2011

Mass wasting as a geologic hazard in the Province of Salta, Argentina

William J. Wayne
University of Nebraska-Lincoln, wwayne3@unl.edu

Wayne, William J., "Mass wasting as a geologic hazard in the Province of Salta, Argentina" (2011). *Papers in the Earth and Atmospheric Sciences*. 561.
https://digitalcommons.unl.edu/geosciencefacpub/561

CENOZOIC GEOLOGY of the
CENTRAL ANDES of ARGENTINA

CENOZOIC GEOLOGY of the CENTRAL ANDES of ARGENTINA

Edited by

José A. Salfity and Rosa A. Marquillas

SCS PUBLISHER
Salta, Argentina

Cenozoic Geology of the Central Andes of Argentina / dirigido por José A. Salfity y Marquillas Rosa A. - 1a ed. - Salta : SCS Publisher, 2011.
458 p. : il. ; 27x21 cm.

ISBN 978-987-26890-0-1

1. Geología. I. José A. Salfity, dir. II. Rosa A., Marquillas, dir.
CDD 558

It is suggested that references to this book and their chapters are written in the following way:
Salfity, J.A., and Marquillas, R.A., eds., 2011, Cenozoic geology of the Central Andes of Argentina: Salta, SCS Publisher, 458 p.
Folguera, A., and Zárate, M., 2011, Neogene sedimentation in the Argentine foreland between 34°30'S and 41°S and its relation to the Andes evolution, *in* Salfity, J.A., and Marquillas, R.A., eds., Cenozoic geology of the Central Andes of Argentina: Salta, SCS Publisher, p. 123-134.

Language review: María Marta Michel
Reception of peer reviews, edition and bibliographical reference check: Henry R. Estrada
Review and correction of illustrations in digital format: Omar Enrique López

Publication design, diagramming and digitalization of originals: Rosanna Caramella de Gamarra
Cover artwork: ADV Group

To purchase this book, request information at the following address:
scspublisher@arnet.com.ar

ISBN: 978-987-26890-0-1

Printed at Artes Gráficas S.A., Salta, Argentina
Printed in Argentina

The editors would like to thank the referees whose opinions and constructive criticism have improved the quality of all contributions and thus of the entire volume. They are:

Ricardo Alonso	Universidad Nacional de Salta-CONICET
Luis Álvarez	Universidad Nacional de Salta
Pablo Caffe	Universidad Nacional de Jujuy-CONICET
Esperanza Cerdeño	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales-CONICET
Alberto Cione	Universidad Nacional de La Plata-CONICET
Carlos Costa	Universidad Nacional de San Luis-CONICET
Cecilia del Papa	Universidad Nacional de Salta-CONICET
Luis Fauqué	Universidad de Buenos Aires
Igor J.C. Gavriloff	Universidad Nacional de Tucumán-CONICET
Klaus Heine	University of Regensburg
Rafael Herbst	Universidad Nacional de Tucumán-CONICET
Fernando Hongn	Universidad Nacional de Salta-CONICET
Jonas Kley	Institut für Geowissenschaften, Univerität Jena
Alejandro Kramarz	Museo Argentino de Ciencias Naturales «Bernardino Rivadavia»
Carlos Oscar Limarino	Universidad de Buenos Aires-CONICET
Vera Markgraf	Institute of Arctic and Alpine Research, University of Colorado at Boulder
Claudia Montalvo	Universidad Nacional de La Pampa
André Nel	Muséum national d'histoire naturelle, Paris
Silvio Peralta	Universidad Nacional de San Juan-CONICET
Mirtha Quattrocchio	Universidad Nacional del Sur-CONICET
Víctor Ramos	Universidad de Buenos Aires-CONICET
Augusto Ernesto Rapalini	Universidad de Buenos Aire-CONICET
Marcelo A. Reguero	Universidad Nacional de La Plata
José Luís Silvestro Dezzi	YPF, Buenos Aires
Luís Spalletti	Universidad Nacional de La Plata-CONICET
Pablo Teta	Universidad de Buenos Aires
Alejandro J. Toselli	Universidad Nacional de Tucumán-CONICET
Daniel Udrizar Sauthier	Centro Nacional Patagónico-CONICET
Gonzalo Veiga	Universidad Nacional de La Plata-CONICET
Gustavo Vergani	Repsol-YPF, Buenos Aires
José Germán Viramonte	Universidad Nacional de Salta-CONICET
Haroldo Vizán	Universidad de Buenos Aires
Guiomar Vucetich	Universidad Nacional de La Plata-CONICET
Juvenal J. Zambrano	Universidad Nacional de San Juan
Roland Zech	University of Bern, Institute of Geography

and two referees who chose not to disclose their names.

Contents

Mass wasting as a geologic hazard in the Province of Salta, Argentina

William J. Wayne[1]

ABSTRACT

The north-south orientation of the mountainous part of the Province of Salta forms a massive barrier to easy communication between the more populated region in the central part of the province and the communities to the west. Routes follow deeply entrenched valleys that are frequently the sites of debris flows that cause disruptions in the flow of traffic during the months of December through March, when most of the precipitation of the region is recorded. The steep topography and the tectonic settings have resulted in nearly 150 large landslides and debris flows most of which were identified through stereoscopic study of airphotos, scale 1/50,000 and 1/70,000. More than 100 of these are in the Cordillera Oriental and Calchaquenia, more than 30 were noted in the Puna, a smaller number in the Sierras Subandinas. Several clusters of large landslides in each of these morphostructural regions undoubtedly were triggered by earthquakes that may have had a magnitude (Richter Scale) of 5.0 or greater; thus their locations provide additional information on the probable epicenters of prehistoric earthquakes. Most of the landslides identified do not in themselves present any hazard or risk at this time. Their locations and geologic setting indicate locations where unstable slopes have failed, which provides a warning that additional slides could take place in similar settings. Their identification and location also serves as a guide to land-use planners of the province, so that if new construction is undertaken, measures to avoid reactivating old and now stable slide masses can be avoided.

Keywords: Salta - Escoipe - landslides - debris flows - rockslides - earthquakes

RESUMEN

La orientación meridional de la parte montañosa de la Provincia de Salta ha generado una barrera que no favorece una fácil y fluida comunicación entre las regiones pobladas de la parte central de la provincia y los pueblos del oeste. Las rutas siguen los valles profundos donde los flujos densos y los derrumbes de roca interrumpen con frecuencia el tráfico entre diciembre y marzo, cuando se registra la mayoría de las precipitaciones. La topografía empinada y el marco tectónico dieron como resultado casi 150 deslizamientos y flujos de escombros que fueron identificados a través del examen de fotos aéreas, escalas 1/50.000 y 1/70.000. De los movimientos en masa registrados, más de 100 ocurrieron en la Cordillera Oriental y Calchaquenia, más de 30 en la Puna, y algunos cuantos en las Sierras Subandinas/Sistema Santa Bárbara. En cada una de las regiones morfoestructurales se ubican grupos de grandes derrumbes que deben haber sido causados por terremotos con una magnitud (Richter) de 5.0 o mayor. La ubicación de estos rasgos distintivos provee la información necesaria para facilitar la identificación de epicentros de terremotos prehistóricos. La mayoría de los derrumbes localizados no indican riesgo alguno en la actualidad. Más bien, los sitios geológicos seleccionados indican lugares donde ocurren pendientes inestables que advierten sobre eventuales deslizamientos que pudieran ocurrir en estos lugares. La localización de estos sitios servirá de guía para quienes planifican el uso del suelo y para evitar daños a obras civiles, accesos viales y, aún, la vida de las personas.

Palabras clave: Salta - Escoipe - derrumbes - flujos de escombros - deslizamientos - sismos

---

[1] University of Nebraska.

INTRODUCTION

The eastern slopes of the Andes in northern Argentina have been the source areas for debris flows as well as other forms of mass wasting throughout the Pleistocene; these processes continue to take place regularly. Those that occur in unpopulated and isolated sites are simply normal geomorphic processes, but those that impact communities, highways, and railroad lines, where they can result in serious damage and economic losses (Jovel 1989; Schuster and Fleming 1986), can be considered geologic hazards. The debris flows, earth flows, and rock slides are a result of a combination of factors that includes high topographic relief, rock type, tectonic setting, climate, and vegetation cover (Polanski 1966; Alonso and Wayne 1992; Wayne and Alonso 1992). Ericksen et al. (1989) and Schuster et al. (2002) pointed out the potential and actual destructive nature of landslides in the southern Andes, along with examples of some of the most damaging of decades.

The purpose of this study has been to prepare an inventory of the recognizable slope failures in the Province of Salta, Argentina, as a first stage in the evaluation of the hazard potential of landslides in the province and as a contribution to the International Decade of Hazard Reduction (Brabb 1991, 1993). Most of the project was done by means of stereoscopic study of airphotos; although many of the landslides and debris flows that were identified on the airphotos were examined in the field. Airphotos used were those taken for the Instituto Geográfico Militar of Argentina during the 1960's. The photos of the part of the province west of 65° 30'W are a scale of about 1/50,000 and were taken in 1966: those of the eastern part of the province are about 1/70,000 and were taken in 1963. The 1/50,000 scale airphotos were made available by the Dirección de Minería de la Provincia de Salta. The smaller scale photos were obtained from the offices of the Instituto Nacional de Tecnología Agropecuaria (INTA) and from the Dirección de Recursos Naturales Renovables of the province. A chart that provides latitude and longitude, airphoto number, and a brief comment about each slide and earth flow recognized is available and is archived in a Data Repository, along with maps showing the location of the landslides and debris flows recorded.

