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Large rock avalanche deposits (Sturzströme, sturzstroms) at Sierra Aconquija, northern Sierras Pampeanas, Argentina

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ABSTRACT

Extensive deposits of presumably dry rock avalanches are present along mountain fronts in the tectonically active northern Sierras Pampeanas of Northwest Argentina. The Quaternary deposits west of Sierra Aconquija (27° S. Lat.) are characterized by a moraine-like morphology and an internal geometry dominated by inverse grading. The avalanche deposits are the product of a two-phase movement history, of an initial rock-fall and subsequent unconfined flowage across the piedmont. The avalanches are interpreted to be related to seismic shaking of already preconditioned weak basement rocks.

ZUSAMMENFASSUNG

Entlang vieler Bergfronten der tektonisch aktiven Sierras Pampeanas von NW-Argentinien finden sich ausgedehnte Sturzstrom-Ablagerungen. Die quartären Sturzstrom-Ablagerungen westlich der Sierra Aconquija (27° südl. Breite) sind durch eine moränenartige Morphologie sowie durch eine inverse Gradierung charakterisiert. Die Ablagerungen sind das Resultat einer zweiphasigen Bergsturzbewegung: einer initialen Fallphase von der Randkette und einer anschliessenden Strömungsphase im Piedmont, die durch mechanische Fluidisierung erreicht wird. Die Entstehung ist an strukturell schwache Gesteine gebunden. Als Auslöser wird seismische Aktivität entlang der Randkette angenommen.

Introduction

Numerous rocky landslide deposits are present in the tectonically active Late Cenozoic Sierras Pampeanas and along the Puna edge of semi-arid northwestern Argentina at about 27° S Lat (Fig. 1). Although local geologic conditions differ, the unifying characteristic of all landslides is their proximity to mountain-bounding faults of Quaternary age. Two principal types of landslide deposits can be distinguished, both involving volumes of several million cubic metres: the first type has a distinct moraine-like morphology and internal depositional character with inverse grading. This type was generated by an initial rock-fall component at the mountain front and subsequent movement in the piedmont. The second, and less common type of landslide-deposit shows minimal disruption of the

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involved rocks; the movement lacks a rock-fall component and it is characterized by en bloc motion along pre-existent planes of weakness that are inclined in the direction of movement.

The landslides from Sierra Aconquija (Figs. 1 and 2) described in this investigation are rock avalanches and are among the best preserved examples of lobate rock-avalanche deposits in the northwestern Sierras Pampeanas. The morphologic features of these avalanches indicate that the avalanches may have streamed across the piedmont analogous to the sturzstroms of HEIM (1932) and HSÜ (1975).

Geological setting

The northern Sierras Pampeanas are located in the foreland of the principal Andes (Fig. 1). The Late Cenozoic Sierras Pampeanas are high-angle reverse fault bounded Precambrian basement blocks and are limited to the north by a small west-verging thrust belt, which primarily involves Mesozoic and Cenozoic sedimentary rocks. To the west the ranges grade into the high intraandean Puna Plateau with Sierra Chango Real, which limits the southeastern part of the plateau.

The western slopes of Sierra Aconquija, one of the northernmost Sierras Pampeanas blocks, are characterized by dark Precambrian biotite schists and Paleozoic granites with adjacent zones of migmatized biotite schists (GONZALES BONORINO 1951). The granites are present in the lower parts of the range and are exposed at the mountain front in the region east of the rock-avalanche deposits. All basement units show N–S to NNW striking foliation that dips to the east. These basement rocks are traversed by numerous pegmatitic dikes that either parallel the foliation of the schists or intrude into east-dipping joint sets that strike NNE to NW.

High angle NNE-trending reverse faults, which dip as much as 85°E, limit the Sierra Aconquija in the southern sector of the range and put the basement rocks in contact with the 2.9 Ma old Corral Quemado Formation (Fig. 2). The Corral Quemado Formation is the youngest member of the conformable Mio-Pliocene Santa María Group, which is exposed in the adjacent Santa María Valley to the north. Because the base of the Corral Quemado Formation is 3.4 Ma old, this relationship documents pronounced uplift of the Sierra Aconquija since 3.4 Ma (STRECKER, 1987). However, the principal deformational event in the region occurred after 2.9 Ma, when the Aconquija basement was thrust over the Corral Quemado Formation and the Santa María Group itself was faulted and folded. Recurrent tectonic activity along these faults and folds is documented for the mountain front and the piedmont regions of Sierra Aconquija and was most pronounced between after 2.5 Ma and before 0.6 Ma (STRECKER 1987). However, the region still is seismically active attesting to a continuing displacement along the principal faults.

