Costa, C., Audemard, F., Audin, L., Benavente, C., 2010. Geomorphology as a Tool for Analysis of Seismogenic Sources in Latin America and the Caribbean. In: E. Latrubesse Ed. Natural Hazards and Human-Exacerbated Disasters in Latin America. Special Volumes of Geomorphology. Developments in Earth Surface Processes, 13, 29-47. Elsevier, 535p., Amsterdam.

CHAPTER 2

Geomorphology as a Tool for Analysis of Seismogenic Sources in Latin America and the Caribbean

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Developments in Earth Surface Processes, Volume 13
ISSN 0928-2025, DOI 10.1016/S0928-2025(08)10002-5
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1. Introduction

Seismicity, volcanism, and related processes have constituted a significant hazard in most regions of Latin America and the Caribbean since the Spanish arrival, and catastrophic events have been recorded in the pre-Hispanic period of America as well. The identification and analysis of most volcanic hazardous sources are quite direct, owing to their prominent geomorphic signature and precursory effects, such as gas emission and local seismicity. However, the recognition of many potential seismic sources commonly expressed at surface as faults and folds is not so straightforward.

In the outer lithosphere, an earthquake implies a sudden release of elastic energy through one or several rupture areas that may remain blind, without affecting the Earth's surface. However, depending on the size of the ruptured area and the depth of the hypocenter, the earthquake-related rupture may reach the surface, causing deformation as faulting or folding phenomena. These ruptured areas are located at major dynamic lithospheric borders as subduction zones and other interplate boundaries. Earthquakes tend to cluster in space and time at these critical zones, being envisaged as seismogenic sources, and therefore these zones are considered to be prone to future hazardous earthquakes.

A significant part of the deformation resulting from the interacting lithospheric plates is accommodated along plate boundaries at rates commonly ranging from 50 to 90 mm/yr. However, part of this deformation at a crustal scale is also transmitted through the continental crust away from these boundaries, elastically stressing the continental interiors at a much lower deformation rate. This fact turns many anisotropies and weaknesses of the continental crust (i.e. faults) into potential seismogenic sources, even those located at areas considered stable continental interiors (e.g., the Mississippi valley in the United States and Marryat and Tennant Creek in Australia). Because of the low slip rates (commonly <1 mm/yr), these structures may not show records of historical seismicity, and usually they cannot even be imaged by seismicity. Consequently, the significance of these structures as potential seismogenic sources can be missed or underestimated if the data for assessing the seismic hazard are based solely on the historical and instrumental seismicity of a region or individual structure.

Active fault studies have demonstrated a consistent relation between the slip rate of geological structures and the recurrence interval for destructive earthquakes along them (Audemard and Singer, 1996; Sieh, 1996; McCalpin, 1996; Villamor and Berryman, 1999; and many others). These results suggest that repetition of large earthquakes may be witnessed at a human temporal scale in structures accommodating significant deformation at interplate boundaries. For these cases, seismicity commonly corresponds to the spatial location of seismic sources, which most frequently correlates at surface with geological structures that show evidence of recent or even historic deformation. These seismic sources may be located onshore (i.e., the Mérida Andes of Venezuela and Tierra del Fuego in South America, the Polochic-Motagua area in Central America), or they may remain offshore such as those represented by shallow earthquakes along subduction zones.

The recurrence pattern for most seismogenic structures in the long term (10^4-10^5 years) could be periodic, clustered or random. However, is common that those structures with significant slip rates (> 5mm/yr) have already produced a large earthquake during the historical record, which in the Americas barely covers the last 500 years. This time span may allow the recording of at least one large earthquake along these structures, which can be regarded as representative for its seismic potential. However, it is well known that elastic energy can be stored for a considerable period of time (10^3–10^5 years) along structures or crustal anisotropies at very slow strain rates, which do not necessarily mean a lower seismogenic capability. Although large earthquakes at intraplate regions are less common, they can produce substantial damage, not only because of the earthquake itself, but also because people are much less prepared and structures are generally not designed to withstand strong ground motion.

When evaluating a seismic source's capability for producing destructive earthquakes in the future, it is important to estimate its maximum seismogenic potential. This is because the ground peak acceleration, which is related to the size of the seismic event among other characteristics, determines the safety parameters for building design and construction in general. Therefore it is a basic input in territorial planning.

Traditionally, seismic hazard assessments, even in intraplate regions, have relied on the seismic catalogue to identify areas where damaging earthquakes might occur in the near future. But based on contemporaneous experiences and on the scientific knowledge of mainly the last three decades, it is now widely accepted that there is a need to widen the possible seismic scenarios by expanding the time window of the seismic record into the past. In other words, it has been demonstrated that seismic hazard cannot be properly assessed with the data illuminating only the last 500 years (or frequently less than that). For areas where the seismic cycle of a source involves a time span beyond historic records, there are significant chances that they are characterized by moderate to long recurrence intervals (10^3–10^5 years). In the Andean region, for example, the geologic structures that show evidence of movements during the Quaternary (<1.8 Ma) are thought to be the ones that exhibit the highest likelihood of experiencing seismic events with social impact in the future.

The scientific approach to expanding the time frame of earthquake records into prehistoric times is based on the wide consensus that earthquakes of magnitude M > 6,5 with depths shallower than 30 km commonly deform the Earth's surface and/or lead to other secondary effects such as liquefaction and slope instability (Slemmons, 1977; Wallace, 1981; Bonilla, 1988; Wells and Coppersmith, 1994, McCalpin, 1996; and many others). Evidence of this sort can be preserved in the landscape and in the Quaternary stratigraphic record at deformation zones, with the analysis and interpretation of such evidence undertaken in the fields of earthquake geology and paleoseismology (Wallace, 1981, 1986; Yeats and Schwartz, 1990; McCalpin, 1996; Yeats and Prentice, 1996, among many others). Geomorphology plays an important role in this multidisciplinary approach because terrain analysis constitutes one of the most important steps in identifying and evaluating geomorphic assemblages potentially related to recent deformation of seismic origin. Although paleoseismic studies have less accuracy than the seismic catalogue, they help to provide more realistic assessments of the seismogenic capability for many structures, particularly in intraplate areas (e.g., Audemard, 2005).