«A landslide is the movement of a mass of rock, earth, or debris down a slope» (Cruden 1991), and the term includes virtually all forms of rapid downslope movement of earth materials. Many classifications of mass movement processes exist, but the ones in most extensive use are those of Varnes (1978) and of Carson and Kirkby (1972). The classification presented by Varnes is the basis for the classification adopted by Commission on Landslides of the International Association of Engineering Geology (IAEG Commission on Landslides 1990; UNESCO Working Party on World Landslide Inventory 1990; Cruden and Varnes 1996). Two criteria form the basis for this classification-type of movement and material involved. To the five types of movements, falls, topples, slides, spreads, and flows, one additional group exists for those complex slides in which two or more kinds of movement have taken place. The material is either rock or unconsolidated materials (soil in the engineering concept). Carson and Kirkby (1972) emphasized the way the movements are related with respect to speed and quality of water involved.

Falls of debris or rock take place on very steep to vertical slopes, where the material is unsupported, and it breaks away, generally along an existing fracture. Topples are a kind of movement in which blocks of rock or debris fall over with the base remaining in place but the top rotating outward. Slides are movements in which an upper mass of rock or debris moves along a discrete plane over a lower mass that has remained in place. Slides may be either rotational (the slide plane spoon-shaped), or planar (slide plane a smooth surface).

Planar slides take place where bedding or foliation planes dip steeply and are unsupported. Either layers of weak rock, such as shale, or a zone of higher moisture content generally exists along the failure plane. Large slides may take place spontaneously but many are triggered by some kind of vibration, such as seismic tremors. The rocks involved generally have been weakened by weathering.

Rotational slides, or slumps, move along a curved plane of failure with little deformation. They are a common type of slide in fine-grained sedimentary materials, particularly those that are thick, massive, and unconsolidated. The surface of the uppermost displaced block of most slumps rotates back, forming a shallow closed depression. Very commonly the material at the base of a slump or rotational slide is deformed and becomes a flow

---

Data repository

Interested readers will find the following complementary information on this chapter in the website of the Instituto del Cenozoico (www.unsa.edu.ar / ince):

1. Table of landslides and debris flows identified in the Province of Salta.
2. Topographic location after the Instituto Geográfico Militar maps, scale 1:250,000.

of earth or rock. Some rotational slides become retrogressive, in that they begin at a steep slope and enlarge in a direction opposite to the movement (Varnes 1978).

Flows are movements in which materials are highly deformed and move as a viscous fluid. Most flows that involve unconsolidated materials are readily recognizable, may be either wet or dry, and move at rates that range from slow to very fast. Rock flow is generally a very slow process that results in bulging or bending plastically, probably with many microfractures, but without movement along a distinct plane (Varnes 1978)

Flows of unconsolidated materials are more readily recognized than rock flows because the material behaves more obviously like a fluid. Mud flows and debris flows contain enough water to cause the sediment-water mixture to move as a slurry, with sufficient density to carry solid particles of various sizes in suspension (Pierson 1986; Pierson and Costa 1987). Mudflow is used for those flows of earth that contain more than 50% sand, silt and clay-sized particles. Debris flow is a material that contains high percentage of coarse fragments, from pebbles to boulders. Earthflows differ from debris flows in that they move slowly. They, too, take place when a large mass of rock and soil on a moderate to steep slope becomes oversaturated and moves as a viscous mass downward. Vibrations, including seismic activity, have triggered earth flows. Some earth flows undergo a single movement, then become stabilized; others are periodically active whenever the moisture content within and along the base of the disturbed mass becomes high enough to reduce the angle of internal friction.

Where lateral extension of blocks, generally of fractured rock, takes place on surfaces of only moderate inclination, the term spread (or lateral spread) is employed (Varnes 1978). These movements are most likely to take place where thick beds of firm rock overlie a layer that is more readily deformable. Spreads that do not involve liquification of the underlying material may require an earthquake shock for mobilization. Because most spreads involve more than one kind of movement, they could be regarded as complex slides.

Complex landslides are those in which more than one of the several kinds of movements are involved, often in sequence as the mass continues to move. Earthflow-slump, for example, is a common combination, with the slump taking place after an earthflow failure on the slope has removed support, or with the earthflow taking place as the lower part of the slump movement deforms.

Moisture content is a major contributing factor in nearly all landslides. Moreiras (2004) pointed out that precipitation is the principal triggering factor for slope movement in the valley of río Mendoza. Many slopes on relatively impermeable bedrock are blanketed with loose weathered rock debris or soil, which becomes unstable on steep surfaces, particularly if moisture within the weathered material reduces its shear strength. Rib and Liang (1978) pointed out that landslides can take place in almost any terrain if slope, moisture content, and vegetation cover are in the right combination. Aerial photographs at scales of 1:50,000 and smaller are adequate for recognition of large landslides, but are not suitable for the identification of the small landslides that are likely to cause problems in engineering projects. In this study, the airphotos were studied carefully in several locations where rockslides were known to exist along roads. Because of their size and the photo scale, they were difficult to recognize even where they had been identified in the field. The smallest landslides recognizable in this study are about 200 m in smallest dimension.

Adequate aerial photography to identify existing and potential areas of small but potentially damaging landslides should be of 1:10,000 or 1:5000 scale. This study, with much smaller scale photos, was able to identify areas of previously unstable slopes, where additional landslide or debris-flow activity can be expected in the future. It also locates a large number of existing slides that could be reactivated if they were to be disturbed by construction.

SIGNIFICANT MASS WASTING IN THE MORPHOSTRUCTURAL REGIONS OF SALTA PROVINCE

Introduction

Slope movements take place with variable frequency in five of the six major morphostructural regions in the Province of Salta, the Puna, the Cordillera Oriental, Calchaquenia, the Sierras Subandinas, and the Santa Barbara System (Fig. 1). The sixth region, the Chaco Plain, has little relief, and except for the collapse of bank material along rivers, mass movements are unlikely to take place or to present a hazard. The geomorphic characteristics of these regions have been described recently by Mon (1979), Igarzábal (1991), Marcuzzi et al. (1994), and Salfity (2006).

Most slope movements involve water, and in northwest Argentina they take place during the season of greatest precipitation, mid-December through mid-March. During the remainder of the year, precipitation rates are much lower, and in the western part of the province, conditions become arid. The Sierras Subandinas and the lower slopes of the Cordillera Oriental are covered with subtropical forest, because the prevailing easterly winds bring warm Atlantic Ocean air masses inland during late spring and summer. Although they lose some moisture crossing the lower Sierras Subandinas to the east, much of it remains. The average annual precipitation at the City of Salta, altitude 1187 m, was approximately 700 mm for the period 1934-1990 (Bianchi and Yañez 1992); at Campo Quijano, altitude 1520 m, where río Toro emerges from the Cordillera, during the short period of record available (1973-1978) an average of 1052 mm per year was registered. Most of the moisture is lost, however, as the air masses rise over the Cordillera, the altitude of which exceeds 4000 m. Dry wind descends the western side of the Cordillera, where desert conditions exist. At Cachi in the Calchaquí valley, for example, precipitation averaged 163 mm/year for the period of record, 1973-1990. With few exceptions, all was recorded during the months of December, February, and March.

Intense frost action at higher altitudes, especially above 4000 m, breaks down exposed rock, making smaller fragments readily available for downslope movements. A few small rock glaciers, masses of frozen rock debris that move slowly down slope, are present along the sierra de Chañi, and an inactive or stable one is in a cirque on the east side of cerro Malcante. Although these features present no direct threat to infrastructure or buildings, they can be a source of sediment for debris flows.

PUNA

The high plateau (3500-3800 m) that makes up the western part of the Province of Salta (Fig. 1), the Puna, is distinguished by its arid climate and interior drainage. Geologically young, with many features of Late Tertiary and Quaternary age. The northern part and the Chilean frontier are marked by volcanoes. Three of these, Socompa, Llullaillaco, and Antofalla, have been active recently, and probably should be considered dormant at this time (Clapperton 1993, p. 125-130; de Silva 1989); many others are extinct now, but volcanoes thought to be extinct have been known to become active again. The major hazards related to volcanoes are lahars and tephra accumulations. Block-faulted mountain ranges bounded by high-angle reverse faults that separate closed basins, many of them the sites of salares or salt lakes, characterize most of the region. Although Paleozoic, Mesozoic, and Cenozoic rocks are present in the Puna, those of Upper Cenozoic age dominate. The volcanic peaks have been glaciated and their upper slopes remain in a periglacial environment.

Mass-wasting features in the Puna include debris flows, mostly in the region underlain by the Puncoviscana Formation, lahars that descend the slopes of volcanoes (Alonso and Wayne 1992); with rotational rock slides/earthflows the dominant type of mass movement in the rest of the region. In addition, features of slope instability that characterize regions of permafrost are common on the mountain slopes. Among the more distinctive are both active and inactive rock glaciers, stone stripes, and gelifluction lobes. These landforms are especially common in the sierra de los Pastos Grandes and the sierra de Cachi. The Puna is a large area that is sparsely populated; except for the rail line, national highway 51 from San Antonio de los Cobres to Chile, and provincial highways 25, 17 and 129 that connect the small communities along them, there are few places where geologic processes of mass wasting can represent a hazard to the population or to routes of communication. Unfortunately, no airphotos of the area west of 67°W and south of 25°S were available during the course of this study, so no landslides were recorded for the southwest quarter of the Puna of Salta.

West of the Calchaquí valley only 33 landslides were recognizable on airphotos (scale approximately 1/50,000). Although they are distributed throughout the Puna, more were noted in the north part, where the altitude is greater, than elsewhere in the region (Fig. 1). Intensive frost action is important in shattering the low grade phyllites and slates of the Puncoviscana Formation into fragments in a silt and sand matrix that accumulates on slopes and in swales where it can become source materials for debris flows at times of intense precipitation. Mass-wasting features that seem to be wholly permafrost-related include gelifluction lobes, stone stripes, and rock glaciers, are abundant in the northern part of the Puna of Salta, but because nearly all of them are remote from structures, they were not considered a risk.