Geometry and structure of the rock avalanches

The rock avalanches are 3 to 4 km long and defined by frontal rims and levees that rise 8 to 15 m above the surrounding alluvial fan deposits and the interior of the rock-avalanche deposits (Fig. 3). The widths of the avalanches range between 0.5 and 1.5 km. At least 8 different avalanche events can be recognized in a 10 km wide strip in front of Sierra

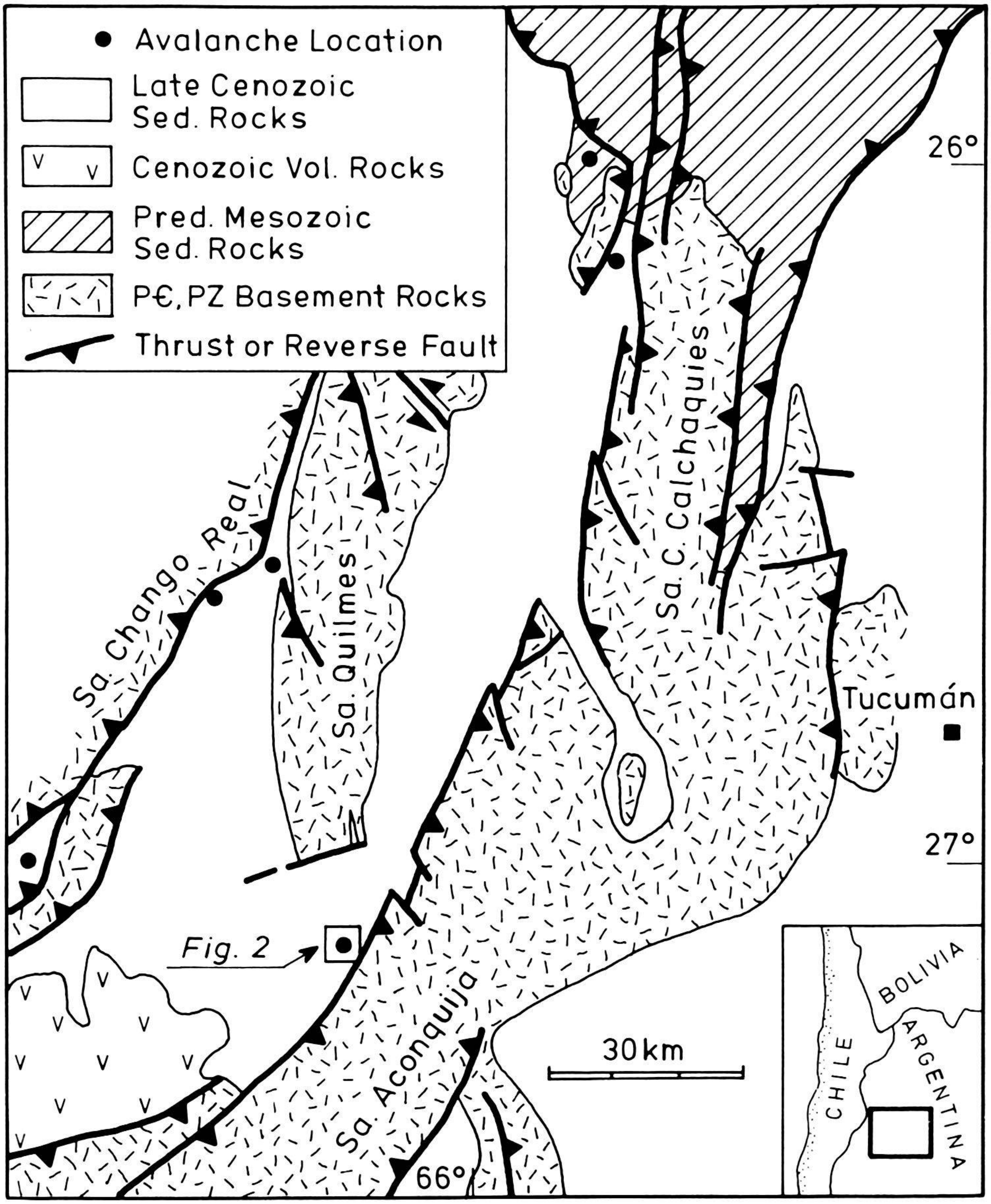

Fig. 1. Location map of the northern Sierras Pampeanas (after Mapa Geologico de la Republica Argentina, 1982; STRECKER 1987).

Aconquija. The rock avalanches with the best preserved morphology occur at Loma de la Aspereza, Avalancha del Zarzo (I and II), and at Loma Redonda (Fig. 2–4). The lobate morphology of these deposits is comparable in shape to that of active glaciers, suggesting that in its final stages of movement, the avalanche behaved like a non-Newtonian viscous fluid that streamed across the piedmont after falling from a high source region at the mountain front.