Some case histories of structures with different tectonic regimes from the Andean region have been selected here to illustrate the role of terrain analysis in recognizing evidence of Quaternary activity. In some cases they have led to more detailed paleoseismic studies for seismic hazard assessments.

2. The Seismotectonic Setting of Latin America and the Caribbean

Western South America and most parts of Central America and the Caribbean lie close to dynamic areas of the Earth's crust, where earthquakes are common and often destructive. Figure 2.1 outlines major lithospheric plate boundaries and

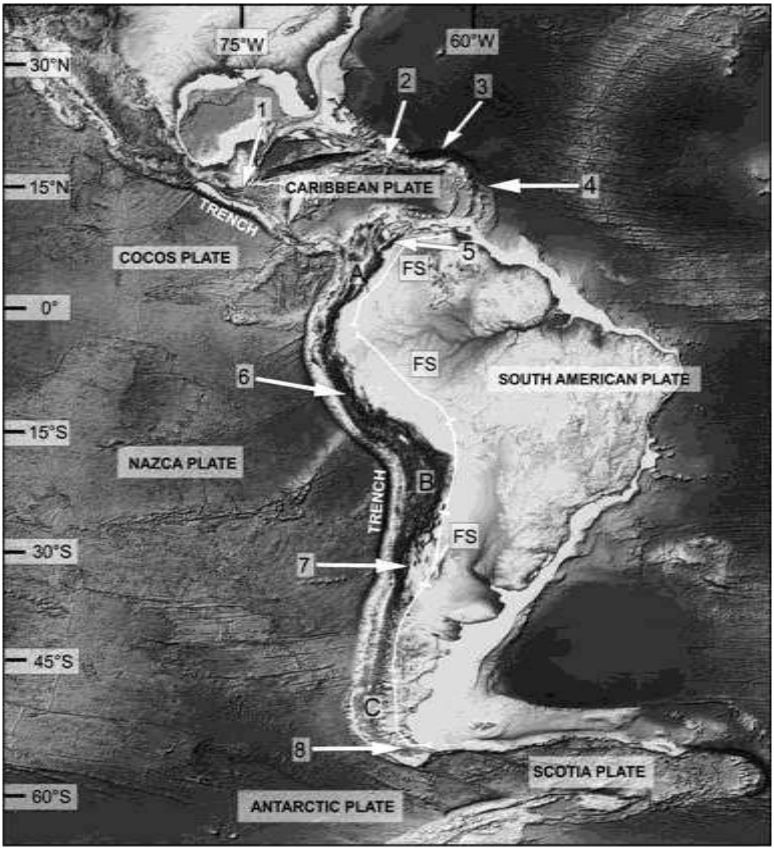

Figure 2.1 Major plate domains of South/Central America and the Caribbean. A, B, C: Northern, Central, and Southern Andes, respectively. 1. Motagua-Polochic deformation zone, 2. Hispaniola island, 3. Puerto Rico trough, 4. Lesser Antilles subduction zone, 5. Merida Andes of Venezuela and Bocono fault, 6. Cordillera Blanca, Peru, 7. Argentina Precordillera, 8. Magallanes-Fagnano transform zone. FS: Flat-slab subduction segments. DEM downloaded from http://www.ngsg.noaa.gov/.

provides a suitable base for understanding the occurrence of earthquakes in space and time, particularly those related to interplate areas.

2.1. The Caribbean and Central America

Most of the Caribbean plate corresponds to oceanic crust and island arcs separating the major plates of North and South America (Fig. 2.1). The main historic earthquakes, current seismicity, and active geological structures are concentrated along plate margin interactions, linked to subduction zones and transform boundaries. In some cases, these transform zones do not exhibit a well-defined margin, but instead constitute a diffuse area characterized by higher seismic activity and slip rates of first-order geological structures.

The boundary with the North America plate (where almost all the territory of Mexico lies) is dominated by a left-lateral regime, expressed onshore near the Guatemala–Honduras border as the Motagua-Polochic deformation zone (Malfait and Dinkelman, 1972). The Motagua fault was the source for a M_s 7.5 earthquake in 1976 (Ms: Surface wave magnitude), accompanied by 230 km of left-lateral slip (Plafker, 1976). An example of the geometric array accompanying the surface rupture is shown in Figure 2.2. Other faults related to this plate boundary are the Oriente-Septentrional fault system in the island of Hispaniola, with active seismicity and documented evidence of prehistoric earthquakes (Prentice et al., 1993). The wrenching interaction between plates changes east of Hispaniola into subduction at the Puerto Rico trench.

The Lesser Antilles subduction zone constitutes the eastern boundary of the Carribbean plate, where an active volcanic arc is the main feature above sea level. Earthquakes and volcanism are related to subduction processes, and although minor

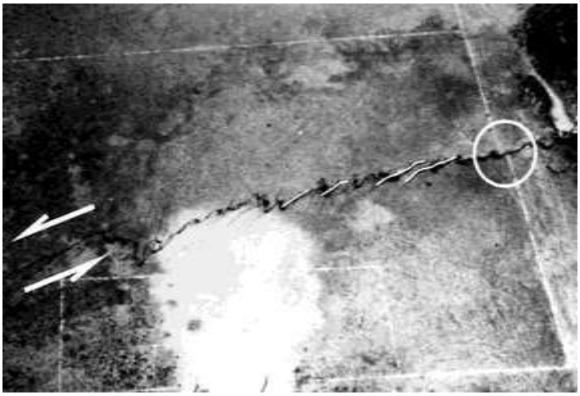

Figure 2.2 Surface ruptures along the Motagua fault at a soccer field, related to the Guatemala 1976 earthquake. Note the en echelon pattern (partly highlighted by white traces) corresponding to Riedel shears resulting from a left-lateral movement of the fault. This sense of displacement is also verified by the offset of the white lines to the right (within the white circle). Photo downloaded from USGS Photolibrary (http://www.usgs.gov).

to moderate seismicity may be tied with volcanic eruption, they are essentially separated processes, particularly for large earthquakes.

