INTRODUCTION

During the last two decades the significance of recent deformation for seismic-hazard analysis and other applications has often been highlighted as a relevant contribution by geological sciences to these critical issues. Seismicity has traditionally been used to characterize some potentially hazardous environments, but more recently it has become clear that the assessment of future seismic activity must be based on a more comprehensive understanding of the tectonic processes. Recent deformation, particularly during the Quaternary, is an important factor in this context. The study of Quaternary deformation provides insights into the dynamics of the Earth's crust and can help to improve our understanding of seismic hazards. Recent deformation is particularly significant for seismic-hazard analysis because it reflects the current state of stress and strain in the crust, and it is an important factor in the development of seismic structures. In this paper, we present an overview of the main Quaternary deformation of South America, focusing on the key tectonic features and the role of recent deformation in seismic-hazard analysis.
dous faults, especially along active plate margin settings. However, faulting events related to recent earthquakes have shown that much of the deformation away from active plate margins occurs along faults with no significant level of modern seismicity and that only a fraction of Quaternary faults are characterized by ongoing seismicity. Most of the seismic hazard in continental South America (inboard from the subduction zone) is related to shallow intraplate crustal seismicity. Thus, developing information on Quaternary faulting should help extend the short time span provided by records of historical and instrumental seismicity into prehistoric time (i.e., the late Quaternary). This longer time span would allow making better assessments of seismic potential and identifying the likely spatial and temporal distribution of future damaging earthquakes.

The state of knowledge of Quaternary deformation in South America is neither homogeneous nor complete. In most cases the information is of a reconnaissance nature, largely based in remote-sensing interpretation and general fieldwork. Many faults have slip rates that are lower than sedimentation and/or erosion rates. Considering that neotectonic analysis is commonly based on geomorphic features that may be related to recent deformation, this kind of approach may identify more inactive features than active ones. Therefore, distinguishing between active control and passive control of structures in the landscape is crucial for successfully identifying a feature with Quaternary activity.

The other issue which hampers a reliable and accurate neotectonic analysis is the limited knowledge of Quaternary chronologies. Regional temporal analyses rely on the recognition of morphostratigraphic units, which are commonly vaguely referred to as Quaternary, such as piedmont deposits or landforms, alluvial deposits, basin fill sediment, etc.

The term “neotectonics” has a floating time frame, even in the specific literature (Mercier 1976, Fairbridge 1981, Vita Finzi 1987, Hancock 1988, Pavlides 1989, Mörner, 1994), as well for different interpretations in South America. For some it is synonymous to “Quaternary Tectonics”, whereas for others it refers to tectonic processes that have occurred since Miocene-Pliocene times (perhaps as much as 25 Myr). In order to provide a more specific time frame to “neotectonics” and despite the problems outlined above, this article will focus on the Quaternary tectonics of South America. This time interval is more suitably considered to include 1) features resulting from the active (modern) stress field; 2) structures related to recent/ongoing topographic changes or mountain building and 3) structures that have produced earthquakes in the past and have the capability of producing earthquakes in the future, thus posing a threat in terms of seismic hazard.

Except for a few cases, there is little reliable information on slip rates, kinematics and paleoseismic record for South American faults. However, three main categories of slip rates can be established from the tectonic setting and some recent results derived from GPS data (Freymueller et al. 1993, Kellogg and Vega 1995, Norabuena et al. 1998, Bevis et al. 2001, Kendrick et al. 1999, 2001, Weber et al. 2001, Pérez et al. 2001, Brooks et al. 2003):

Slip rates higher than 5 mm.yr⁻¹: These occur on faults related to onshore plate-interaction, such as the Bocón fault system in Venezuela and probably the Magallanes-Fagnano fault zone in Chile-Argentina, or on subduction zone megathrusts such as the type commonly located off the western coast of South America.

Slip rates between 1-5 mm.yr⁻¹: These occur on faults related to stress-partitioning or to major tectonic-terrane boundaries (i.e., Cordillera Blanca -Peru-, Atacama -Chile-, El Tigre-Argentina-, Ibagué -Colombia-, Oca-Áncón -Venezuela).

Slip rates lower than 1 mm.yr⁻¹: These occur on most intraplate faults within the interior of South America.