Most of the features recorded are rock falls; some, though, involve an entire slope and resemble a huge flow of rock and soil. One of these lateral spread movements, in the Serranía del Barreal east of Santa Rosa de los Pastos Grandes, covers a slope that is 2000 m from crown to toe and more than 7000 m across. Gullies have cut into the north part of this mass, but the south part is uneroded. Only an earthquake of magnitude 5.0 or greater (Keefer 1984), could have triggered a mass movement so large. Four others, all large rock falls that surely mark the epicenter of another significant earthquake, are clustered together near the west side of the Puna along longitude 68°W and between 24°24'S and 25°00'S

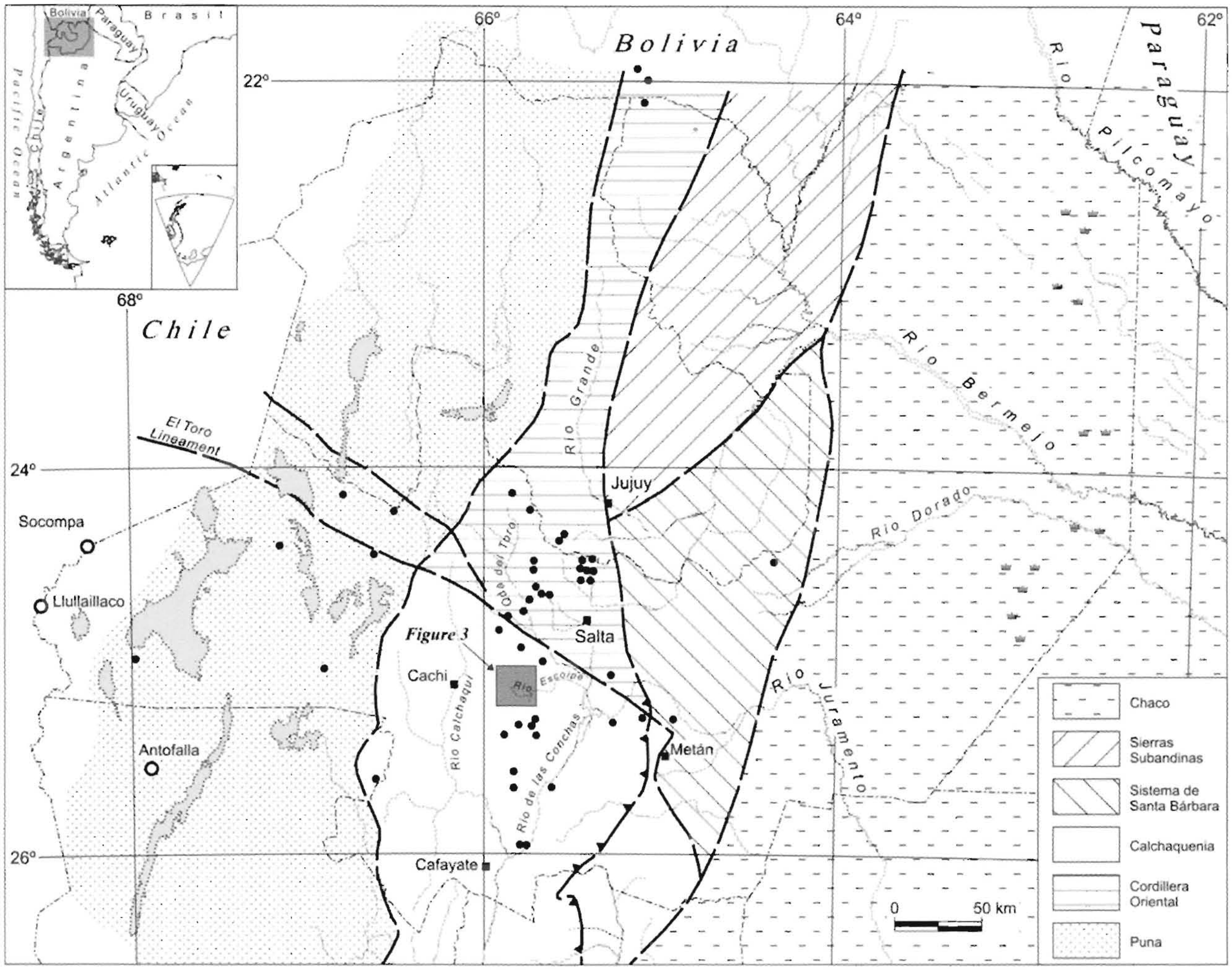

Figure 1. Map showing morphostructural regions of northwestern Argentina (Salta and Jujuy). Black dots show the distribution of landslides in the Province of Salta (because of scale, not all landslides are shown), and circles show volcanoes.

in latitude. Even though none of the Puna landslides recognized and located through this airphoto study represents a risk in itself, their existence provides evidence not previously available on probable epicenters of large earthquakes in the region during the past few thousand years.

The Puna is arid, and landforms are altered very slowly in dry regions. It is difficult, therefore, to evaluate from an airphoto study of the morphology of any feature how long it may have existed. The fresh-looking landslides in the Puna, therefore, could have formed as recently as a few hundred to a few thousand years ago or they may be several tens of thousands of years old. Those with muted features may have taken place as long ago as the last major glaciation (25,000-15,000 years B.P.).

CORDILLERA ORIENTAL AND CALCHAQUENIA

The Cordillera Oriental, a region of faulted rocks that has great relief, borders the east side of the Puna north of the El Toro lineament. It, together with Calchaquenia, the morphostructural region south of the El Toro lineament, has the greatest number of landslides recognized in this study. The rocks that form the crests of both the Cordillera Oriental and Calchaquenia are slates, phyllites, and graywackes of the Upper Precambrian-Lower Cambrian Puncoviscana Formation (Turner and Mon 1979; Salfity 2006). North of the El Toro lineament the Puncoviscana Formation is overlain by Ordovician marine sediments. South of the El Toro lineament, Ordovician rocks are missing and those of the Cretaceous-Paleogene Salta Group overlie the metamor-

Figure 2. Small debris flows produced by an intense rainfall on colluvium-filled hollows in the headwaters of río Escoipe.

phic rocks of the Puncoviscana Formation. The eastern edge of the Cordillera Oriental is the eastward sloping Oclóyoco thrust fault. South of the El Toro lineament, the Santa Barbara System and the Aconquija lineament mark the eastern and southern limits of Calchaquenia (Salfity 2006).

Tectonically folded and faulted, the low grade metamorphic rocks of the Puncoviscana Formation in both the Cordillera Oriental and Calchaquenia weather readily in the frost-dominated climate that exists above 3500 m. Although rocks of the Puncoviscana Formation are the source of most of the landslides and debris flows recognized in these two morphostructural provinces, some of the mass movements in the Cordillera Oriental involve Ordovician Santa Bárbara Formation; shales and rocks of the Salta Group are involved in some of the mass movements in Calchaquenia. These two, then, are the morphostructural provinces that contain the greatest number of landslides identified in this study as well as the greatest number of potentially hazardous conditions resulting from landslides (Fig. 1). Because they were treated as a single unit, the Cordillera Oriental, at the time this study was made, they are dealt with together in this report.

Altogether, more than 100 landslides large enough to recognize on the airphotos used this study were identified. Ridge crests in the mountains range from 5000 to 6000 m in altitude and the piedmont plain that extends eastward from the mountain front is about 1250m. This difference produces a total relief of more than 3700 m in a distance of 12 to 14 km. Streams that flow eastward from the crests of both the Cordillera Oriental and Calchaquenia have high gradients, as much as 0.10 or greater in their upper reaches. They have cut steep-walled gorges in which local relief exceeds 2200 m in 5 km. Debris-covered slopes that stand at angles of 30° are common.

Debris Flows

Most of the rocks that form the upper slopes and crests of the Cordillera Oriental and Calchaquenia are slates, phyllites and graywackes of the Upper Precambrian/Lower Cambrian Puncoviscana Formation and related igneous rocks (Salfity et al. 1998). These low grade metamorphic rocks have been folded and faulted; thus they are highly fractured. In the frost-dominated climate above 3500 m. they weather readily to angular rock fragments in a matrix of silt and sand-sized particles. This rock debris covers most of the slopes and moves slowly downward into swales at the heads of ravines, where it becomes mobilized into debris flows during episodes of heavy precipitation in early summer. Airphoto review and field observations indicate the existence of many colluvium-filled hollows in the higher parts of both the Cordillera Oriental and Calchaquenia that are underlain by the Puncoviscana Formation. These thick accumulations that result from creep and solifluction of frost-shattered rock (Fig. 2) provide source material for potentially destructive debris flows.

Several studies relating the amount and intensity of rainfall to the generation of debris flows have pointed out that few debris flows develop unless the soil has become saturated from rainfall during the previous week or longer, and that a threshold intensity generally must be exceeded during a particular storm. The «threshold» intensity noted by Neary and Swift (1987) for the southern Appalachians in the U. S. was 125 mm in one day. Wieczorek (1987) established the need for a minimum amount of previous rainfall (28 cm in southern California). Before debris flows would take place and an intensity-duration relationship for severe storms that produce debris flows. Hauser (1985) noted that a precipitation rate that exceeded 60 mm in 24 hours in a high probability of debris flows on the western slopes of the Andes in central Chile. Church and Miles (1987) found that debris flows in British Columbia took place following varying amounts of rainfall, but they were dealing with an area where high snowfall and thawing of frozen ground were contributing factors.

Although large debris flows that incorporate thousands of cubic meters of debris are both spectacular and especially destructive, most of them take place at decade-long intervals or longer. Annually though, smaller masses of debris become detached during storms to become a dense fluid that follows a channel downstream. Studies in California (Dietrich et al. 1986; Reneau and Dietrich 1987) and in New Zealand (Crozier et al. 1990) have emphasized the significance of accumulation of colluvium in upland swales for the initiation of debris flows. The soil/rock interface, where pore pressure is greatest, was the most frequently observed detachment plane in debris flows studied in the Appalachian mountains of northeastern United States (Kochel 1987).