The southeastern boundary of the Caribbean plate and its present interaction with the South American plate is still a matter of controversy (e.g., Audemard and Audemard, 2002 and references therein). Yet there is general agreement that the plate boundary comprises several broad deformation zones where most relative plate motion is accommodated. The plate interaction also involves minor blocks, such as the North Andean, Maracaibo, and Panama blocks, whose affiliation and relationships to both plates have received several interpretations.

The subduction zone between the Cocos plate and Central America constitutes the southwestern boundary of the Caribbean plate, as well as the main seismic threat to the population established along the Central America isthmus. This is due to the shallow depth and seismic potential of the north-dipping subduction zone. Therefore, most damaging historic earthquakes correspond to this interplate seismicity, such as those that heavily damaged San Salvador city (El Salvador) in 1917 and Managua (Nicaragua) in 1972.

The Central America volcanic depression is a regional physiographic feature linked to the subduction polarity. It is highlighted by two large lakes, Managua and Nicaragua, and runs partly parallel to the active volcanic arc (Cowan et al., 2000). Although the tectonic nature of this depression is still a matter of debate, some authors have linked it to bounding faults with active seismicity (Dewey and Algermissen, 1974). The chain of active volcanoes is dissected by several steps, and it ends near the Costa Rica–Panama border in apparent relation to the flattening of the Cocos plate and the change of the subduction regime into a transform interaction between the Cocos and Caribbean plates (Taboada et al., 2000).

Earthquakes and active deformation in eastern Central America are concentrated along the Panama block boundaries. They relate to offshore deformed belts in many parts (North Panama and South Panama deformed belts) where plate interaction is accommodated mainly by shortening and strike-slip deformation. Other regions, such as its eastern boundary, also correspond to a zone of active but diffuse deformation, partly comprising the rain forest areas of northwestern Colombia. The Panama block seems to be colliding against the Colombian Andes, causing significant seismicity (Taboada et al., 2000).

2.2. South America

The Andean cordillera is considered to be the tectonic backbone of continental South America, and it has a long and complex history of terrain accretion along the former western boundary of Gondwana. It concentrated significant mountain-building processes during the Cenozoic, resulting in the highest non-collisional orogen worldwide (Ramos, 1999). This 8000-km-long chain has been traditionally divided into three main sectors: the Northern, the Central, and the Southern Andes (Fig. 2.1).

The most significant seismic hazard for South America in terms of recurrence and capability for producing very large earthquakes is the trench-related seismicity along the Pacific border (Fig. 2.1), which threatens the western Andean areas. This interplate seismicity is very shallow near the oceanic trench and coastal Pacific areas, and gets deeper below continental South America. The Mw 9.4 1960 Chilean earthquake, which is the largest earthquake ever recorded, was located at the shallow part of the subduction zone in south central Chile (Plafker and Savage 1970; Atwater et al., 1992). These shallow, trench-related earthquakes may also involve secondary effects that are sometimes even more dangerous than the earthquake itself, such as tsunamis and hillslope instability. This first-order tectonic feature caused the most important seismic crisis in South America. However, many other destructive earthquakes have been located within the South American plate, related in many cases to crustal features whose activity is connected to the Andean geodynamics. The seismic monitoring of these structures and their links with current seismicity is not as straightforward as at interplate margins.

The northernmost and southernmost ends of the Andes are currently dominated by strike-slip tectonics due to plate interaction, whereas the Andes comprised between 4 and 46 30^0 are considered to be the pure Andean-type orogen, where orogeny, magmatism, and earthquakes are basically driven by subduction (Ramos, 1999). The main geologic differences along the Andes are related to crustal nonhomogeneities linked to evolution of the terrain of western South America and to the geometry of the subducting Nazca plate (Barazanghi and Isacks, 1976, Ramos, 2008). The geometry of the subduction of the Nazca plate is the dominant factor that controls the characteristics of current seismicity and volcanism. Several latitudinal segments characterized by normal or subhorizontal subduction angles have been recognized based on interplate seismicity (Barazanghi and Isacks, 1976; Jordan et al., 1983; Ramos, 1999; Gutscher et al., 2000; Fig. 2.1).

At normal subduction segments, current deformation and crustal seismicity are concentrated within the Andean chain. Large earthquakes and active deformation at the foreland and other areas of the continental interior are rare. These segments exhibit active magmatism and a well-defined volcanic arc, hosting the most prominent Andean volcanoes.

Three segments where the Nazca plate subducts with subhorizontal angles have been recognized along the Andes (Fig. 2.1), in agreement with volcanic gaps of active magmatism. Another significant difference implies that active deformation processes, as well as crustal seismicity, are not constrained to the Andean orogen, but are also distributed within the foreland region as well (Jordan et al., 1983; Gutscher et al., 2000).

The tectonic setting of the Andes north of 4 30^{0}S is characterized by a complex interaction between the South American, Caribbean, and Nazca plates (Fig. 2.1), without a direct relation to active subduction zones (Audemard and Audemard, 2002). Earthquake sources are clustered along mountain chains, mainly in Venezuela and Colombia where major Quaternary deformation is concentrated.