There is no general agreement about when a fault should be considered “active” and most definitions put forth are based on the tectonic setting, type of study and type of data available, and/or the author’s perception of the problem. Moreover, geologic scenarios of Quaternary deformation vary from very active plate boundaries to virtually stable cratonic areas, where instrumental seismicity generally has little correspondence with morphostructural features. In areas where structures portray long recurrence intervals and very slow slip rates, faults with the shortest elapsed time since the last rupture (those considered most “active”), might not be the most hazardous in terms of seismogenic capability (Machette 2000, Costa 2004). Thus, the well-engrained term “active fault” is not considered suitable and could even be misleading in terms of objective and homogeneous mapping legends and accurate outreach.

Accordingly, characterizing deformation based on the time since the last-recorded fault slip (i.e., faults with late Quaternary, Holocene or Historic displacement) is considered more suitable than characterization as active, capable, potentially active, inactive fault, and so on. This time-based categorization allows some flexibility in reporting among different tectonic settings or countries owing to the differing complexities or levels of investigation and abilities to date prehistoric faulting events.

HISTORICAL SCOPE

The development of systematic and regional neotectonic studies in South America is quite recent. Except for specific reports spurred by earthquakes having surface deformation and other reconnaissance studies for critical facilities, there are few references to mapping Quaternary deformation on a regional basis (see for example, Saint Amand and Allen 1960, Arabasz 1968, Okada 1971, Souls 1978, Iriondo and Suguio 1981, Lavenu 1981, Sébrier et al. 1982, Lavenu 1986). Venezuela has been the leading country in developing regional neotectonic maps starting in the early 1980s (Schubert 1979, 1980a, 1980b, 1982, 1984, Souls 1986). At the same time, international projects such as IGCP 202 and IGCP 206 promoted studies of many Quaternary faults of South America. Also in the mid-1980s the Preliminary Neotectonic Map of South America was compiled under the framework of the SISRA Project (González-Ferrán 1985), being the first contribution of this type. This map depicted Quaternary faults, although with a strong bias toward seismology.
The launching of the International Lithosphere Program II-2 (World Map of Major Active faults) during the 1990s (Trifonov and Machette 1993), provided a more ambitious effort to develop digital country or regional maps and inventories of Quaternary faults for the Andean countries and Brazil (Audemard et al. 2000, Costa et al. 2000, Lavenu et al. 2000, Paris et al. 2000, Saadi et al. 2002, Egíuez et al. 2003, Macharé et al. 2003). When this project was completed, Costa et al. (2003) undertook further development of a dynamic, computer database. The ILP II-2 Project meetings allowed many researchers with different backgrounds to meet and discuss common approaches for studying active deformation along a wide variety of tectonic settings, with the aim of achieving homogeneous mapping. A considerable part of the compilation presented in this article is based on information resulting from that decade-long effort.

GENERAL TECTONIC SETTING

As a response to complex, contemporary geodynamical processes, the distribution of neotectonic strain is not homogeneous in continental South America and accordingly Quaternary deformation is concentrated along the more than 8,000 km of the Andean orogen (Fig. 1). The patterns and discontinuities of the Andes orogen, which are inherited from a long and complex evolution and terrane history as well as the present plate tectonic setting, cause a wide variety of neotectonic deformation in terms of both styles and geographical occurrences.

At a continental scale, South American neotectonics is characterized by a dominance of E-W trending strike-slip faulting at the northernmost and southernmost ends owing to plate interactions. On the other hand, Quaternary deformation is fueled by different and variable sources such as strain release related to subduction in a large part of its western border and crustal weaknesses in intraplate and stable continental regions.

The main areas of recent faulting and folding have been ascribed to the Andean region including adjacent foreland regions and intraplate extra-Andean South America. The Andes have traditionally been divided into three main sectors, namely the Northern Andes, the Central Andes and the Southern Andes (Auboin et al. 1973, Gansser 1973, Zeil 1979, Ramos 1999 and many others) (Fig. 1).

Quaternary fault systems juxtaposing the bounding area between the Northern Andes and continental South America from the Caribbean coast to the Gulf of Guayaquil (Fig. 2) show slip rates higher than mm.yr⁻¹ and a clear association with historical seismicity.