Years of higher than normal precipitation in summer (January and February) are those during which debris flows have caused significant damage to roads, structures, and cultivated fields, and notable inconvenience to the communities. For example, January 1976, when San Fernando in the Escoipe valley was destroyed, 207 mm were recorded for that month at Cachi; Chicoana, on the eastern border of Calchaquenia, recorded 313 mm for the same month, more than double the January average for that station from 1934-1976. Two deeply entrenched valleys that serve as the main routes westward through the Cordillera are most at risk from the hazard of debris flows: the quebrada del Toro (Igarzábal 1971) and the quebrada de Escoipe (Igarzábal 1979; Wayne 1993) (Fig. 1).

The quebrada del Toro is the route through the Cordillera Oriental for both route 51 and the railway from the Valle de Lerma and the city of Salta to the Puna and Chile. The highway is closed each summer because of rock falls from the steep road cuts and debris flows that emerge from the small but steep valleys that have built alluvial cones that the route crosses. The railroad is less affected than the highway, because it crosses most of the fans on bridges high enough to allow the passage of debris flows, and chutes carry debris over the railway where it passes beneath the small steep water courses that drain the slopes of the quebrada.

Between Ingeniero Maury and El Mollar, near the mouth of the quebrada del Toro, the highway crosses a series of steep alluvial cones built by the streams that drain southwestward into río Rosario. Downstream from the railroad bridge (Puente del Toro), route 51 is perched along the northeast side of the quebrada. Only a few small ravines flush across the road surface in this reach, but they do sometimes leave a cone of debris that must be cleaned off to allow traffic movement. Rockfalls from the cliffs of highly fractured metamorphic rocks that stand above the road, however, are a detriment to traffic movement.

From El Mollar to El Alisal the highway crosses four steep alluvial cones that undoubtedly cover the route with debris that must be removed regularly. Hyperconcentrated flow carried by these channels also erodes the downstream edge of the road surface, which must then be rebuilt. The highway crosses the river to the west side of the quebrada about 500 m upstream from the junction with quebrada de Capillas, and for several kilometers it is on a bench cut into the valley wall. Through much of this reach the metamorphic rocks appear to highly fractured, as though this were a zone where faulting had taken place. The road surface is narrow and small cones of talus accumulate on it at the base of the cuts. Through this reach, the largest streams that bring flows of debris into the quebrada are on the east side; the railway crosses them on bridges. Swales in the headwater areas of some streams contain accumulations of loose debris weathered from the rocks in the slopes above them that is source material for the generation of future dense flows during times of unusually high precipitation.

Two large ancient landslides near Ingeniero Maury dammed the valley and produced lakes. Freshwater snails recovered from the lake sediments and dated by radiocarbon indicate that the upper and larger slide took place more than 26,000 years B.P. and the lower one more than 30,000 years B.P. (Trauth and Strecker 1999; Trauth et al. 2003).

Debris flows in the quebrada de Escoipe originate in steep colluvium-filled hollows (Wayne 1993) that become gullied during storms (Fig. 2), particularly after the material has been saturated by several weeks of low intensity rainfall. Where impermeable rock lies beneath a thick accumulation of colluvium, such precipitation raises the seasonal perched water table within these sediments, causing them to lose shear strength and become a dense fluid.

A low clay content is typical of the debris weathered from the siliceous metasediments of the Puncoviscana Formation in the Cordillera Oriental and Calchaquenia. Dry, these colluvial materials have a high effective angle of internal friction (ø); saturated, though, ø is likely to be as low as half of the unsaturated value, and may be less than the surface slope of the materials. Crozier et al. (1990) have determined for New Zealand a relationship between slope angle (in degrees) and the critical thickness in meters of colluvial fill in swales, both with and without forest cover. Nearly all the surfaces in these two morphostructural regions where large debris flows originate are treeless, so if the relationship they determined should hold, a colluvial accumulation less than two meters in thickness in swale slopes of 25°-30° would be sufficient to be debris-flow source material when it becomes saturated.

Identification of source areas for debris flows involves the mapping of steep colluvium-filled hollows at the heads of first order streams, the recognition of channels through which rapidly moving surges of debris will pass, and the delineation of the deposition zones, where velocities are lower but objects can become buried (Hungr et al. 1987). Where debris-flow sediments accumulate on alluvial fans, it is often possible to distinguish flows in the sediment record (Wayne 1990) and determine from their characteristics whether, at that particular place, deposition took place at the head or tail of the flow.

Dietrich and others (1986) worked out a relationship between undrained hollow length and gradient for hollows that had failed, and they arrived at a regression equation for hollows in southern California of $L = 87.75^{-0.67}$, where L = length (m) and S = slope (m/m). Other studies have suggested that the greatest potential damage from high flow velocity is in second-order streams fed by many first-order streams with undrained hollows. Jackson et al. (1987) plotted basin ruggedness against fan slope. And found a relationship that helps distinguish between fluvial and debris-flow fans. Basin ruggedness (R) is a function of basin height (H_b) and basin area (A_b) in the following equation: $R = H_b A_b^{-0.5}$. Fluvial fans have a slope of less than 2.5° and R of <0.3; fans with a major debris-flow component have slopes of more than 4° and basins with R values >0.25 to 0.3. For comparison, the lower part of the fan of arroyo del Medio north of Jujuy, a debris-flow fan, has a 4° slope and the upper part has a slope of 9° (González Díaz and Fauque 1987).

In addition to the debris flows that originate on the higher slopes of the Cordillera Oriental, small but potentially very destructive soil slips on the lower eastern slopes of the range take place from time to time during episodes of unusually high precipitation. Debris flows of this kind, such as the one that damaged Chicoana in February (Amengual 1992), occur as a result of precipitation that accompanies the orographic rise of moist Atlantic air. Tree-covered slopes from 10° to 20° that have moderate soil cover over impermeable rock are most susceptible to this kind of mass movement, in which masses of saturated earth, rocks, and trees flush downslope onto alluvial fans at the base of the mountain front.

Major roads that follow valleys, route 51 along quebrada del Toro, route 33 along quebrada de Escoipe, route 68 from Salta to Cafayate along río de las Conchas and route 40 northward from Cafayate through the Calchaquí valley, are affected during each rainstorm by many small debris flows and/or hyperconcentrated flows that emerge from the ravines that descend the slopes along these valleys. At these times accumulations of stream sediment and occasionally debris-flow cones bury the road beneath deposits from a few centimeters to more than a meter thick that block traffic until they can be scraped away. On unsurfaced roads and gravel-surfaced roads with fords at the stream crossings, the hyperconcentrated flow such streams produce sometimes erodes the stream bed at the ford to make it impassable. Grading equipment is stationed nearby where such flows make fords impassable so that traffic can be maintained.

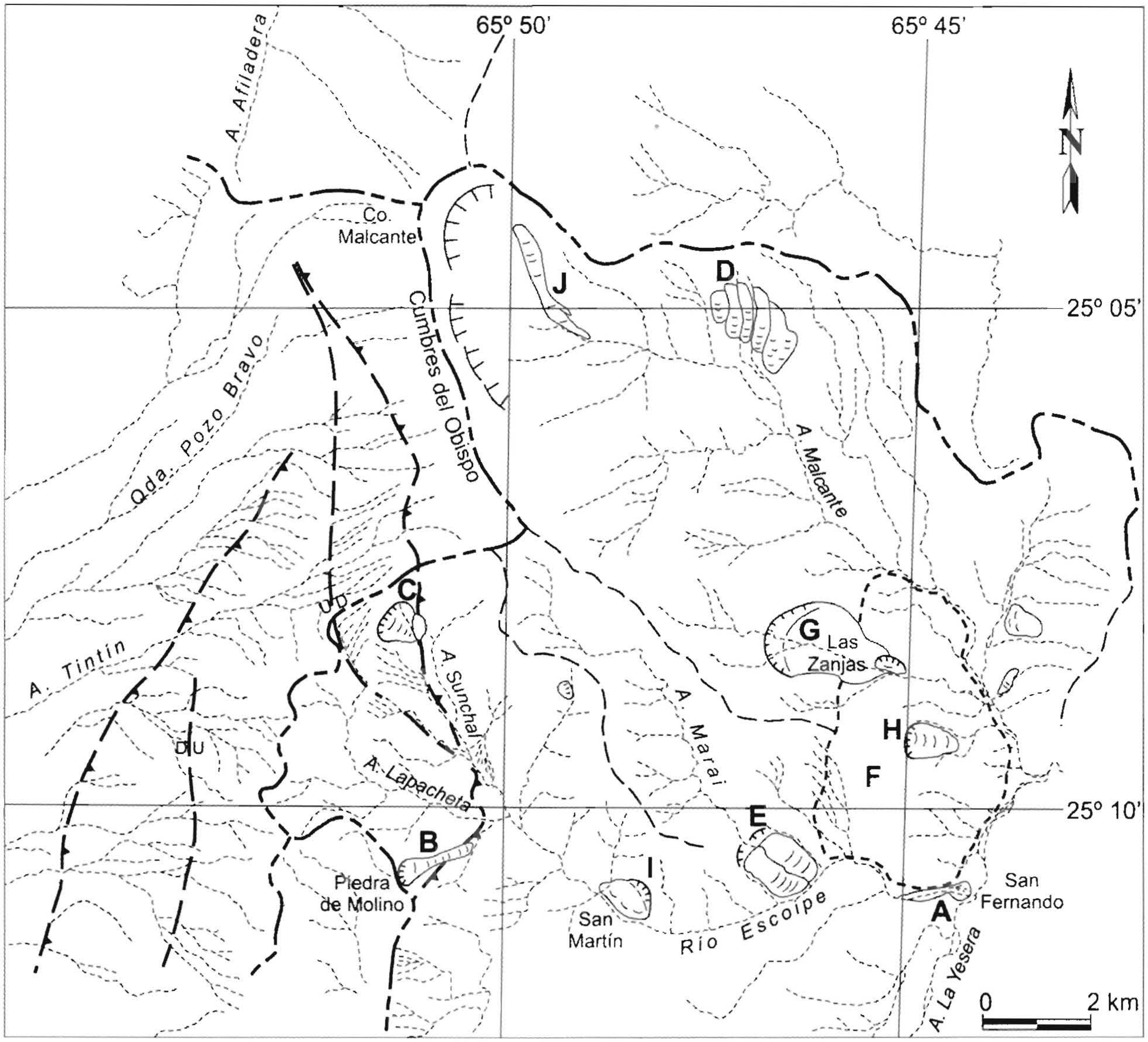

Figure 3. Map of the basin of the Quebrada de Escoipe, showing the large number of mass wasting features in the basin. Specific mass wasting features indicated by letters:

A, Debris flow 19 January 1976; destroyed San Fernando de Escoipe.