This complex tectonic patchwork includes major features such as the northeast–southwest trending Boconó fault along the Venezuelan Mérida Andes and the east–west trending San Sebastián and El Pilar faults along the Caribbean coast of Venezuela (Schubert 1979, 1980, 1982, 1984; Soulas, 1986; Audemard et al., 2005), the Eastern Cordillera frontal fault zone in Colombia (Pennington, 1981), and the Dolores–Guayaquil megashear in Ecuador (Campbell, 1974). This belt of active deformation concentrates the highest known slip rates in continental South America (around 10 mm/yr) and is considered to be a diffuse boundary that detaches the Northern Andean Block from the remainder of South America (Pérez and Aggarwal, 1981; Schubert, 1982, 1984; Lavenu et al., 1995; Audemard et al., 2000, 2006; Taboada et al., 2000; Audemard and Audemard, 2002; Lavenu, 2006). These major deformation zones show a clear association with crustal seismicity and the location of historic damaging earthquakes.

The northern Andes comprise the Bucaramanga flat-slab. Although it exhibits strong differences with the other Andean flat-slab segments in terms of its geological past and current tectonic setting, all flat-lying subduction segments share a lack of active volcanism. This part of the Andean chain is also developed in close relation with a normal subduction segment of the Nazca plate in Colombia and northern Ecuador. Accordingly, it is characterized by active volcanism, namely, the Northern Volcanic zone. It is developed along the inter-Andean depression in Ecuador (i.e., Chimborazo, Cotopaxi, and Pichincha volcanoes) and along the Central and Western cordilleras in Colombia (i.e., the Nevado del Ruiz, Nevado del Huila, and Galeras volcanoes). Owing to eruption-related phenomena, they have produced many recent episodes of social concern and even catastrophes.

The long segment ascribed to the Central Andes (4° 30^{0}–46° 30^{0}S) is developed between the gulfs of Guayaquil and Penas. It is recognized as the typical Andean-type orogen, which exhibits a direct interaction between the upper South American plate and the subducting oceanic Nazca plate. It comprises two alternate segments of flat and normal subduction geometry.

The development of the Peruvian flat-slab segment (4° 30^{0}–14° 00^{0} S) has been related to the subduction of the Nazca aseismic ridge (Gutscher et al., 2000). The Cordillera Blanca, one of the Andes' highest areas and most breathtaking landscape, is located here, bounded by an active normal fault system (Schwartz, 1988; McNulty and Farber, 2002; Farber and Hancock, 2005). Shallow crustal seismicity characterizes the Eastern Cordillera and Subandean zone (Suárez et al., 1983; Dorbath et al., 1991). This region has witnessed two of the most prominent fault-related ruptures during historic earthquakes at the Quiches (M 7.25 in 1946) and Huaytapallana (M 6.2 in 1969) faults (Phillip and Mégard, 1977; Silgado, 1978). Although this latitudinal segment is also characterized by the lack of active volcanism, the active deformation and seismicity at the foreland areas are much less significant than in the other flat-slab segments (Ramos, 1999).

The normal subduction segment of the Central Andes, developed between 14° 00^{0} and 27° 00^{0}S, is characterized by a widely distributed active volcanism (Central Volcanic zone) where the Altiplano and Puna plateaus stand out. They constitute andesitic-dacitic stratovolcanoes that erupted significant volumes of lavas and ignimbrites (Harmon and Rapela, 1991). This segment exhibits the widest section across the Andes (Fig. 2.1), where active deformation and potential seismogenic sources related to blind thrusting are concentrated at the Subandean zone (Dumont, 1996; Costa et al., 2006a).

The Pampean flat-slab (27 00^{0}–33 30^{0}S) documents one of the most widespread seismicity and active deformation at foreland areas (Jordan et al., 1983), being characterized by the block uplifts of the Sierras Pampeanas (Pampean Ranges).

According to GPS results, current deformation related to subduction is being accommodated at both margins of the Andean orogen (Kendrick et al., 1999). Therefore it has been proposed that the Andes itself behaves as a microplate at these latitudes (Brooks et al., 2003; Kendrick et al., 2003). Not very many active structures are reported at the western hillslope, although numerous Quaternary deformations have been described for the eastern Andean hillslope along the Precordillera piedmont (Costa et al., 2000a), including those related to historic destructive earthquakes in 1944 (Mw 7.0) and 1977 (Mw 7.4) (Mw: Moment magnitude). The shallowing of the subduction zone during the last eight Ma is considered to be the main reason for the eastward migration of magmatism and further cessation (Kay et al., 1991).

The seismic potential of the normal angle subduction zone of the south central Andes (33° 30′–46° 30′S) was verified by the large Chilean earthquake of 1960. Even 40 years after this event, GPS measurements indicate that the crust is still adjusting to this sudden strain release (Kendrick et al., 1999). Although generally clustered, crustal shallow seismicity does not show particular relation with active structures at the backarc.

The Southern Volcanic zone is developed overall in this latitudinal segment, as underlined by widespread volcanoes. Some of the volcanoes are active (i.e., the Lonquimay, Descabezado, Chaltén, and Hudson volcanoes), with contemporary episodes of ash fall.

The tectonic setting of the Southern Andes developed south of the gulf of Penas (46° 30′S) up to the Beagle Channel area in Tierra del Fuego is dominated by the kinematic interaction among the South America, Scotia, and Antarctic plates. The strike-slip regime related to the interaction between the first two plates becomes dominant onshore in Tierra del Fuego, where the Magallanes-Fagnano fault constitutes a clear onshore transform boundary (Klepeis, 1994; Pelayo and Wiens, 1989). Two Ms 7.8 events took place within a few hours of each other in December 1949 and have been related to this fracture zone. Even if the total length of the seismic rupture remains unknown, it is considered to be one of the largest earthquake ruptures onshore in South America (Costa et al., 2006b).

3. Geomorphologic Analysis of Neotectonic Structures

The effect of tectonic features on landscape development and evolution has been widely recognized. However, the modification of tectonic-derived landforms by geomorphic processes under different morphoclimatic environments results in a wide variety of geomorphic signatures. To determine whether or not the resulting landforms are linked to active tectonic processes is not commonly a straightforward analysis. The essence of it involves recognizing the passive or active control of structures on landform assemblages.