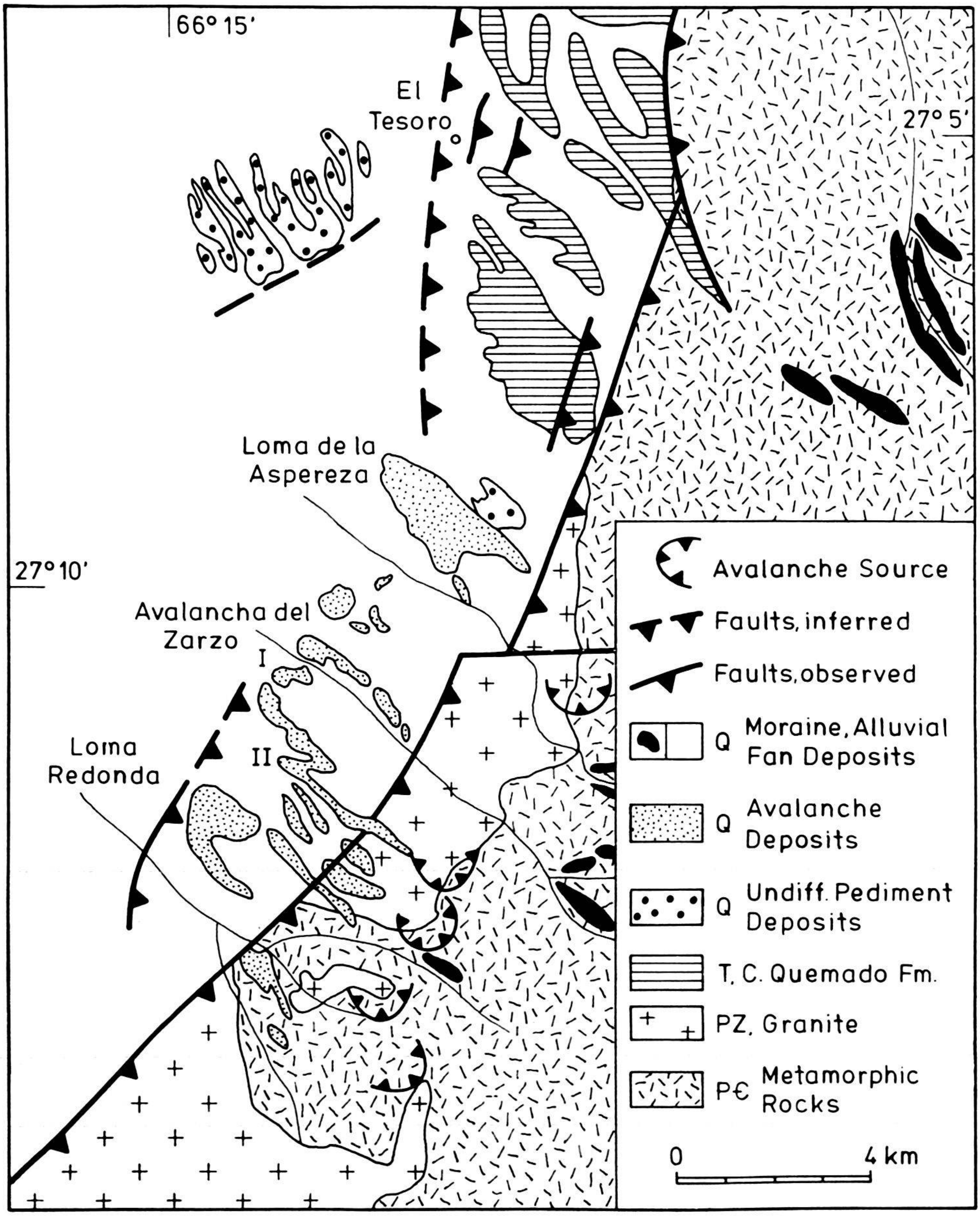

Fig. 2. Generalized geologic map of the SW-sector of Sierra Aconquija (after GONZALES BONORINO 1951; STRECKER 1987).

Apart from the sharply defined levees and frontal rims, the northern levees of the El Zarzo and Loma de la Aspereza avalanches are characterized by a succession of obliquely trending imbricated ridges reminiscent of marginal glacial crevasses. The ridges point uphill and towards the central part of the avalanche, as well as pointing outward within the frontal lobes, indicating that radial spreading of the rock mass was progressively

Fig. 3. Airphoto of the rock-avalanche deposits at Sierra Aconquija. See Fig. 2 for location and scale.

constrained as flow continued, i.e. the flow was greatest and moved farthest in the axial parts of the avalanche (Fig. 3 and 4). Some of the rock-avalanche deposits also display a hummocky interior topography, although the original topography has been altered by erosion and the accumulation of alluvial fan gravels (Fig. 3). Fluvial erosion has cut through the lateral and distal avalanche rims with the result that the lower interior parts are now being graded to the adjacent alluvial fan surfaces.