B, Active slump/earthflow; cuts highway that climbs Cuesta del Obispo below Piedra de Molino and requires constant maintenance during rainy season.

C, Active slump/earthflow at head of arroyo Malcante.

D, Three earthflow sheets on headwater slopes of arroyo Malcante.

E, Stable slump/rockslide trenched by arroyo Marai; sandstone of Carahuasi Formation and shale of Santa Bárbara Subgroup dammed río Escoipe, lake now drained.

F, Large rock block slide, 5000 m by 3000 m, Carahuasi Sandstone slid over crushed Santa Bárbara Subgroup shales.

G, Stable slump/rockslide at Las Zanjas; ponds on top surface.

H, Recent slump/rockslide. Carahuasi Formation over Santa Bárbara shales; flat surfaces between sandstone ridges are farmed.

I, Slump/rockslide at San Martín ranch, features muted by erosion.

J, Relict rock glacier in southeast-trending cirque of cerro Malcante.

Figure 4. Slump blocks at the top of the active slump/earthflow that is crossed by the Chicoana-Cachi highway.

Earthflows

Two large active earth flows are in the headwaters of río Escoipe, where structurally shattered limestone along the thrust-fault zone beneath the Puncoviscana Formation has become saturated and has flowed, glacier-like, down steep ravines at the west end of the Cuesta del Obispo (Polanski 1966; Igarzábal 1979; Wayne 1993). The slump blocks of the larger of these are crossed repeatedly by the Chicoana-Cachi highway (Figs. 3 and 4), and heavy equipment is maintained in the reach to keep the road traversable. To relocate the road would be impractical, though, because any other route that rises to the top of the Cuesta del Obispo probably would disturb the land and result in additional slope failure. The smaller of these active flows occupies a similar position on the opposite side of the Cuesta del Obispo. Small earthflows are abundant on slopes of about 20° or greater above 3000 m where the Puncoviscana Formation is present.

More than 10 translational rock spreads or flow slides have taken place on slopes of 10°-15° underlain by sandstone beds of the Tertiary Jujuy Subgroup in sierra de Vaqueros, between 20 and 30 km directly north of the city of Salta. The largest of these, 3 km north of La Caldera, is a chaotically-tumbled south-facing slope, 1500 m from headscarp to toe and 3000 m across. A second one, nearly as large, covers a south-facing slope about 1000 m farther north. Eight additional similar, though smaller, slides are within a distance of 10 km to the north and east of these two. All are now completely tree-covered; their surface features, relatively unmodified by erosion, suggest that all may have taken place about the same time, probably within the past few thousand years. These slopes ordinarily should be stable, so the existence of so many large flow-slides of this kind suggests that this area also may have been near the epicenter of a prehistoric earthquake of 5.0 or greater magnitude.

Rockfalls and Rockslides

Two areas of massive rockfall exist along río de las Conchas between Alemanía and Cafayate (Frenguelli 1936). Both blocked the valley long enough for stratified silt and clay to accumulate in the lake that formed upstream from the dam. The larger and older of these slope failures is in the south end of the valley, about 25 km north of Cafayate. In this location huge masses of rock evidently fell from both the east and south faces of cerro Zorrito, at the south end of sierra del León Muerto. Composed of thick bedded Lower Tertiary conglomerate, the masses came to rest at Casa de los Loros and La Yesera (Alonso and Wayne 1992). A study by Gallardo (1988) indicates that three such movements must have taken place. The earliest one dammed the valley and created a deep lake in which many tens of meters of silty clay accumulated. Mollusks recovered from these lake sediments, dated by ^{14}C, indicate an age of 25,820 and 29,790 years ago (Trauth et al. 2000; Bookhagen et al. 2001). The last one, which contains huge blocks of conglomerate from cerro El Zorrito, buried the lake sediments at La Yesera. The second and younger of these failures is a large mass of crumbled and crushed sandstone that fell from the cliffs 2,5 km south of Alemanía (Ruiz Huidobro 1949; Wayne 1999). This rockfall produced a dam 2000 m long that blocked río de las Conchas long enough for several meters of stratified silt and clay to accumulate in a lake that was at least 9 km long. Both of these huge rockfalls surely were generated by earthquakes, the first took place during the late Pleistocene (Trauth et al. 2000), the second much more recently. It has been dated at about 5000 years ago (Wayne 1999; Trauth et al. 2000). The debris that blocked the river at both sites filled the valley and spread both upstream and downstream; thus they were Type III of Costa and Schuster (1988). When the outlet to landslide-dam lakes of these dimensions is breached by erosion, the lake generally drains rapidly, producing catastrophic flooding downstream (Costa and Schuster 1988).

Rockfalls and rockslides can take place at anytime along the road cuts that follow rivers into the mountains but are especially common during the rainy season. The steep road cuts along quebrada del Toro are the sites of frequent rockfalls. Several places along route 68 between Alemanía and Cafayate have been partially blocked by small slides. One at Alemanía that has kept the highway surface broken results from unsupported dip-slope beds of Yacoraite Formation in the cut made for the highway and from the fracturing of rock along a fault that runs through the exposure (Balderrana 1989). Small rockfalls are common along route 9 where it winds from Abra de la Sierra to the border with Jujuy.

Planar rock slides, in which dipping blocks of sedimentary rocks have slid downward along bedding surfaces, are especially notable along the quebrada de Escoipe, where eastward-dipping sedimentary rocks have moved downslope as translational rock slides into the valley (Wayne 1993). The largest of these slides, mapped originally as a thrust fault (Ruiz Huidobro 1960), extends from río Escoipe on the south to arroyo Malcante on the north, a distance of 5000 m (Fig. 3). It is about 3000m from the mountain slope to its distal end along the Escoipe river; and probably is between 50 and 100 m thick, thus it incorporates between 0.75 and 1.5 x 10^9m of rock. This mass of chaotic rock, mostly sandstone, has been further cut by at least two younger slides, both of which moved as slump blocks. The larger one rises above the village of Las Zanjas, and, although it still has some ponds on its upper surface, the small lake on the reversed surface of the dropped block has been drained. This slide probably is only a few thousand years old. The smaller slump just east of the village shows very fresh topographic features and may be little older than a few hundred years.

Two other large translational rock slides are present in the Escoipe valley. One, at Finca San Martín, is relatively old and its form has been muted by erosion. The other, at arroyo Maray, is so young that a fracture pattern across the surface, formed as the block came to rest, is still very evident (Wayne 1993). This slide, which dammed the valley briefly, incorporated about 50 x 10^6 m of rock, and may have occurred at the same time as the slump above Las Zanjas. At this time, the river flows through a narrow gorge around the toe of the slide.

Rock slides of this magnitude are unlikely to have taken place without some triggering event, although weathering and high moisture content along the slide plane surely weakened the slide area. Other geomorphic evidence suggests that the cumbre del Obispo has continued to rise in the past 10,000-15,000 years, undoubtedly generating earthquakes. Keefer (1984, 1994) pointed out that earthquakes of magnitude less than 5.0 evidently have not caused rock slides in historic time, so it seems reasonable to conclude that the Escoipe valley may have been the epicenter of at least three earthquakes of magnitude 5.0 or greater in the past 10,000 years.

Small slump slides can be found along the steep slopes of nearly all of the valleys that are eroded into the Puncoviscana Formation. The surfaces of those that are low on the slopes and accessible provide relatively level sites for small cultivated fields.