For instance, scarps are the typical morphology related to faults, commonly represented by linear features. However, such morphologies can result from opposite processes such as Quaternary coseismic surface ruptures (purely tectonic), or they can evolve from ancient features (fractures, shear zones, and even lithologic anisotropies) enhanced by erosion. Alternatively, they can develop from many other situations not derived from structures that have undergone recent movements (purely morphodynamics). The successful discrimination between passive or active control by structures on landscape evolution then becomes a crucial issue.

A passive control is defined when the geomorphic signature of a tectonic landform is enhanced or overimposed by a geomorphic process, but not by the activity of the structure itself. On the contrary, an active control of structures on landscape implies the modification of a certain landform or landform assemblage due to a dynamic (continuous or periodic) tectonic process. Fault scarps, warping of alluvial surfaces, deflected drainages, and sudden changes in drainage patterns, among many reasons, could be a consequence of active control.

The geomorphic imprint of an active structure depends mainly on the dynamic interaction between the slip rate of a fault or the uplift rate of a fold and the erosion or sedimentation rate. Therefore, although the lack of diagnostic morphologies does not preclude the existence of shallow subsurface active structures with seismic capability, they provide the basic input in regional terrain analysis and semidetailed studies, favoring the selection of target areas for detailed paleoseismic studies.

4. Case Histories of Geomorphic Signature of Potential Seismogenic Sources

Through the following examples, we seek to illustrate the geomorphic expression of structures resulting from different tectonic regimes. Each example summarizes the evidence that led to the recognition of related Quaternary activity and consequently to more detailed *in situ* studies.

4.1. Geomorphic Signature of Quaternary Active Normal Faults: The Cordillera Blanca Fault System, Perú

The Cordillera Blanca is located in the Peruvian Andes and constitutes one of the most breathtaking Andean landscapes, with many peaks and glaciers above 6,000 m above sea level and deeply carved glacial valleys. The Cordillera Blanca fault system is the bounding structure of this mountain chain with a NNW trend and dominant normal-slip component of movement (Bonnot, 1988; Schwartz, 1988; McNulty and Farber, 2002; Farber and Hancock, 2005; Macharé et al., 2009. among many others), running approximately 200 km along its western hillslope (Fig. 2.3). The northern part of the fault system is expressed through a single fault trace dipping 35° to 45° W, whereas the southern section is characterized by several fault splays with a similar trend.

The Neogene vertical movements related to the fault activity and the Cordillera Blanca uplift are recorded in west-facing bedrock-cumulated scarps. The Quaternary and postglacial activity of the Cordillera Blanca can be recognized due to scarps affecting moraine deposits, whose estimated ages range from 11 to 14 ka (Farber and Hancock, 2005; Siame et al., 2006).

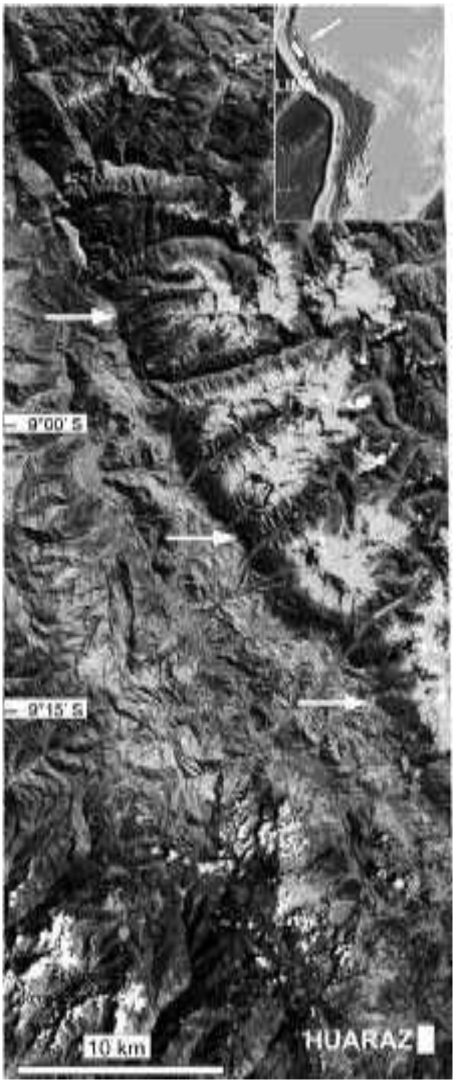

Figure 2.3 Satellite image of the Cordillera Blanca in Peru, where the snow-capped peaks stand out in light-gray -or similar-tones. The white arrows indicate the curvilinear trace of the Cordillera Blanca fault system.

Figure 2.4 shows multiple parallel scarps affecting unconsolidated moraine and hillslope deposits near the Cojup Creek. These linear features are directly related to the main fault trace, and a gravitational origin cannot be imputed. They are well preserved despite the significant slope angles, which suggest an active control due to repeated fault movements, together with the high resistance of the exposed bedrock to erosion. This fact accounts for the Late Pleistocene-Holocene activity of this fault and provides a rough estimation of its slip rate, ranging from 0.7 mm/yr

Figure 2.4 Oblique aerial photo (southeast-looking) of the western flank of the Cordillera Blanca at the Quebrada Cojup (middle-left). Main traces of the Cordillera Blanca fault system affecting moraine and hillslope deposits are indicated with arrows. Note the vertical offset of moraine arcs within the white circle. Photo courtesy of the Servicio Aerofotografico Nacional, Peru.

(Bonnot, 1988) up to 3 mm/yr (Siame et al., 2006). Faulted moraine axis, as well as numerous slickenside striations, indicate that a normal faulting component of slip prevails, without a significant strike-slip component.