The erosional cuts reveal the internal character of the deposits and show that the upper parts of the deposits consist of large angular blocks that commonly range in size from several meters to 20 m in their maximum dimension, whereas the lower parts are made up of finer grained material ranging from powder-size debris to entirely fractured blocks smaller than 1 m in diameter (Fig. 5 and 6). The lithologic composition of the deposits is essentially monomictic and consists of granite and a small percentage of other rock types derived from the contact zone between the granite and the biotite schist. Inverse grading and distinct lithologic composition clearly separate rock-avalanche deposits from diamictons of other origins in the area.

Morphometric parameters

The volumes of the avalanche deposits range from 5 to 65 $\times$ 10^6 m^3 (tab. 1). They are, therefore, comparable in volume to sturzstrom deposits (Hsü 1975). The velocity of rock-avalanches can be evaluated if they surpass obstacles, whose dimensions are still measurable (Naranjo & Francis 1987). In the case of the rock avalanche at Loma de la

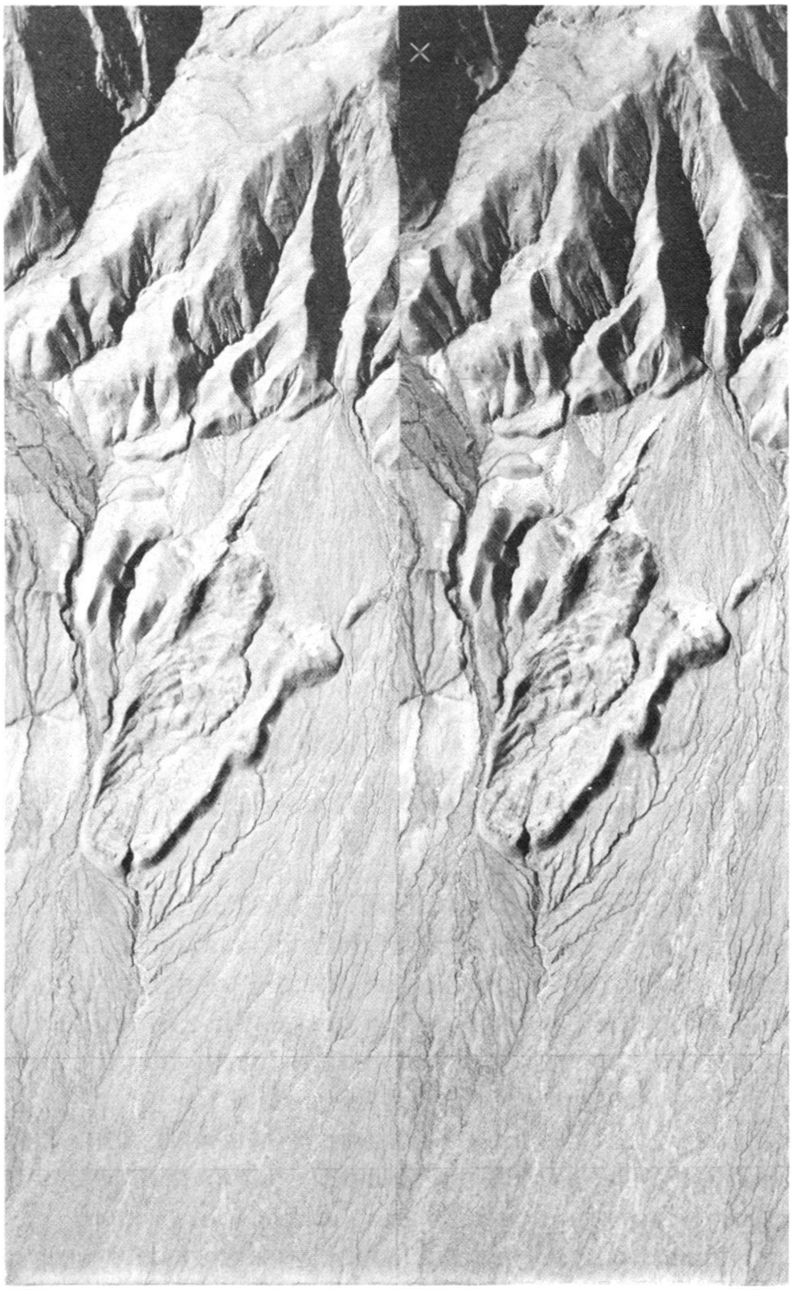

Fig. 4. Stereopair of the Loma de Aspereza rock-avalanche deposit. See Fig. 2 for location and scale