Along the Central Andes, the main constraint for grouping and describing Quaternary deformation is the subducting geometry of the Nazca plate. The western slope and coastal areas are direct manifestation of interplate processes and seismicity at the Benioff zone. Related megathrusts are offshore, whereas onshore evidence of Quaternary tectonics are mostly related to coastal tectonics and a few large structures that are being driven by strain partitioning.

At most retroarc areas and at the eastern slope of the Andes, major Quaternary structures are related to crustal weaknesses rather than to interplate processes and crustal seismicity does not necessarily image Quaternary deformation.

Subduction zone segments with a normal subduction angles show noticeable differences in Quaternary occurrence and tectonic style than adjacent flat-subduction segments. Quaternary deformation is more

![Figure 1: Main neotectonic settings and geotectonic features of continental South America and surrounding areas. 1. Northern Andes; 2. Central Andes; 2A. Peruvian flat-slab; 2B. Normal subduction segment; 2C. Pampean flat-slab.](image-url)
constrained to the Andean orogen in the former and more efficiently transmitted to the foreland region in the latter (see for example, Jordan et al. 1983a, 1983b, Gutscher et al. 2000).

In contrast, little is known about the Quaternary tectonics of the Southern Andes. The main tectonic settings are here related to oceanic-ridge subduction and a transform interaction between the South America and Scotia plates.

In extra-Andean South America, structures with Quaternary activity are generally located on pre-existing shear zones or weaknesses. They typically have very long recurrence intervals, although recent studies have highlighted their capability of producing surface ruptures as well as liquefaction (Bezerra et al. 1998, Riccomini and Assumpção 1999, Bezerra and Vita Finzi 2000).

**QUATERNARY DEFORMATION ALONG THE ANDES AND ADJACENT AREAS**

**QUATERNARY DEFORMATION AT THE NORTHERN ANDES**

The geology and tectonics of the Northern Andes is dominated by a complex interaction between the South American, Caribbean, and Nazca plates. Quaternary deformation is largely concentrated along mountain chains with the dominating structures being reverse and strike-slip faults (Pérez and Aggarwal 1981, Schubert 1982, 1984, Lavenu et al. 1995, Singer and Audemard 1997, Audemard et al. 2000, Taboada et al. 2000, Audemard and Audemard, 2002, Audemard et al., this volume, Lavenu, this volume)

The NE and E-trending megafaults such as the Boconó-San Sebastián-El Pilar fault system in Venezuela (Schubert 1979, 1980a and 1980b), the Eastern Cordillera frontal fault zone in Colombia (Pennington, 1981) and the Dolores-Guayaquil megashear (Campbell, 1974) (Fig 2) are considered to comprise the long boundary that detaches the Northern Andean Block from the remainder of South America. In fact, the Northern Andean Block is bounded by an active right-lateral fault system and dextral motion along these regional faults translated into compressional motion where the faults have a N-S trend; they all accommodate E-W compressional stresses produced by the rapid convergence of the South American and Nazca plates (Fig. 2). Eastward motion of the Caribbean plate relative to South America drives Quaternary tectonics along northern Venezuela (from Colombia to Trinidad) and determines the dominant strike-slip complex regime of the Oca-Ancón fault system. However, a significant part of this dextral slip seems to be currently distributed along the 1200 km-long fault system comprised of the Boconó, San Sebastián, El Pilar, Los Bajos, and El Soldado faults and their southern connections through the Gulf of Guayaquil (Pérez and Aggarwal 1981, Schubert 1980a,b, 1982, Stephan 1982, Aggarwal 1983, Schubert 1984, Soulas 1986, Beltrán and Giraldo 1989, Singer and Audemard 1997, Audemard et al. 2000, Audemard and Audemard 2002, Audemard et al. 2005, Audemard et al., this volume) (Fig. 2). This major strike-slip fault system concentrates the highest slip rates (around 10 mm/yr) along northern South America, as such; many authors have proposed that this fault system constitutes the current plate boundary between the South America and Caribbean plates. This would imply that
most part of the Northern Andes is structurally detached from the South American plate (Hess and Maxwell 1953, Schubert 1979, Aggarwal 1983, Souls 1986 and many others). However, this major issue is still a matter of debate (Audemard et al., this volume).