Geomorphic evidence of recent activity led to investigation of the related seismic record of the Cordillera Blanca fault at the Querococha Creek, whose postglacial activity is well depicted by the faulted edge of a moraine (Fig. 2.5). Schwartz (1988) found evidence for at least five earthquakes preserved in 14 kyr-old fluvial and glacio-lacustrine deposits, which yielded estimates of slip rates ranging from 0.86 to 1.36 mm/yr and derived recurrence intervals of 1500 years.

There are no reported historic damaging earthquakes related to this fault system (Silgado, 1978), and the zone is at present characterized by low to moderate crustal seismicity (Macharé et al., 2009). The active landscape imprints related to faulting and the prehistoric record suggest that the Cordillera Blanca fault system is a main potential seismic source. Because of the high hillslope angles, the whole area is also susceptible to earthquake-induced phenomena. A widely known natural disaster took place here in 1970 when massive avalanches (causing 5000 casualties) were triggered by a subduction earthquake. These avalanches started from huge ice detachments from the Nevado Huascarán, from altitudes higher than 6300 m, destroying the villages of Yungay and Ranrahirca, located 2000 m below.

4.2. Geomorphic Signature of Quaternary Reverse Faults: The La Rinconada Fault, Argentina

This reverse fault crops out at the eastern Precordillera foothills in arid western Argentina, located within the most active seismic corridor of the Pampean flat-slab backarc. Although most reverse and thrust faults exhibit a sinuous trace, the La Rinconada fault-related scarp stands out from the alluvial plain as west-facing

Figure 2.5 North-looking view taken from the Quebrada Querococha where the fault trace and the west-dipping attitude of the Cordillera Blanca fault are clearly visible. Note the vertical offset of the moraine arc at the skyline.

rectilinear esscarpments (Fig. 2.6). This fact is due to a high angle bedding-parallel fault surface interpreted as a consequence of flexural-slip folding (Costa et al., 1999, 2006a; Meigs et al., 2006). The La Rinconada fault has been identified as the seismic source of the Mw 6.8 earthquake that struck the region in 1952, although no evidence of coseismic surface deformation has been reported.

The fault scarp accounts for decametric displacement of older Quaternary strath terraces, even if the scarp amplitude is enhanced in many cases by subsequent streams controlled by this tectonic feature. Therefore it is difficult to estimate the overall slip because the alluvial surfaces on both fault walls do not correlate.

Gentle scarplets affecting young alluvial deposits (Fig. 2.7) have been identified due to the preferred vegetation lineament and subtle tone variation caused by the ponding of fine-grained material against the hanging-wall (to the east). They were thought to be related to low-angle propagating thrusts resulting in fold limb scarps (Costa, 2009a) rather than in rectilinear scarps. The fault-related stratigraphy investigated through trenches confirmed the low-angle thrusting of recent

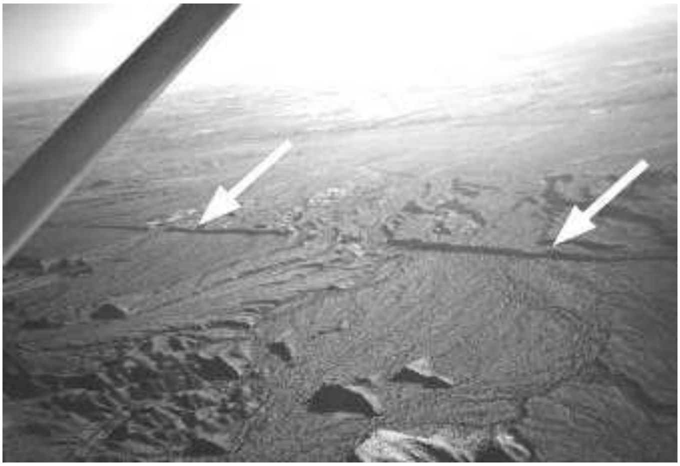

Figure 2.6 Northeast-looking bird's-eye view of the clearly visible rectilinear trace of the La Rinconada fault, standing out from the piedmont alluvial plane of the Eastern Precordillera, south of San Juan city in western Argentina. The scarp is cored in Neogene sedimentary rock (with light colors in the photo).

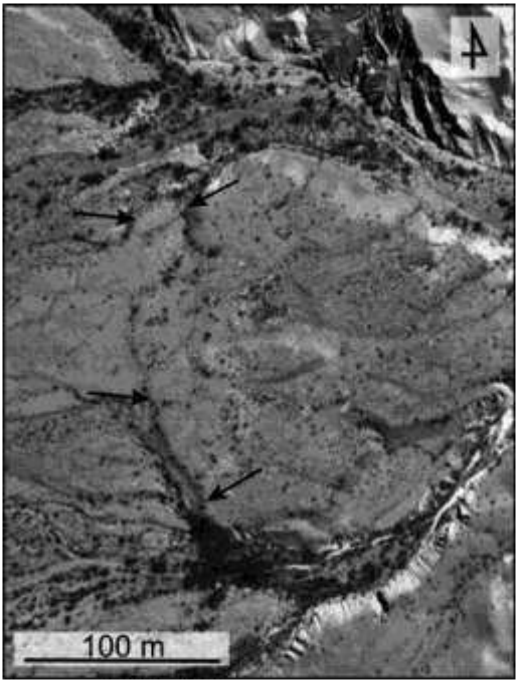

Figure 2.7 Gentle scarps in young alluvium (Holocene) (pointed out by black arrows). The fault propagation into unconsolidated and nonstratified deposits results in a lobate contour rather than a rectilinear trace. Image downloaded from Google Earth.

(Holocene?) fine-grained alluvium ponded due to recent fault movements. The upper propagating trace is flat-lying, giving rise to a monocline in the youngest uplifted alluvium rather than a clear surface faulting.

4.3. Geomorphic Signature of Quaternary Active Strike-slip Faults: The Boconó Fault, Venezuela

The Boconó fault system is a first-order structure that runs along the Mérida Andes in Venezuela, from the Caribbean coast down to the Venezuela–Colombia border. It concentrates the highest slip rates (up to 10 mm/yr) in northern South America and is probably the most studied and best known feature in terms of its neotectonic significance. Historical and instrumental seismicity also characterizes this region, and several significant earthquakes between the seventeenth and nineteenth centuries have been linked to this seismic source.