Aspereza, the moving rock mass overtopped a 50 m high and 1 km long isolated pediment remnant and continued 1.5 km downhill before it stopped. Following CRANDELL & FAHNESTOCK (1965), a minimum velocity can be calculated assuming that all potential energy $(m \cdot g \cdot h)$ was transformed into kinetic energy $\frac{(m \cdot v^2)}{2}$: $m \cdot g \cdot h = \frac{m \cdot v^2}{2}$ or $v = (2 \cdot g \cdot h)^{0.5}$, where m is the mass of the mobilized rock material, g the gravitational acceleration and h the height of the obstacle in the direction of movement. Accordingly velocities of 31.5 m/sec or 144 km/h are obtained for the Loma de la Aspereza rock avalanche.

Table 1: *Morphometric parameters of the avalanche deposits.*

	Loma de la Aspereza	Avalancha del Zarzo I	Avalancha del Zarzo II	Loma Redonda
h	50 m	-	-	-
H	800 m	900 m	850 m	700 m
S	4.25 km^2	7.53 km^2	1 km^2	5.52 km^2
L	7 km	6.5 km	5 km	7 km
T	5 m	5 m	5 m	30 m, 5 m
Vol	21.10^6 m^3	37.10^6 m^3	5.10^6 m^3	65.10^6 m^3
V1	114 km/h	-	-	-
V2	227 km/h	-	-	-
V3	266 km/h	-	-	-
H/L	0.11	0.13	0.17	0.10
Le	5.71 km	5.05 km	3.63 km	5.87 km

h height of obstacle
H total height between avalanche toe and source
S surface area
L length of movement
T medium thickness of the avalanche deposit
Vol avalanche volume
V1 velocity calculated with $v = (2 \cdot g \cdot h)^{0.5}$
V2 velocity calculated with frictional loss
V3 velocity calculated with $v = (2 \cdot g \Delta h)^{0.5}$
H/L apparent coefficient of friction
Le excessive travel distance

Another way to approximate avalanche velocity involves the calculation of the percentage of frictional loss (F) through comparing the height from which the rock mass descends (H) to the height (h) of the obstacle (Francis & Baker 1977). The value of frictional loss results from $F = 100 \cdot \left[\frac{1 - (h)^{0.5}}{H}\right]$, and equals $F = 75$ with the known values for the Loma de la Aspereza avalanche. With $v = 10 \cdot \frac{(2 \cdot g \cdot h)^{0.5}}{100 - F}$, a velocity of 63 m/sec or 227 km/h can be calculated. The value for F is certainly overestimated in this calculation because the avalanche not only completely overtopped the obstacle but also continued its movement downslope. Hence, the velocity may have been even more than 227 km/h.

If the velocity is calculated according to the principle of energy lines (Energielinien) according to Heim (1932; for review, also see Erismann 1986) the velocity for the Loma de Aspereza avalanche is 266 km/h (Table 1) which may represent a more realistic value. All calculated velocities are of the same order of magnitude and are only to be understood as approximations. However, these values are in the range of velocities for the Elm (160 km/h) and pre-Columbian avalanches in Peru with velocities of 316–335 km/h (Hsü 1975; Plafker & Ericksen 1978).

Avalanche mobility is commonly expressed by an apparent coefficient of friction expressed by height/distance (H/L). In the H/L ratio, H is the height between the avalanche source and the lowest elevation reached by the avalanche, and L, the horizontal distance between the source and the distal avalanche limit. For the avalanches at Sierra Aconquija, the H/L values vary between 0.10 and 0.17 (Table 1). The values are comparable to values obtained from dry volcanic and dry non-volcanic avalanches (Hsü 1975; Siebert 1984).

Another way in which avalanche mobility is expressed, is the excessive travel distance $L_e (L_e = L - H/\tan 32°)$. L_e is the distance between the theoretical avalanche terminus calculated assuming sliding motion and an internal angle of friction of 32°, and the observed avalanche terminus (Hsü 1975). The excessive travel distances at Sierra Aconquija are between 3.6 and 5.8 km.

Thus both, excessive travel distances and low apparent coefficients of friction indicate a high degree of mobility for the avalanches at Sierra Aconquija.