In particular, the right-lateral Bocón fault has a sinuous trace that traverses the Mérida Andes in Venezuela (Fig. 2), and is flanked on both sides by a series of low-angle thrusts (Audemard 1999). This configuration attests to active strain or stress partitioning in this chain (Audemard and Audemard 2002). Some second-order faults that are diverging or oblique to this major southern Caribbean fault system are interpreted as synthetic Riedel shears, such as the Tacagua-El Avila, Tácata and La Victoria (Audemard et al. 2000, 2005, this volume).


There is a general agreement that the Caribbean plate movement (Jordan 1975, Sykes et al. 1978, Duncan and Hargraves 1984) and the southeastward accretion of the Panama-Chocó block (Duque-Caro 1980) are the main driving processes of the contemporary tectonics in Colombia (Kellogg and Vega 1995, Paris et al. 2000, Audemard and Audemard 2002). In this sense, Taboada et al. (2000) have proposed that a continental wedge with eastward indentation bounded by the Santa Marta-Bucaramanga fault to the NE and by the Itsmina-Ibague faults to the south cause ongoing thrusting at the Eastern Cordillera front as well as transpressive deformation at the Santander Massif in Colombia. Within this framework, the Santa Marta-Bucaramanga fault displays Quaternary morphotectonic features (Paris and Sarria 1986) related to sinistral movement (Fig. 2).

The continued eastward subduction of the Nazca plate beneath Colombia induces most of the deep seismicity along the Wadati-Benioff zone (Case et al. 1971, Lonsdale and Klitford 1978, Pennington 1981, Gutscher et al. 2000, Taboada et al. 2000). Therefore, southeastward and flat-slab subducting geometry of the Caribbean plate (Kellogg et al. 1983) beneath the northern margin of Colombia defines the so-called Bucaramanga flat-slab with low associated seismicity (Ramos 1999). Southward of 3°N, the main Quaternary deformation and related landforms in the Eastern Cordillera frontal fault system are translated into a dominant strike-slip regime through the Algeciras fault system (Velandia et al. 2005), which extends across the Gulf of Guayaquil.

The interaction of the Nazca, Caribbean and South American plates causes striking regional differences in the patterns and style of Quaternary faulting. For example, the principal compressive-stresses in Colombia are NW oriented in the northern Andean region and oriented E to NE in the southern Andean region. By acting on faults that trend N-S (i.e., major faults), these stresses induce left-lateral movement on the faults located to the north and right-lateral movement on faults located to the south in both the Western and Eastern Andean regions. In addition, reverse and normal displacement takes place as a result of oblique compression (Paris and Romero 1994, Paris et al. 2000).

The Romeral fault system (McCourt et al. 1983, Hutchings et al. 1981) extends along the western slope of the Central Cordillera in Colombia (Fig. 2). It separates accreted oceanic rocks to the west from a domain of continental rocks with associated crustal seismicity to the east. Audemard et al. (2005) have proposed that the change of slip along strike of this major N-S-trending fault partly results from strain partitioning along a curved subduction front.

North of the Gulf of Guayaquil, the Ecuadorian Andes comprise five main morphotectural regions from west to east: 1) the Coastal Plain, 2) Western Cordillera, 3) Interandean Valley (also called the Inter-Andean Tectonic Depression), 4) Real Cordillera and, 5) Andean foothills or sub-Andean region of the upper Amazon basin. The first order onshore Quaternary tectonic features in the Northern Andes of Ecuador are related to the geometry of the subduction zone and kinematics involved in plate interactions. Both the morphostructural and Quaternary faults appear to be controlled by conspicuous NNE-SSW trending Quaternary fault systems that are acting partially along ancient regional suture zones. This part of the Andes represents a region where the subducting Nazca Plate dips at 35°E. Nevertheless, detailed E-W cross-sectional profiles of seismicity show a more complex behavior of the slab (Gutscher et al. 1999).

The tectonic regime of the coastal region shows deep imprints of the subduction of the Carnegie Ridge and the oblique convergence of the Nazca Plate (Gutscher et al. 1999). Thus, normal and reverse faults bound small blocks to the east of the Carnegie Ridge, whereas a transpressional fault system (Naranjal and Ponce Enríquez faults) (Fig. 2) borders the northern coastal ranges and the uplifted Western Cordillera, defining an active fore-arc basin (Egüez et al. 2003).