The Boconó fault has a sinuous trace that traverses the Mérida Andes for more than 400 km, flanked on both sides by low-angle thrusts (Audemard, 1999; Audemard et al., 2000; Audemard and Audemard, 2002). The fault usually runs in an axial position along this mountain chain at different altitudinal levels and morphoclimatic settings. One of the best exposed fault-related landforms as evidence of Quaternary activity is located near the village of Apartaderos (about 40 km northeast of the town of Mérida). This sector corresponds to a major drainage divide above 3000 m.a.s.l, where distal moraines formed during the Last Glacial Maximum (18 Kyr) have been laterally offset in plan view (Schubert, 1980b; Soulas, 1985; Audemard et al., 1999, Carrillo et al., 2006).

Figures 2.8 and 2.9 show the Los Zerpa offset moraine, which constitutes not only excellent kinematic evidence for the right-lateral regime of the Boconó fault,

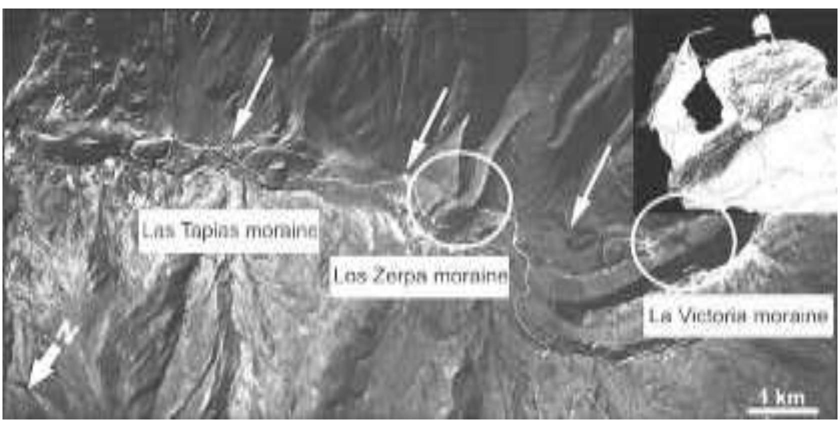

Figure 2.8 Aerial photo of LGM moraines affected by the Bocono fault at the Merida Andes, accounting for Quaternary postglacial slip. The right-lateral sense of movement is indicated by the offset moraine crestlines within the white circles (Los Zerpa and La Victoria moraines). See detail in Figure 2.9. Aerial photo of mission 010455. Courtesy of Cartografía Nacional (currently IGVSB).

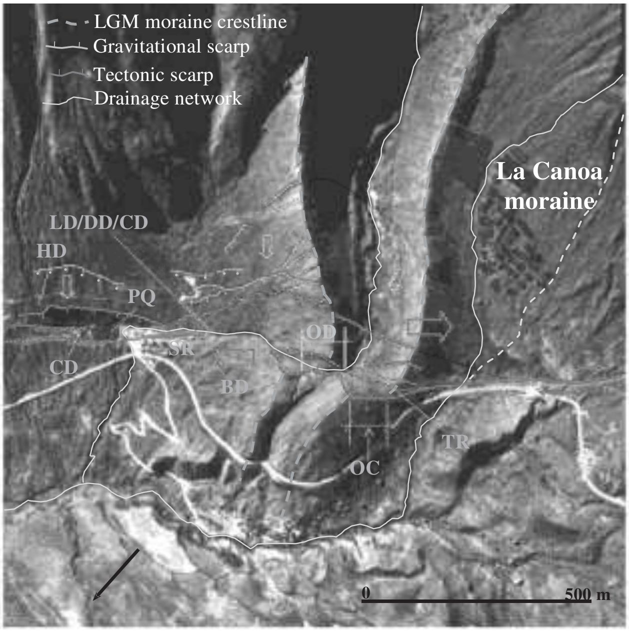

Figure 2.9 Aerial photograph of the Los Zerpa moraine with the main trace of the Bocono fault outlined by fault-related landforms (translated from Audemard, 2009). Moraine crestlines are shown in yellow, while fault traces are highlighted in red. An active, only 10-m deep, small pull-apart basin forms at the back of the frontal moraine, at a lazy releasing bend of the Bocono fault main active trace, which induces the gravitational collapse of the right-lateral moraine. OC and OD allow an estimation of the brittle dextral offset of the frontal moraine with respect to the lateral moraines. Also notice that the original late glacial drainage outlet is abandoned across the frontal moraine. The current drainage is deflected and captured to the east, giving the impression of a larger amount of dextral slip. Blow-up of aerial photo of mission 010455 (Courtesy of Cartografía Nacional; currently IGVSB).

but also a good constraint for the slip rate (in the order of 5 to 10 mm/yr) of this fault during the last 15 kyr (Schubert, 1980a; Soulas, 1985; Audemard, et al., 1999; Audemard and Audemard, 2002). The active fault trace is underlined here by a deformation zone, composed of north- and south-facing scarps bounding a depressed zone across the distal moraine deposits. Other morphologies related to prevailing strike-slip movements are also present, such as shutteridges, fault trench and related pounded alluvium, as well as secondary gravitational-induced scarplets (Audemard, 2009; Fig. 2.9).

The right-lateral displacement of the fault during the last 15 kyr resulted in the development of several diagnostic tectonic landforms highlighted in Figure 2.9. The tectonic offset of the frontal moraine has forced stream deflection and capture, with periods of alluvial ponding and upstream lake formation. The sedimentary record of lacustrine and fluvial deposits has been used to reconstruct the postglacial fault seismic history (Carrillo et al., 2006). It has also shed light on how the sliding of the right lateral moraine has been interplaying with tectonic fault slip, as recorded by the moraine-dammed paleolake at Los Zerpa (Carrillo et al., 2006).