Age

The age of the avalanches is difficult to assess since they apparently rest on the alluvial fans of Sierra Aconquija that were regraded several times during the Quaternary Period. The alluvial fans were deposited over the Corral Quemado conglomerate. A retransported volcanic ash collected form a lacustrine deposit from within the low interior avalanche remnants between Loma de la Aspereza and Avalancha del Zarzo unfortunately did not provide a minimum age for the avalanche emplacement because the ash contains three different zircon populations. Two populations supply ages older than the Corral Quemado Formation and must be of detrital origin, and in the third no fission tracks are developed.

Although the high degree of preservation of the avalanches suggests a young age at most sites, the pronounced carbonate accumulation in the upper parts of the avalanche deposits indicates a middle-Pleistocene age for the rock-avalanche deposits. For example, the southernmost avalanche at Loma Redonda is cemented by a stage III–IV carbonate soil horizon. In comparison with similar soil-horizon development on pediment cover gravels in the adjacent Santa Maria Valley, this may indicate a middle-Pleistocene age for the deposit, as stage III–IV soil horizons are present on 0.6 to 1.2 Ma old pediment cover gravels (STRECKER 1987). However, neither absolute nor relative age data exist for carbonate horizons in other non-gravelly materials in this region.

Mechanics of movement

Theories that explain rock-avalanche movement include concepts of mechanical fluidization attained by high-energy grain collisions (HEIM 1932; HSÜ 1975; DAVIES 1982), air lubrication (SHREVE 1968), self-lubrication by basal molten rock (ERISMANN 1979) and acoustic fluidization. In the latter the rock mass is supported by particle groups that move in elastic waves, rather than a multitude of dispersed individual clasts (MELOSH 1979; 1987). Concrete evidence for the validity of acoustic fluidization and the air-lubrication hypotheses does not exist. In fact, HSÜ (1975) and ERISMANN (1979) showed that the air-lubrication hypothesis is wrong. In contrast, based on eye-witness reports, model experiments and detailed studies of avalanche deposits self-lubrication by rock melting (ERISMANN et al. 1977; ERISMANN 1979; 1986) and mechanical fluidization by high-energy collisions (HEIM 1932; HSÜ 1975; DAVIES 1982) appear to be realistic mechanisms. In areas where rock melting provided lubrication it is typical to find the pumice-like rock frictionite in the basal portions of the rock mass (ERISMANN et al. 1977; MASCH & PREUSS 1977). In the erosional cuts in the avalanche deposits in front of Sierra Aconquija this characateristic rock type was not found. It therefore appears unlikely that molten rock lubricated the moving rock mass and mechanical fluidization due to high-energy collisions is a more likely mechanism.

According to HEIM (1932) and HSÜ (1975), a falling rock mass will disintegrate upon its contact with the piedmont, and the fractured rock clasts will continue to move farther by means of high-energy collisions that permit maintainance of the original kinetic energy of the rockfall component. HSÜ (1975) viewed this portion of movement as being equal to the behavior of dispersed individual clasts in a fluid-like medium as in Bagnold grain-flow. In this analog to grain flow, the collision of the moving particles transfers and maintains kinetic energy throughout the entire moving mass of particles floating in a finer-grained lubricating matrix. According to HSÜ (1975) the 'interstitial fluid' is the result of the initial rockfall and subsequent collisions in the second part of movement. In contrast, ERISMANN (1979) disregards interstitial dust as a means to reduce the pressure on grains and frictional resistance. However, model experiments confirmed that fluidization can occur due to high impulsive contact pressures between individual grains, which cause their statistical separation and flowage under the influence of gravity DAVIES (1982).

Considering the height of the source of the avalanche-deposits material and the great distance traveled from the mountain front, as well as the large values of L_e and low coefficients of friction, the avalanche movements in front of Sierra Aconquija are interpreted to consist of two components: 1) an initial rockfall and, 2) subsequent unconfined fluidized movement in the piedmont region.

Fig. 5. Maximum clasts on top of the Loma de la Aspereza rock-avalanche.