The eastern structural limit of the Western Cordillera oceanic terrain in Ecuador extends along the western border of the Inter-Andean Valley via the San Isidro, El Ángel and Otavalo faults (Egüez et al. 2003). Souls et al. (1991) have interpreted this fault system as the southern extension of the Romeral fault system. Field observations suggest that the main Quaternary fault systems are oblique to the Ecuadorian Andes, starting at the Gulf of Guayaquil (Pallatanga fault) and cutting northeastward across the ranges toward the eastern border of the Real Cordillera (Chingual fault) in northern Ecuador (Souls et al. 1991, Ego et al. 1995, Ego and Sévrier 1996, Ego et al. 1996). These two main NE-trending faults show significant strike-slip morphology and right-lateral kinematic indicators, and correspond to the southern extension of the Eastern Cordillera frontal fault system in Colombia. They are probably responsible for the main crustal earthquakes recorded historically in Ecuador (Fig. 2).

Between the Pallatanga and Chingual faults,
the slip motion is accommodated by minor NE-SW-trending oblique faults and by N-S fault zones along the Inter-Andean Valley, where folds, flexures, and related reverse faults (including the Quito fault and associated Nagsiche, Latacunga and Yanayacu anticlines) have been mapped (Lavenu et al. 1995, Egüez et al. 2003, Lavenu, this volume).

The sub-Andean zone (Napo and Cutucu foothills) lies at the eastern margin of the Andean Range and western border of the upper-Amazon basin. This zone includes folded Mesozoic sedimentary rock bounded by thrust systems with significant Neogene and Quaternary displacement, such as the Payamino, Sumaco, Pusuno and Aranjuno faults (Iglesias et al. 1991, Egüez et al. 2003).

QUATERNARY DEFORMATION AT THE CENTRAL ANDES (4°S-46°30'S)

The Central Andes are considered to be a typical Andean-type orogen, where mountain building has been driven primarily by subduction processes through the collision of the Nazca and the South American plates (Ramos 1999). The Central Andes represent more than 4000 km of the Andean chain, encompassing a wide variety of Quaternary tectonic styles and settings. They are commonly divided into the Northern, Central, and Southern sectors (Ramos 1999).

In a diverse array of tectonic styles and settings, the main controllers of the distribution and style of Quaternary deformation appear to be the current subduction regime and the inherited geological history. The characteristics and occurrence of Quaternary deformation follow in a broad sense this general division, having a strong correlation between the distribution and characteristics of the deformation and the geometry of the subducting Nazca plate. Although the western piedmont of the Andes and coastal regions are closest to the epicenters of large subduction-related earthquakes, there are just few examples of Quaternary faulting onshore, with their occurrence much better developed and documented at the morphostructural units located eastward.

The description of Quaternary tectonic features in the Central Andes are grouped and described as follows:

**Peruvian flat-slab (4°S - 14°S)**
**Normal subduction segment (14°S - 27°S)**
**Pampean flat-slab (27°S-33°S)**
**Central Andes south of 33°S**

THE PERUVIAN FLAT-SLAB (4°S - 14°S)

This sector exhibits a temporal migration of deformation toward the foreland (to the east) as a result of flat-slab subduction geometry during the past 5 Ma (Sébrier and Soler 1991, Sébrier et al. 1988, Gutscher et al. 2000). Uplifted marine terraces are among the few deformed features that have been described onshore, which highlight the vertical component of subduction related processes and crustal elastic response along the Peruvian flat-slab sector (Macharé and Ortlieb 1992).

The resulting overthickening of the crust gave rise to the Cordillera Blanca uplift, which has some of the highest elevations in the Andes and where Quaternary normal faults are associated with recent surface faulting (Bonnot 1984, Bonnot et al. 1988, Schwartz 1988, Macharé et al. 2003) (Fig. 3).