One additional large area of landslide activity is at the north end of sierra Santa Victoria, and involves sedi-

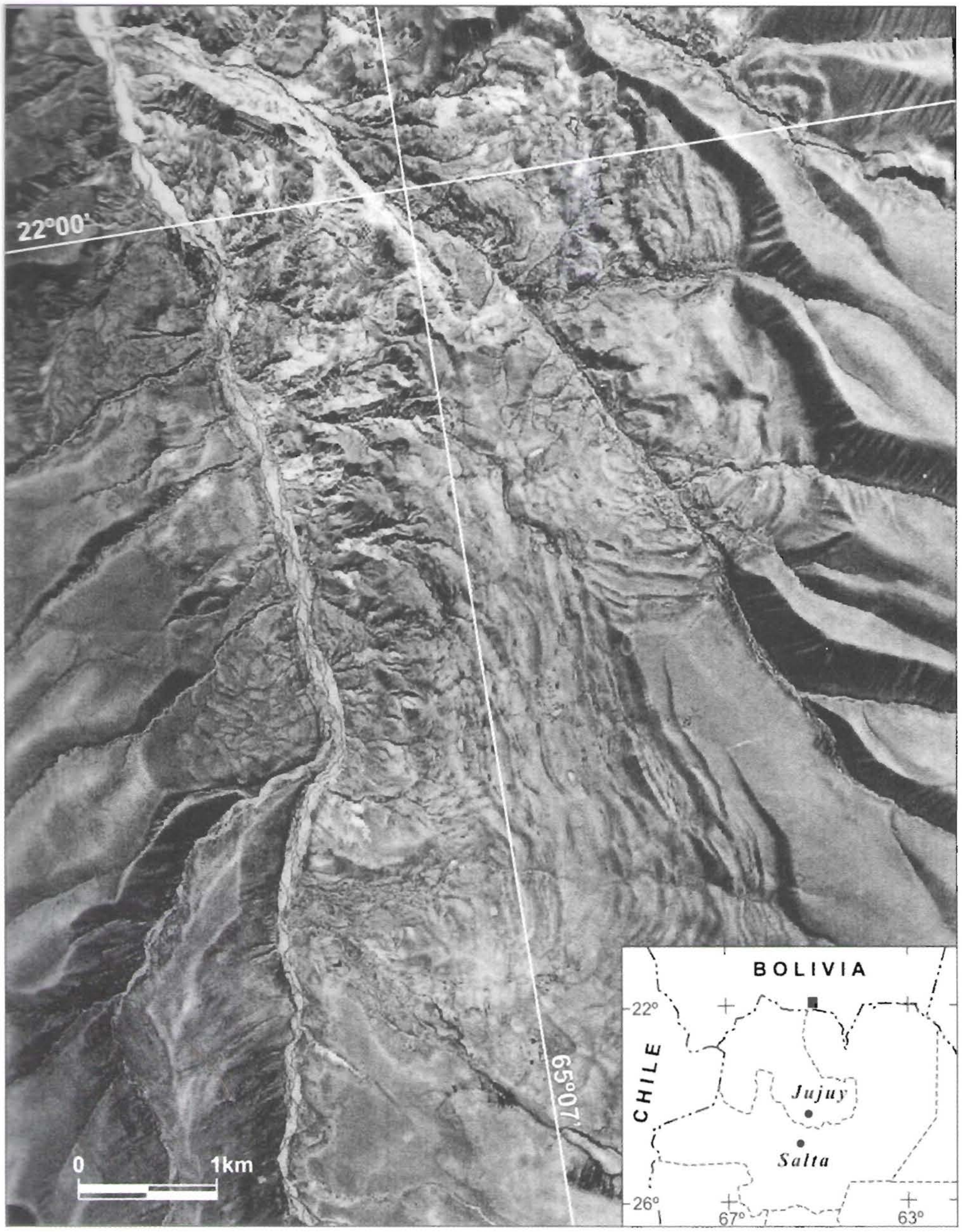

Figure 5. Retrogressive slump blocks along a stream flowing through rocks of the Santa Victoria Group, about 15 km north of the Argentina-Bolivia border.

ments of the Ordovician Santa Victoria Group. Multiple retrogressive rotational slides have broken an area 2000 m wide along quebrada Tres Lagunas that extends 2500 m east from the stream. An even larger area of retrogressive slumps or rotational slides begins about 7 km north of the frontier with Bolivia (Fig. 5). The large number of multiple slumps in this slide complex must have been started by earthquake vibrations. The highest scarps in the complex are somewhat rounded, others are more sharp, suggesting that at least two episodes of movement have taken place. The overall freshness of their appearance, however, suggests that they took place recently, perhaps no more than a few hundred years ago.

Soil slips, some of which have generated small debris flows, are common in the headwater slopes of sierra de Vaqueros during episodes of precipitation that is heavier than normal. Within few decades, however, the scars they produce become muted and vegetation-covered and may be difficult to identify. Few show up on the airphotos that were taken in 1966, but at this time (1994), one can see many fresh scarps on the slopes, where colluvial debris or weakened rock has broken away and slid downward recently.

Construction of roads and residences on the lower slopes of cerro San Bernardo in Salta has resulted in small slides, particularly where the activity has involved steeply dipping beds of the Ordovician rocks (Sastre 1999). No large scale slides have taken place, but the many small movements pose a risk to future construction on these slopes.

SIERRAS SUBANDINAS AND SANTA BARBARA SYSTEM

Recent studies (Kley and Monaldi 1999, 2002) show that the Sierras Subandinas are structurally distinct from the Santa Barbara System, which was described by Rolleri (1975). Nevertheless, I have grouped the two together for discussion of landslides.

Only a few landslides were detected in the course of an airphoto survey of the Sierras Subandinas and Santa Barbara System in the Province of Salta. The only airphotos available for this region are relatively small scale (about 1:70,000); as Rib and Liang (1978) point out, large landslides may be recognizable at this scale, but small landslides, such as the one described near Rosario de la Frontera described by Abascal and González (2006) are difficult to detect on photos at scales smaller than 1:10,000. Some of the largest landslides observed on the airphotos used are on the slopes of cerro Ceibal, along the Salta-Jujuy provincial boundary in sierra de Centinela (Fig. 1). The largest of a group of 3 is a slump-earth flow 1700 m across and 2000 m from crown to toe. The second largest in this group is on the Jujuy side of the same peak. Another large slump-earthflow about 1800 m across and more than 3000 m from crown to toe is 10 km SSE of the junction of río El Tunel with río Juramento, in sierra de Guanacos. Lake sediments in the displaced block beneath the main scarp are still undissected but the stream draining from that surface has eroded deeply into the earthflow beneath it. A second slide just east of the large slump-earthflow resembles a lateral spread.

The succession of anticlines and synclines in the Sierras Subandinas has resulted in many rock escarpments. Rock falls from the cliffs undoubtedly take place regularly, producing a talus of scree below the fall face, although few talus accumulations were recognizable on the small scale airphotos. Sierra Maíz Gordo is an anticlinal mountain range, with thick-bedded sandstone supporting the crest and upper slopes. The sandstone has formed cliffs at the top of steep-walled canyons eroded by the small streams that hear on the crest of the range.

All the Sierras Subandinas are highly dissected. Most of the slopes that dominate them are forested, so small mass-wasting features are obscured by vegetation. Nevertheless, steep fans that emerge from the mouths of streams that drain these mountains are evidence that debris flows have occurred. Soil slips, scarcely detectable on photos of the scale available, take place during times of high precipitation, producing small debris flows that inundate segments of roads and cultivated fields along their paths.

Mass-wasting processes on the slopes in the Caraparí-Itiyuro river basin north of Tartagal, on the eastern flank of the Serranía de Itau near the Bolivian frontier, filled the reservoir along the river with sediment much faster than had been expected (Amengual 1991). In the same region, the severe storms of March 1984 produced damaging mass wasting processes on the eastern slopes and the piedmont of the sierra de Aguaragüe (González Díaz and Malagnino 1990). Mudflows and debris flows generated by this and other intense rainfalls of the early 1980's extended fans across the railroad and highway at General Mosconi and approached the power plant of Tartagal.

ACTIVE FAULTS

Earthquakes of (Richter) magnitude 5.0 and greater have triggered landslides in many parts of the world, but few historic slides have been recorded for earthquakes of lesser magnitude (Keefer 1984, 1994). Completely sound rock is unlikely to be disturbed by an earthquake, but weathered rock, rock with higher than normal moisture content, and rock that contains significant structural zones or planes of weakness will be seriously affected. Historic earthquakes in the Province of Salta include some near the city of Salta and in a seismic belt that runs through the Santa Barbara System and the Sierras Subandinas from south of Rosario de la Frontera through Metán and Oran to the north limit of the province (Marcuzzi et al. 1994). Two factors of concern need to be considered with respect to earthquakes in this zone. The first is the existence of recently active faults, some of which were observed in the airphoto study of landslides; the second is the presence in the Sierras Subandinas and the east of the Cordillera Oriental and Calchaquenia of basins filled with unconsolidated sediments of Quaternary age.

Amos and others (1981) mentioned 3 faults in the Province of Salta, citing maps by Ruiz Huidobro (1960, 1968) as the source. A fault east of cerro San Miguel near Cerrillos and 15 km south of Salta and a second one 45 km east of Salta (Los Nogales fault) cut Quaternary alluvial sediments; thus they were presumed to be active. The third, along arroyo La Yesera on the west side of cerro Agua de Castilla, 20 km southwest of Chicoana, cuts sediments of alluvial fans.

Fresh fault scarps offset the lower part of upper Pleistocene/Holocene alluvial fans on both sides of the sierra de La Candelaria south of Rosario de la Frontera. The fault scarp along the west side is 19,5 km long and strikes about N7 ° E from 10 km northeast of La Candelaria to 22 km south of Rosario de la Frontera. This scarp is very fresh looking and the streams emerging from the mountains have eroded trenches through the uplifted lower part of the fan. The fault scarp along the east side of the sierra de La Candelaria also has offset upward the lower part of the fans, but the most recent movement on it took place longer ago. The fault is difficult to trace across the Holocene fan surfaces, but is evident where remnants of an older fan surface remain.

Three faults strike N45°E cross the alluvial fans along the southeast side of río Guachipas, northeast of the village of Guachipas (Wayne 1999, Fig. 3). Two of these faults bound the margin of a horst that has risen across the distal part of the bajada. The third is nearly parallel with them but is a very low scarp higher on the fan that can be traced across the Holocene surface. Another zone of Quaternary faulting marked by a belt of low hills underlain by Upper Tertiary and Lower Quaternary sediments strikes about N40° E across the middle of the alluvial fans from near Coronel Moldes to west of La Viña. Upper Quaternary sediments have not been disturbed by these faults, though, so they may no longer be active.