A minimum post–15 kyr lateral offset of about 100 m can be measured at Los Zerpa moraine complex from at least two different criteria (OC and OD in Fig. 2.9). This value can be even larger if ductile deformation of the lateral moraine crestlines is taken into account; reaching values on the order of 10 mm/yr (Audemard et al., 1999). Similarly, a vertical throw of about 10 m can be estimated at the pull-apart basin affecting the frontal moraine (Audemard, 2009). This attests to the clearly dominant recent strike-slip component of motion of this fault, even inside transtensional jogs or bends (equal to ten times the vertical component).

4.4. Geomorphic Signature of Quaternary Active Folds: Montecito Anticline, Argentina

The Montecito anticline is located at the eastern foothills of the Southern Precordillera, Argentina, 50 km to the north of Mendoza city (1.5 million inhabitants), where the active Andean thrust front is underlined by current seismicity and historic destructive earthquakes. The arid climate and the scarce vegetation turn this Andean frontal section into a suitable area for landform preservation and outcrop exposure. The fold is located within a linkage zone between two oblique antithetic thrust systems, being interpreted as the surface expression of a west-verging fault-propagation thrust (Vergés et al., 2007).

The positive relief of the fold limbs reveals the doubly plunging fold trace, which clearly emerges from the surrounding alluvial plain (Fig. 2.10). The western fold limb stratigraphy exhibits a dynamic interaction between the fold growth and the Quaternary alluvial fan sedimentation recorded as onlap geometries (Costa et al., 2000b, Costa, 2009b). The anticline is cored with Late Tertiary continental beds (the light-colored unit in Fig. 2.10), whereas conglomerates and gravels of Late Pliocene and Quaternary age are exposed at their limbs.

The drainage network also suggests the Quaternary uplift of this structure. Some streams have been deflected, as indicated by parallel arc patterns at both fold periclinal closures. Other stream courses merged at the western outer limb and carved epigenic valleys across the structure where pseudo-meandric patterns dominate westward from the fold axis. The adjustment of the longitudinal profile of streams that run across the structure determined the development of alluvial fans, with their apex at the outer eastern flank of the anticline. Young terrace surfaces assigned to the Holocene are tilted against slope up to 12 W, accounting for the recent, and probable ongoing, activity of this structure. The geomorphologic analysis complements the stratigraphic evidence for Quaternary uplift of this fault-related fold and suggests that piedmont slope changes due to fold growth took place in a coeval relation with the surrounding alluvial plain development during the Quaternary. Although instrumental seismicity does not image this source for potential earthquakes at depth, we suspect that fold growth was accompanied by shallow prehistoric earthquakes.

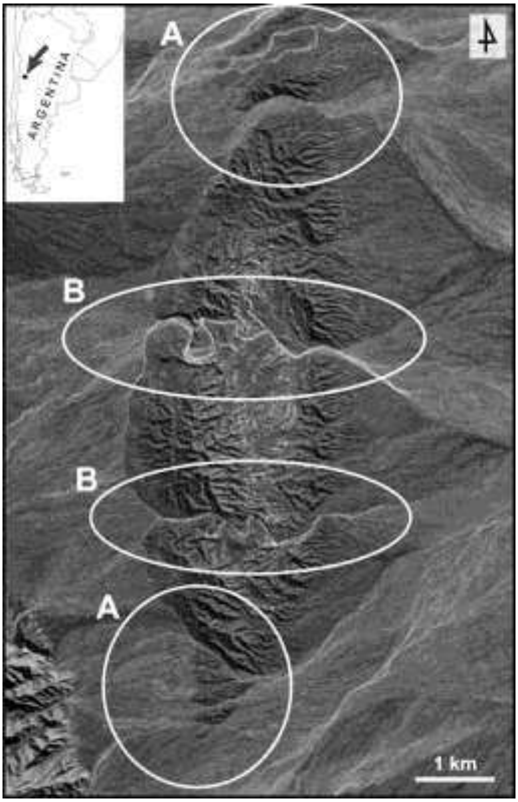

Figure 2.10 Aerial image downloaded from Google Earth of the Montecito anticline, in the Mendoza Precordillera piedmont (western Argentina). Note the parallel arc of the drainage at both periclinal closures and the water gaps related to the main two courses running across the structure.

5. Concluding Remarks

Because of their tectonic setting, many areas in Latin America and the Caribbean have been or could be seriously damaged by earthquakes. Considering the severe social and economic effects that these natural catastrophes can produce, identification and characterization of potential seismic sources with and without previous seismic records are mandatory for land-use planning and decision-making purposes.

Based on the concept that active geological structures during the Quaternary could be the source and epicenter of future seismic activity, many efforts during the last decades have focused on the identification and study of these features. Terrain analysis through aerial images has proved to be a necessary approach for recognizing potentially hazardous structures. This is particularly useful in areas lacking a suitable background of geologic/seismologic knowledge, as well as for structures without records of present seismicity.

Geomorphologic analysis of the active or passive control that tectonic features produce on landscape evolution is crucial for determining whether or not Quaternary movements have been experienced. This in turn leads to select targets prone to detailed paleoseismic studies whose main goal is to recognize evidence of prehistoric hazardous seismic crisis with associated surface deformation.

The examples selected in this chapter are case histories of structures resulting from different tectonic regimes under diverse morphoclimatic conditions. Their morphologic imprints allow the recognition of activity during the Quaternary, envisaged as a consequence of past earthquakes. These basic considerations help optimize the selection of suspected zones for field studies, which is crucial with regard to making the best use of time and resources when exploring large regions with basic data.

Almost 600 structures with proved or suspected activity during the Quaternary have already been recognized as a result of a recent international effort (Multi Andean Project-Geosciences for Andean Communities –http://can.geosemantica.net-). For most cases, their recognition was based on the geomorphic signature of these structures.