Also, it is important to note that shallow seismicity characterizes the Eastern Cordillera and the sub-Andean zone (Suárez et al. 1983, Dorbath et al. 1991) where active deformation is dominated by fault-related folds such as the Shitari fault system and
other unnamed structures (Macharé et al. 2003).
The most significant Quaternary deformation reported so far in Peru is located along this flat-slab sector where historic surface ruptures have occurred along the Chaquilamba and Quiches faults (Silgado 1951, Doser 1987, Bellier et al. 1989, 1991, Macharé et al. 2003), whereas seismicity is ongoing along the Huaytapallana fault zone (Macharé et al. 2003). There is outstanding morphogenetic expression of the Cordillera Blanca fault (Bonnot 1984, Schwartz et al. 1984, Bonnot et al. 1988, Schwartz 1988) as well as good geomorphic expression of both normal and reverse faults in southern Peru along the Cuzco and other fault systems (Sébrier et al. 1985, Macharé et al. 2003) (Fig. 3).
One of the most distinctive tectonic expressions of flat-lying subduction at the Pampean segment of the Central Andes, is the development of broken foreland uplifts between 27°S and 33°S (the Sierras Pampeanas in Argentina) (Jordan et al. 1983a,b). However, no similar features with associated Quaternary activity have been described so far in the Peruvian flat-slab.

THE NORMAL SUBDUCTION SEGMENT OF THE CENTRAL ANDES (14°S - 27°S)

This segment is underlain by normal subduction with a sharp change in subduction angle at its northern end and a smooth transition to a flat-slab sector to the south (Barazangi and Isacks 1976, Chinn and Isacks 1983). The Central Andes at these latitudes, particularly between 14°S and 20°S are the widest part of the Andean chain (as much as 600 km). From west to east, the main morphostructural Andean units in Peru, Bolivia, Chile and Argentina are composed of the Pacific Coast (which includes the offshore Perú-Chile trench, the Coastal Cordillera and the Central Valley), the Western Cordillera, the Altiplano-Puna plateau, the Eastern Cordillera and the sub-Andean zone.

Quaternary deformation is represented by high-angle normal faults in internally drained plateaus such as the Puna and Altiplano, high-angle reverse faults along the thick-skinned basement-cored uplifts of the Cordillera Oriental, and low angle thrusts and fault-related folds at the sub-Andean thin-skinned fold-and-thrust belt.

Geomorphic evidence of recent tectonic activity with different geometries and kinematics have been reported between the Coastal Cordillera and the western piedmont of the Western Cordillera, north and south of the Arica elbow in Perú and Chile (Muñoz and Charrier 1996, Jacay et al. 2002, González et al. 2003, Audin et al. 2003, this volume, Allmendinger et al. 2005).
The NNW-trending Incapuquio fault system (Jacay et al. 2002, Audin et al., this volume) located at the western piedmont of the Western Cordillera has reactivated old tectonic structures and is associated with thrust-related folds, strike-slip faults and normal faults that extend about 200 km over the Western Cordillera piedmont (Fig. 3). The coastal ranges in Peru exhibit normal faults trending perpendicular to the coast, whereas in northern Chile reverse or normal faults trend obliquely to the coast (González et al. 2003, Allmendinger et al. 2005).

In the northern part of the Chilean Andean fore arc, the Pampa de Tamarugal represents a young tectonic depression (also known as the Northern Central Depression or Longitudinal Valley) which morphologically separates the Coastal Range from the Precordillera. Extensional tectonics does not seem to have played a role in the formation of the Central Depression (Reutter et al. 1988) in contrast to coastal marine terraces that are affected by E-W extensional deformation.

Andean subduction in Chile is characterized by a general oblique convergence vector with respect to the plate boundary. The different ways this oblique convergence is accommodated and their links with resulting Quaternary features is still not well understood (Lavenu et al. 2002). Onshore uplift is demonstrated by elevated Quaternary marine terraces suggesting Quaternary uplift rates from 0.2 to 0.6 mm.yr⁻¹ (Ortlieb et al. 1996, Marquardt et al. 2004, 2005, Lavenu this volume). In those coastal areas (23°S-27°S) about 100 km to the east of the trench, the stress regime during the late Pleistocene is reflected by E-W extension on the nearly 800-km-long Atacama fault (Fig. 3). This fault probably represents the most significant geomorphic imprint of Quaternary deformation at the fore arc. Its varying kinematic signatures have inspired different interpretations including right-lateral (Saint Amand and Allen 1960, Arabasz 1968, Okada 1973, Dewey and Lamb 1992), left-lateral (Armijo and Thiele 1990), and normal faulting (Delouis et al. 1998, Lavenu et al. 2000, Lavenu this volume).