CONCLUSIONS

Rapid slope failures have caused significant damage to property and to highways in the Province of Salta. Routes of communication –roads and railroads– must be located along lines of low to moderate gradient; therefore, those that provide pathways into and through the Cordillera Oriental and Calchaquenia follow valleys. Because many of the valleys that emerge from the rising mountains are narrow with steep valley sides, the potential for slope failures that block or destroy segments of the routes in them is always present. The only way to avoid major damage from large debris flows that follow the main channel is to build a railroad or road high enough to be completely clear of a flowing mass of debris in those valleys, such as Escoipe and Toro, where the upper part of the basin is underlain by large amounts of loose rock debris weathered from slates and phyllites of the Puncoviscana Formation. This was done along route 33 following the destruction of San Fernando de Escoipe in 1976. Similar reconstruction was done for both the highway and railroad along the río Grande valley in the province of Jujuy following disastrous debris flows and floods in 1986 (Chayle and Wayne 1995). Where a raised roadbed is on an embankment above the valley floor adequate drainage must be provided beneath it to avoid ponding on the upslope side.

Nearly all non-volcanic debris flows originate in steep colluvium-filled hollows at the heads of first-order streams; therefore, repeated surveys by both large scale air photography and field checking of these sites in the basins of the stream most frequently affected by debris flows would provide useful for predictions. No hazards exist unless communities or structures have been built along the routes followed by debris flows, so these kinds of monitoring methods need not be employed except where something can be damaged. Canadian engineering geologists have compiled a wide range of defensive measures to mitigate damage from debris flows (Hungr et al. 1987; Eisbacher and Clague 1984).

Two active earthflows were recognized in this study; both are on the slopes of the Cuesta del Obispo, but only one crossed repeatedly by route 33 constitutes a hazard. This earthflow is stable during the dry months but moves slowly in summer. Rainfall saturates the gravel in the slumped surface at the top of the earthflow and the water is transmitted downward through the permeable material to the highly broken sedimentary rocks beneath. Drainage of water from the surface of the upper displaced block would reduce the amount available to infiltrate the flow, and emplacement of horizontal conduits in the flowing mass beneath the top may reduce the water content to slow the flowage significantly, perhaps even stabilize it, thus reducing the annual costs of maintenance of the road (Gedney and Weber 1978).

Effective methods to reduce rockfall damage to highways include use of wire mesh (Piteau and Peckover 1978, p 219-220), benches, and ditches beneath the vertical slope. Space is not available for relocation of the highway along quebrada del Toro where rockfall is a hazard, and space is inadequate at this time to construct a ditch between the roadbed and the vertical rockwall. Benching may be possible to reduce the height of the vertical face above the road surface, but a wire mesh may be the least expensive way to prevent rockfalls onto the surface.

Most of the rock slides and slumps identified in this study are now stable and probably will not become reactivated unless construction activity should make them unstable again. The greatest advantage to this part of the inventory is to recognize their existence and the conditions that probably caused the slope failure. By identifying the locating the sites of past landslides, a foundation is established for determining where additional geotechnical study is called for if construction is planned near them. A major concern is the failure to recognize older slides and, in the course of construction work, reactivating them. Methods have been developed to prevent reactivation of slides, provided they are recognized (Gedney and Weber 1978; Leighton 1966). The identification of clusters of large landslides in this inventory provides additional data on probable epicenters of high (>5.0) magnitude seismic events that have taken place in the province during the past few thousand years.

ACKNOWLEDGEMENTS

Financial support for the field work that was done in preparation of this report was provided by the National Geographic Society (Grant No. 3438-86) and by the Fulbright Commission (Council for the International Exchange of Scholars), American Republics Research Program (1993-4). An administrative leave from my teaching responsibilities at the University of Nebraska allowed me to undertake the 1987 work. Ricardo N. Alonso, National University of Salta, provided helpful background and introduced me to the stratigraphic units exposed in the province. Dr. José A. Salfity helped obtain maps of the province, both topographic and geologic. The Dirección de Minería de la Provincia de Salta, the Instituto Nacional de Tecnología (INTA), and the Dirección de Recursos Naturales Renovables of the province permitted me to borrow stereo coverage of air photos from their files. My wife, Naomi L. Wayne was my field assistant and typist throughout all phases of the project.

REFERENCES CITED

Abascal, L. del V., and González Bonorino, G., 2006, Kinematics of a translational/rotational landslide, central Andes, northwestern Argentina: Environmental and Engineering Geology, v. 12, no. 4, p. 369-376.

Alonso, R.N., and Wayne, W.J., 1992, Riesgos geológicos en el norte argentino, *in* Resúmenes y Programas, Congreso Geológico Boliviano, 10th, La Paz: La Paz, Sociedad Geológica Boliviana, Boletín, v. 27, p. 213-216.

Amengual, R.E., 1991, Fenómenos de remoción en masa en la cuenca del río Caraparí-Itiyuro: Revista de Geología Aplicada a la Ingeniería y al Ambiente, Buenos Aires, Asociación Argentina de Geología Aplicada a la Ingeniería, v. 6, p. 94-102.

Amengual, R.E., 1992, Estudio de las avalanchas de detritos (volcanes de barro) en los alrededores de la localidad de Chicoana: Salta, Administración General de Aguas de Salta, 25 p., map, 50 photos (unpublished).

Amos, A., Caligari, R., and Siches, C., 1981, Las fallas activas de la República Argentina, *in* Actas, Congreso Geológico Argentino, 8th, San Luis: Buenos Aires, Asociación Geológica Argentina, v. 2, p. 233-242.

Balderrama, C.A., 1989, Estudio geológico-geotécnico aplicado a estabilidad de taludes: ruta nacional no 68-km 79.5 [Tesis Profesional]: Salta, Universidad Nacional de Salta, Facultad de Ciencias Naturales, 99 p.

Bianchi, A.R., and Yañez, C.E., 1992, Las precipitaciones en el noroeste Argentina: Salta, Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Agropecuaria Salta, 50 p.

Bookhagen, B., Haselton, K., and Trauth, M.H., 2001, Hydrological modeling of a Pleistocene landslide-dammed lake in the Santa María Basin, NW Argentina: Paleogeography, Paleoclimatology, Paleoecology, v. 169, p. 113-127.

Brabb, E.E., 1991, The world landslide problem: Episodes, v.14, no. 1, p. 52-61.

Brabb, E.E., 1993, Proposal for worldwide landslide hazard maps, *in* Novosad, S., and Wagner, P., eds., Landslides, International Conference and Field Workshop on Landslides, 7th, Proceedings, p. 15-24.

Carson, M.A., and Kirkby, M.J., 1972, Hillslope form and process: Cambridge, Cambridge University Press, 475 p.

Chayle, W., and Wayne, W.J., 1995, Impact of erosion, mass wasting, and sedimentation on human activities in the Rio Grande basin, Jujuy Province, Argentina: Environmenrtal and Engineering Geoscience, v. 1, p. 403-416.

Church, M., and Miles, M.J., 1987, Meteorological antecedents to debris flow is southwestern British Columbia: some case studies, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 63-79.

Clapperton, C., 1993, Quaternary geology and geomorphology of South America: Amsterdam, Elsevier, 779 p.

Costa, J.E., and Schuster, R.L., 1988, The formation and failure of natural dams: Geological Society of America Bulletin, v. 100, p. 1054-1068.

Crozier, M.J., Vaughan, E.E., and Tippett, J.M., 1990, Relative instability of colluvium-filled bedrock depressions: Earth Surface Processes and Landforms, v. 15, p. 329-339.

Cruden, D.M., 1991, A simple definition of a landslide: International Association of Engineering Geology, v. 43, 27-29.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Shuster, R.J., eds., Landslides, investigation and mitigation: Transportation Research Board, National Research Council, Special Report 247, p. 36-90.

de Silva, S.L., 1989, Altiplano-Puna volcanic complex of the central Andes: Geology, v. 17, p. 112-1106.

Dietrich, W.E., Wilson, C.J., and Reneau, S.L., 1986, Hollows, colluvium, and landslides in soil-mantled landscapes, *in* Abrahams, A.D., ed., Hillslope Processes: Binghamton Symposium Series in Geomorphology, Winchester, MA, Allen and Unwin, Inc., v. 16, p. 361-388.

Eisbacher, G.H., and Clague, J.J., 1984, Destructive mass movements in high mountains: hazard and management: Geological Survey of Canada, Paper 84-16, 230 p.

Ericksen, G.E., Ramírez, C.F., Concha, J.F., Tisnado, G., and Urquidi, B.F., 1989, Landslide hazards in the central and southern Andes, *in* Brabb, E.E., and Harrod, B.L., eds., Landslides: extent and economic significance: Rotterdam, Balkema, p. 111-117.

Frenguelli, J., 1936, Investigaciones geológicas en la zona salteña del valle de Santa María: La Plata, Obra del Cincuentenario del Museo de la Plata, v. 2, 572 p.

Gallardo, E. F., 1988, Geología del Cuaternario en la confluencia de los ríos Calchaquí y Santa María (Salta): Revista de la Asociación Geológica Argentina, v. 43, p. 435-444.

Gedney, D.S., and Weber Jr, W.G., 1978, Design and construction of soil slopes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides, analysis and control: National Research Council, Transportation Research Report 176, Chapter 8, p. 172-191.

Gonzáles Díaz, E.F., and Fauque, L.E., 1987, Proveniencia del material componental del torrente de barro de «El Volcán» –Quebrada de Humahuaca (Jujuy)– República Argentina, *in* Actas, Congreso Geológico Argentino, 10th, Tucumán: Buenos Aires, Asociación Geológica Argentina, v. 3, p. 309-312.

González Díaz, E.F., and Malagnino, E.C., 1990, El proceso de la remoción en masa: su incidencia como riesgo natural en el fenómeno del 29-3-1984 en el sureste de la Sierra de Aguaragüe, Salta (República Argentina): Revista de Geología Aplicada a la Ingeniería y al Ambiente, Buenos Aires, Asociación Argentina de Geología Aplicada a la Ingeniería, v. 5, p. 7-18.

Hansen, M.J., 1984, Strategies for classification of landslides, *in* Brunsden, D., and Prior, D.B., eds., Slope instability: Chichester, John Wiley & Sons, p. 1-25.