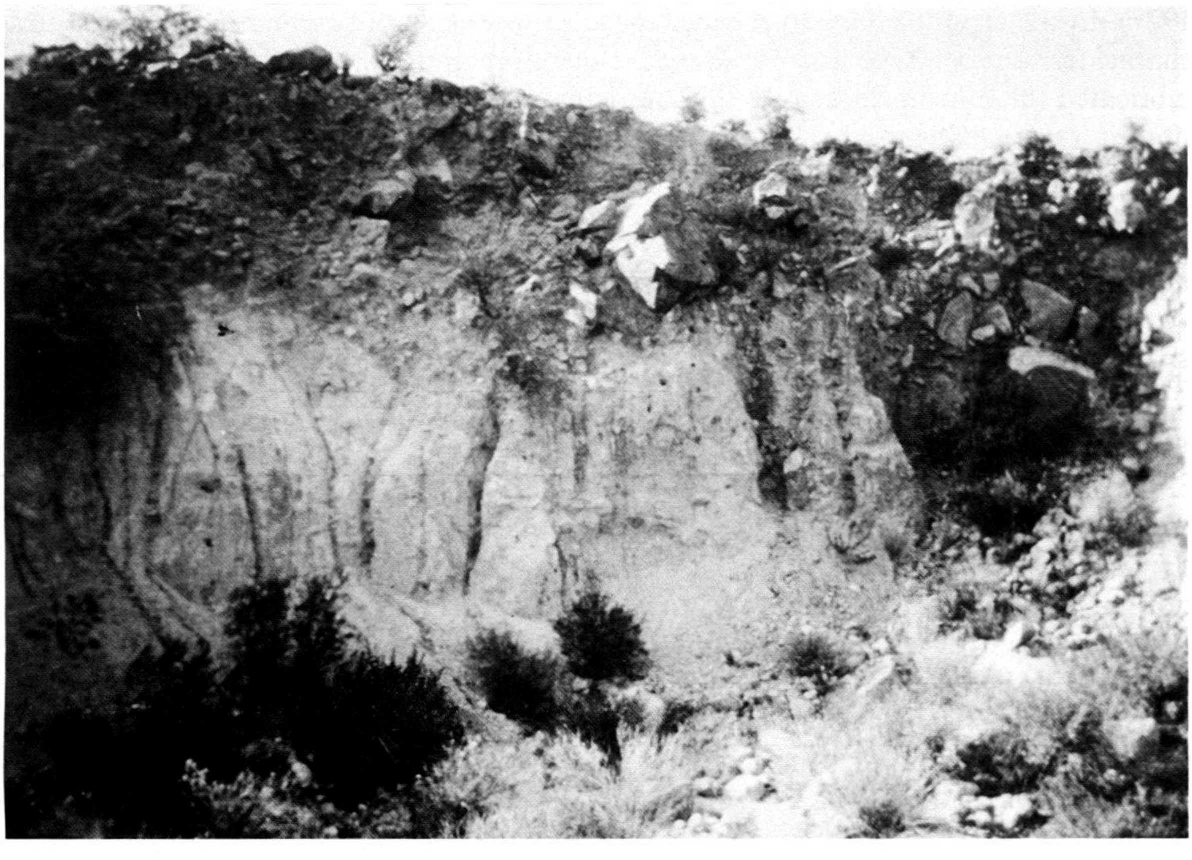

Fig. 6. Inverse grading at the Loma de la Aspereza rock-avalanche.

According to the values computed in table 1 rock masses must be voluminous in order to provide the necessary kinetic energy for movement in the piedmont, but the fall height is of secondary importance. These observations concur with the "Grösseneffekt" (size effect) in the results of HEIM (1932) and HSÜ (1975), who found an inverse relationship between the volume of the rock fall and the coefficient of friction; a similar relationship between volume and length of movement was found by DAVIES (1982). In conjunction with the findings of these other workers the avalanches in front of Sierra Aconquija demonstrate that the motion of avalanches of this type cannot be viewed as a sliding motion with an internal angle of friction of 32°, but rather as the movement of a fluidized mass of blocks. Mechanical fluidization due to collision between blocks also explains the well developed inverse grading of the investigated avalanche deposits at Sierra Aconquija. In Bagnold grain-flow the dispersive pressure on the individual clasts increases with clast size (BAGNOLD 1954). It follows that during movement in the piedmont the larger blocks move away from the highest shear stress at the ground/avalanche interface. Thus, in the course of movement the larger blocks move toward areas of lower stress, that is, toward the top of the moving avalanche. In contrast, the smaller blocks remain at lower positions and are further destroyed into the disintegrated and milled clasts (Fig. 6).

Water is excluded as a lubricant and fluidizing agent for the avalanches at Sierra Aconquija because the avalanches have maintained their original morphology with sharply defined frontal lobes. The lobes are not disturbed by any outrunner blocks or protrusions of debris-flow like material, as might be expected after a water/mud-based transport. Furthermore, for the involvement of a fluid component the fine material fraction of medium to fine sand and of silty sand appears too coarse to cause the buoyancy of larger particles as in a debris flow, for example. Case histories of wet rock avalanches clearly show that debris and mud flows continue the principal avalanche movement (PLAFKER & ERICKSEN 1978), whereas dry avalanches are "frozen" into place after the avalanching stops (PORTER & OROMBELLI 1980).

In conclusion, the inverse grading, avalanche morphology, and excessive travel distances indicate that the avalanche movement must have been dry and was facilitated by a mechanical fluidization analogous to Bagnold grain-flow.