Quaternary deformation and related state of stress of the Transversal Cordillera (between 18°S and 22°S) is still poorly documented. The uplift of the Altiplano-Puna plateau has been thermally induced (Froidevaux and Isacks 1984). It has a mean elevation of 3800 m, but lies below the Western and Eastern Cordillera. The Central Altiplano, which was the more subsiding region in the Cenozoic, is characterized by important continental sedimentation. Faults and folds resulting from Neogene compressive Andean tectonics affect this entire region (Lavenu and Mercier 1991, Mercier et al. 1992). In addition, during the Quaternary, the Altiplano has been affected by N-S extensional tectonics that can be related to the effect of high topography (Sébrier et al. 1985). A side effect of this process has been basinal collapse and associated landsliding along these and other piedmont faults (Lavenu et al. 2000). This deformation is responsible for important normal faults with a cumulative displacement of more than 400 m near the city of La Paz (Lavenu et al. 2000).

The Eastern Altiplano, which forms the western piedmont of the Eastern Cordillera, is bounded on the east by a major fault zone (Escoma, Achacachi, Peñas and Kenko fault zones in Fig. 3) that forms the escarpment of this Cordillera (Lavenu 1981, Lavenu and Mercier 1991, Lavenu et al. 2000). The tectonic basin occupied by Lake Titicaca is controlled by these normal faults and is one of the consequences of N-S Quaternary extension (Lavenu 1992).

Quaternary deformation affecting Quaternary bajadas and other alluvial surfaces and resulting from different stress regimes has been reported from the Altiplano south to...

The Eastern Cordillera has been an area of uplift during the entire Cenozoic (Sebrier et al. 1988, Mon 1993). Neogene deformation of the Cochabamba and Tarija basins and other places in Bolivia has been reported (Lavenu et al. 2000). In Argentina, basement-related deformation gave rise to faults and folds in Neogene strata and sometimes Quaternary sediment, but without strong geomorphic evidence of Quaternary activity (Mon 1976).

The sub-Andean lowlands fold-and-thrust belt constitutes an Andean orogenic front that has been dominated by contraction since the Neogene (Baby et al. 1989, 1992, Dumont 1996). Pleistocene deposits are thrust along the Mandeyapecuá fault (Moretti et al. 1996) (Fig. 3), and thus could confirm recent deformation along the orogenic front. In Argentina, it has been suspected that important Quaternary deformation and seismic potential must be related to thrust faults and growing anticlines (Stein and Yeats, 1989) along the sub-Andean region (here including the Sierras Subandinas and Santa Bárbara ranges). One of the most important historic Argentinean earthquakes (Talavera de Esteco, 1692) occurred in this region (Salta province); Castano and Zamarbide (1978) calculated a magnitude of 7.3 for this historic event. The forest cover has hampered recognition of all but the most prominent morphogenic Quaternary structures, although Ramos et al. (2003, this volume) reported significant evidence of this style of Quaternary deformation at the Lomas de Olmedo fault system (Fig. 3).

To the north, the Beni foreland basin is located northeast and east of the Bolivian Andean chain in front of the sub-Andean fold-and-thrust belt. As with other foreland basins, the Beni basin is a flexural basin that is presently subsiding. Dumont (1996) has suggested that the Beni River is currently being deflected northward by the north-trending Beni fault (Fig. 3).

THE PAMEAN FLAT-SLAB

Quaternary deformation above the Pampian (Chilean) flat-slab is better exposed at the eastern Andean slope. This latitudinal section concentrates more than 90 percent of the Quaternary deformation currently documented in Argentina (Costa et al. 2000a) which is particularly prominent at its southern half (30°S-33°S). Quaternary deformation includes historic surface rupturing on La Laja fault during the 1944 Mw 7.0 San Juan (Castellanos 1944, Groeber 1944, Harrington 1944) the 1977 Mw 7.4 Caucete earthquakes on the Ampacama-Niquizanga fault (Volponi et al., 1978, Bastías 1985) (Fig. 4), as well as the more significant historical and instrumental seismic events. The reported concentration of Quaternary structures on the flat-slab subduction segment matches the observation that seismic energy released in the upper plate is on average 3 to 5 times greater than in sectors with normal subduction angles (Jordan et al. 1983a,b, Smalley et al. 1993, Gutscher et al. 2000, Ramos et al. 2002).