Hauser, Arturo, 1985, Flujos de barro en la zona preandina de la Región Metropolitana: características, causas, efectos, riesgos y medidas preventivas: Revista Geológica de Chile, no. 24, p. 75-92.

Hermanns, R.L., and Strecker, M.R., 1999, Structural and lithologic controls on large Quaternary rock avalanches, sturzstroms, in arid northwestern Argentina: Geological Society of America Bulletin, v. 111, no. 6, p. 934-948.

Hermanns, R.L., Trauth, M.H., McWilliams, M., and Strecker, M.R., 2000, Tephrochronologic constraints on temporal distribution of large landslides in NW-Argentina: Journal of Geology, v. 108, p. 35-52.

Hungr, O., Morgan, G.C., VanDine, D.F., and Lister, D.R., 1987, Debris flow defenses in British Columbia, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 201-222.

IAEG Commission on Landslides, 1990, Suggested nomenclature for landslides. International Association of Engineering Geology, Bulletin, v. 41, p. 13-16.

Igarzábal, A.P., 1971, Remoción en masa en la Quebrada del Toro (Salta): Tucumán, Universidad Nacional de Tucumán, Opera Lilloana, v. 21, 70 p.

Igarzábal, A.P., 1979, Los flujos densos de la Quebrada de Escoipe, *in* Actas, Congreso Geológico Argentino, 7th, Neuquén (1978): Buenos Aires, Asociación Geológica Argentina, v. 2, p. 109-117.

Igarzábal, A.P., 1991, Morfología de las provincias de Salta y Jujuy: Jujuy, Universidad Nacional de Jujuy, Revista del Instituto de Geología y Minería, v. 8, p. 97-121.

Jackson, L.R., Jr., Kostaschuk, R.A., and MacDonald, G.M., 1987, Identification of debris-flow hazard on alluvial fans in the Canadian Rocky Mountains, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 15-124.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

Keefer, D.K., 1994, The importance of earthquake-induced landslides to long-term slope erosion and slope-failure hazards in seismically active regions: Geomorphology, v. 10, p. 265-284.

Kley, J, and Monaldi, C.R., 1999, Estructura de las Sierras Subandinas y del Sistema de Santa Bárbara, *in* Geología del noroeste argentino, Relatorio, Congreso Geológico Argentino, 14th, Salta: Buenos Aires, Asociación Geológica Argentina, v. 1, p. 415-425.

Kley, J., and Monaldi, C.R., 2002, Tectonic inversion in the Santa Barbara System of the central Andean foreland thrust belt, northwestern Argentina: Tectonics, v. 21, no. 6, p. 1-18.

Kochel, R.C., 1987, Holocene debris flows in central Virginia, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 139-155.

Leighton, F.B., 1966, Landslides and hillside development, *in* Engineering Geology in Southern California: Los Angeles, Association of Engineering Geologists, Special Publication, p. 149-207.

Marcuzzi, J.J., Wayne, W.J., and Alonso, R.N., 1994, Geological hazards of Salta Province, Argentina, *in* Proceedings, International Association of Engineering Geology Congress, 7th: Rotterdam, Balkema, p. 2039-2048.

Mon, R., 1979, Esquema tectónico de los Andes del norte argentino: Revista de la Asociación Geológica Argentina, v. 34, no. 1, p. 53-60.

Mon, R., 1999, Cordillera Oriental, *in* Geología del noroeste argentino, Relatorio, Congreso Geológico Argentino, 14th, Salta: Buenos Aires, Asociación Geológica Argentina, v. 1, p. 426-431.

Moreiras, S.M., 2004, Landslide incidence zonation in the río Mendoza valley, Mendoza province, Argentina: Earth Surface Processes and Landforms, v. 29, p. 255-266.

Neary, D.G., and Swift, L.W., Jr., 1987, Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 81-92.

Pierson, T.C., 1986, Flow behavior of channelized debris flows, Mount St. Helens, Washington, *in* Abrahams, A.D., ed., Hillslope Processes: Binghamton Symposium Series in Geomorphology, Winchester, MA, Allen and Unwin, Inc., v. 16, p. 269-296.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 1-12.

Piteau, D.R., and Peckham, F.L., 1978, Engineering of rock slopes, *in* Schuster, R.L., and Krysek, R.J., eds., Landslides: Analysis and control: Transportation Research Board, National Research Council, Special Report 176, Chapter 9, p. 192-225.

Polanski, J., 1966, Flujos rápidos de escombros rocosos: Buenos Aires, Editorial Universitaria de Buenos Airess, Manuales, 67 p.

Reneau, S.L., and Dietrich, W.E., 1987, The importance of hollows in debris flow studies. Examples from Marin County, California, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 165-180.

Rib, H.T., and Liang, T., 1978, Recognition and identification, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides, analysis and control: National Research Council, Transportation Research Report 176, Chapter 3, p. 34-80.

Rolleri, E.O., 1975, Sistema de Santa Bárbara: una nueva provincia geológica argentina, *in* Actas, Congreso Geológico Argentino, 6th, Bahía Blanca: Buenos Aires, Asociación Geológica Argentina, v, 1, p. 239-255.

Ruiz Huidobro, O. J., 1949, Estudio geológico de la región de los cerros Quitilipi y Pirgua: Revista de la Asociación Geológica Argentina, v. 4, no. 1, p. 40-75.

Ruiz Huidobro, O.J., 1960, Descripción geológica de la Hoja 8e Chicoana, provincia de Salta: Buenos Aires, Dirección Nacional de Geología y Minería, Boletín 89, 46 p.

Ruiz Huidobro, O.J., 1968, Descripción geológica de la Hoja 7e, Salta, provincias de Salta y Jujuy: Buenos Aires, Instituto Nacional Geología Minería, Boletín 109, 48 p.

Salfity, J.A., 2006, Geología regional del valle Calchaquí: Buenos Aires, Academía Nacional de Ciencias Exactas, Físicas, y Naturales, Anales, v. 56 (2004), p. 133-150.

Salfity, J.A., Monaldi, C.R., Guidi, F., and Salas, R.J., 1998, Mapa geológico de la Provincia de Salta, escala 1:500,000: Buenos Aires, Servicio Geológico Minero Argentino, 2 sheets.

Sastre, J.E., 1999, Geología urbana de la ciudad de Salta, *in* Geología del noroeste argentino, Relatorio, Congreso Geológico Argentino, 14th, Salta: Buenos Aires, Asociación Geológica Argentina, v. 2, p. 99-111.

Schuster, R.L., 1996, Socio-economic significance of landslides, *in* Turner, A.K., and Shuster, R.J., eds., Landslides, investigation and mitigation: Transportation Research Board, National Research Council, Special Report 247, p. 12-35.

Schuster, R.L., and Fleming, R.W., 1986, Economic losses and fatalities due to landslides: Association of Engineering Geologists, Bulletin v. 23, p. 11-28

Schuster, R.L., and Kockelman, W.J., 1996, Principles of landslide hazard reduction, *in* Turner, A.K., and Shuster, R.J., eds., Landslides, investigation and mitigation: Transportation Research Board, National Research Council, Special Report 247, Chapter 5, p. 91-105.

Schuster, R.L. Salcedo, D.A., and Valenzuela, L., 2002, Overview of catastrophic landslides of South America in the twentieth century, *in* Evans, S.G., and De Graff, J.V., eds., Catastrophic landslides: Effects, occurrence, and mechanisms: Boulder, Colorado, Geological Society of America Reviews in Engineering Geology, v. 15, p. 1-34.

Trauth, M.H., and Strecker, M.R., 1999, Formation of landslide-dammed lakes during a wet period between 40.000-25,000 yr B.P. in northwestern Argentina: Paleogeography, Paleoclimatology, Paleoecology, v. 153, no. 1-4, p. 277-287.

Trauth, M.H., Alonso, R.A., Haselton, K.R., Herrmans, R.L., and Strecker, M.R., 2000, Climate change and mass movements in the northwest Argentine Andes: Earth and Planetary Science Letters, v. 179, p. 243-256.

Trauth, M.H., Bookhagen, B., Marwan, N., and Strecker, M.R., 2003, Multiple landslide clusters record late Pleistocene climate changes in the NW Argentine Andes: Paleogeography, Paleoclimatology, Paleoecology, v. 194, p. 109-121.

Turner, J.C.M., and Mon, R., 1979, Cordillera Oriental, *in* Turner, J.C.M., coord., Geología regional argentina, Segundo Simposio: Academia Nacional de Ciencias de Córdoba, v. 1, p. 57-94.

UNESCO Working Party on World Landslide Inventory, 1990, A suggested method for reporting a landslide: International Association of Engineering Geology, v. 41, p. 5-12.

Varnes, D.G. 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides, analysis and control: National Research Council, Transportation Research Report 176, Chapter 2, p. 11-33.

Wayne, W.J., 1990, The diamictons of the Río Blanco basin, Cordón del Plata, Mendoza, *in* J.Rabassa, ed., Quaternary of South America and Antarctic Peninsula: Rotterdam, A.A. Balkema, v. 6, p. 2-31.

Wayne, W.J., 1993, Escoipe valley and the Cuesta del Obispo: a classic region of slide movement: National Geographic Society, Committee for Research and Exploration, Final Report of project: 3438-86, 53 p. (unpublished).

Wayne, W.J., 1999, The Alemanía rockfall dam: A record of a mid-Holocene earthquake and catastrophic flood in northwestern Argentina: Geomorphology, v. 27, p. 295-306.

Wayne, W.J., and Alonso, R.N., 1992, Catastrophic debris flows, eastern slope of the Andes, northern Argentina: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. 165-166.

Wieczorek, G.E., 1987, Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, *in* Costa, J.E., and Wieszorek, G.F., eds., Debris flows/Avalanches: Process, Recognition, and Mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 93-114.