terra Nostra*, Vol. 5, 112 p.

Sebrier, M.; Marocco, R.; Gross, J.J.; Macedo, B.S.; Montoya, R.M. 1979. Evolución neógena del piedemonte de los Andes del Sur del Peru. *In Congreso Geológico Chileno, No. 2, Actas*, Vol. 1, p. 71-88. Arica.

Sheffels, B.M. 1990. Lower bound on the amount of crustal shortening in the central Bolivian Andes. *Geology*, Vol. 18, p. 812-815.

Skarmeta, J.J.; Marinovic, N. 1981. Hoja Quillagua, Región de Antofagasta. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 51, p. 63, 1 mapa 1:250.000.

Skarmeta, J.J. 1983. The structural geology of the Sierra Moreno, Northern Chile. Ph.D. Thesis (Unpublished), *University of London*, 299 p.

Thorpe, R.S.; Francis, P.W.; Harmon, R.S. 1981. Andean andesites and crustal growth. *Philosophical Transactions of the Royal Geological Society of London*, Vol. 301, p. 305-320.

Tosdal, R.M.; Clark, A.H.; Farrar, E. 1984. Cenozoic polyphase landscape and tectonic evolution of the

Cordillera Ooccidental, southernmost Peru. *Geological Society of America, Bulletin*, Vol. 95, No. 11 p. 1318-1332.

Vening-Meinesz, F.A. 1928. A formula expressing the deflection of the plumb-lines in the gravity anomalies and some formulae for the gravity field and the gravity potential outside the geoid. *Koninklijke Akademie van Wetenschappen*, Vol. 31, p. 315-331.

Whitman, D.; Isacks, B.L.; Chatelain, J.-L.; Chiu, J.-M.; Pérez, A. 1992. Attenuation of high frequency seismic waves beneath the central Andean plateau. *Journal of Geophysical Research*, Vol. 97, p. 19929-19947.

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ADDITIONAL INFORMATION

For additional information concerning gravity data, topographic grids, sample site coordinates, abstracts as well as organisation and services of the Berlin SFB 267 (Deformation Processes in the Andes) do not hesitate to contact the website: http://userpage.fu-berlin.de/~geoinfhb/