Avalanche origin

The fact that the rock avalanches are restricted to the mountain front sector of Sierra Aconquija, which is characterized by heavily fractured granite, suggests a close relationship between the occurrence of avalanches and a certain lithologic predisposition for their generation. The small percentage of rocks from the granite/schist contact zone and the otherwise monomict granitic avalanche composition emphasize that the fractured granitic intrusion and its host rock contact area is a major zone of structural weakness in the mountain. In addition, the topographic conditions with a steep mountain front are favorable for the vertical movement of larger rock masses.

Apart from lithologic conditions, the avalanches in front of the formerly glaciated Sierra Aconquija (Fig. 2) suggest a causative connection between avalanche generation and deglaciation processes similar to events reported for the Alps (PORTER & OROMBELLI 1981). A relationship between deglaciation processes, higher water availability, and, thus, greater reduction in the internal angle of friction in this environment is plausible. However, in the light of the essentially monomict granitic rock-avalanche lithology, glacial or postglacial processes are not likely; the glacial deposits in Sierra Aconquija are always characterized by their polymict nature and large amounts of biotite schist, which only occurs at high altitudes above the avalanche source region, where the cirque and limited valley glaciation took place (Fig. 2).

The avalanches have a morphology that is reminiscent of present-day rock glaciers or older inactive rock glaciers in Sierra Aconquija and other high ranges in the region. However, they are not considered to be periglacial relict forms because they are very isolated and other relict periglacial landforms occur at much higher elevations around 3800 m (STRECKER 1987). Intense hydrofracturing associated with periglacial conditions in the past is not viewed as a likely trigger mechanism for the rock avalanches either, as the source region of the avalanches was located only at the lower limits of sporadic permafrost or beyond that zone. Large rock avalanches of deep-seated origin are common throughout the tectonic valleys of northwestern Argentina (Fig. 1) and most of these locations were neither under the influence of a periglacial nor a glacial climate at any time.

Alternatively, evidence for wetter climatic periods that could have facilitated rock failure through higher pore pressures and reduced angles of friction is not viewed likely either. This part of northwestern Argentina remained under arid/semiarid conditions throughout the Pleistocene and glaciations only were caused by a reduction of temperature and not by an increase in precipitation (STRECKER 1987; SAYAGO et al. 1987).

Another common trigger mechanism for catastrophic rock avalanches other than those described above, is of tectonic nature and involves seismic shaking of already weakened rock units (PLAFKER & ERICKSEN 1978; EISBACHER 1979; KEEFER 1984; EISBACHER & CLAGUE 1984; EVANS et al. 1987; FAUQUE 1987). An origin that combines seismic shaking with areas of lithologic predisposition for avalanching is the preferred interpretation for the avalanches at Sierra Aconquija. Due to the principal uplift and erosion of Sierra Aconquija which occurred after 2.9 Ma, granite became exposed at the mountain front and underwent exfoliation. Exfoliation began because of much lower confining pressures; this process reduced the cohesive strength of the granite and made it susceptible to avalanching. Furthermore, the heavily jointed and fractured granite is cut by several east-dipping reverse faults, which are part of the Aconquija mountain-bounding fault. Numerous sites along this fault and the adjacent piedmont areas show evidence of repeated tectonic activity of the Aconquija fault system during the Quaternary. The same conditions apply to the setting of the other avalanches shown in Figure 1 and many more observed rock-avalanche deposits in the tectonically active Argentine Northwest, suggesting tectonic factors as the main trigger mechanisms of avalanche generation.

Conclusion

At least eight lobate Pleistocene rock avalanche deposits in the piedmont of Sierra Aconquija in the northern Sierras Pampeanas of Argentina record two-phase dry rock-avalanche movements that consisted of an initial rock-fall component at the mountain front and subsequent flowage in the piedmont. After the disintegration of the rock mass as a consequence of the fall, the flowage in the piedmont was accomplished by mechanical fluidization. The movement in the piedmont region is best explained by processes that involve acoustic fluidization and grain flow, or a combination thereof. Related to such movements of rock fragments is the inverse stratification of the avalanche deposits, as large blocks move away from the highest shear stress at the bottom of the avalanche, whereas smaller blocks stay in lower positions. The process of mechanical fluidization does not appear to have been aided by water because all avalanche deposits have sharply defined rims that lack protrusions and outrunner blocks, which could be expected if water had been involved. Excluding climatic effects, the most likely trigger mechanism for these avalanches in an area with a long documented history of tectonic activity is the sudden increase of shear stress and decreased rock strength due to seismic shaking of already heavily basement rocks.

Acknowledgments

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