As a result of the eastward migration of the Andean orogenic front during the Neogene, orogenic activity during Pliocene-Pleistocene is evidenced by the rise of the Precordillera fold-and-thrust belt (Ramos 1988). The active Andean front and main Quaternary structures are currently located between its eastern foothills and the westernmost Sierras Pampeanas (Fig. 4) (Bastías et al. 1984, 1990, 1993, Cortés et al. 1999, Costa et al. 2000a, 2000b). The Quaternary structures have overprinted previous structures in both the Precordillera and Sierras Pampeanas.

The Western and Central Precordillera north of 32°S behave as a thin-skinned thrust belt with east-verging (Andean-type) thrusts. The Eastern Precordillera exhibits basement-cored, west-verging (Pampean-type) thrusts, and has been defined as a thick-skinned triangle zone by Zapata and Allmendinger (1996). If one considers mainly tectonic heritage, the styles of Qua-
ternary deformation of the Precordillera along the Andean front and seismic belt can be divided in two sections-north and south of 32°S.

North of 32°S, evidence of Quaternary tectonics is concentrated mainly along the Pliocene-Pleistocene-uplifted Eastern Precordillera. This morphostructure exhibits a main west-bounding thrust fault (Villavicencio–Zonda–Pedernal thrust), although the most impressive Quaternary deformation is at the eastern backbone of this range. The deformation is represented by rectilinear and parallel fault traces that are coincident with bedding planes in pre-Quaternary rocks as backlimb tightening-type structural morphologies showing this style of deformation (Fig. 4).

The rectilinear trace and Holocene morphology of El Tigre strike-slip fault is clearly seen along at least 200 km of the western slope of the Precordillera fold-and-thrust belt (Bastías et al. 1984, 1987, 1990, Bastías 1985, Bastías and Bastías 1987, Bastías and Uliarte 1987, Siame et al. 1997a, 1997b, 1998, 2002, 2005) (Fig. 4). As a consequence of stress partitioning at this latitude, this fault is the main Quaternary structure that releases the longitudinal (N-S) component of continental plate motion. Although this is a striking and major fault, its slip rates are likely below 1 mm/yr\(^1\) (Siame et al. 1997).

South of 32°S at the southern Precordillera in Mendoza province, major Quaternary deformation is transferred to emerging or blind east-verging thrusts (Las Peñas and Las Higueras thrusts (Fig. 4), Cortés and Costa 1996, Cortés et al. 1999, Costa et al. 2000b, Costa et al. 2006), many of which evolved from inverted normal faults of a Triassic rift (Ramos and Kay 1991, Dellape and Hegedus, 1995). The thick-skinned triangular zone that characterizes the interaction between the Eastern and Central Precordillera (Zapata and Allmendinger 1996) seems to vanish south of Las Peñas River (32°30' S), instead blind thrusts and growing anticlines that have evolved from inverted Triassic basins are recognized both at surface and at depth to the southern end of the Precordillera (33°S) (Triep 1987, Brooks et al. 2000, Chiaramonte et al. 2000) and as far south as 34°S (Polanski 1963, Kozlowsky et al. 1993, García et al. 2005).

The striking change in style and concentration of Quaternary deformation marks the hinge area between the flat-lying and normal-subduction segments. Epicentres of historic earthquakes as well as northward deviation of the Mendoza River at 33°S (Ortiz and Salfity 1989) may suggest that ongoing deformation at this latitude has shifted eastwards to the foreland from the main outcropping thrusts and is now being expressed through a west-verging Pampas-type blind thrust in its initial stage of development and landscape imposition (Costa et al. 2006).

The Sierras Pampeanas of Argentina are generally regarded as the broken foreland adjacent to the Andean orogen and as a main morphotectonic expression of flat-slab subduction (Jordan et al. 1983a,b). This feature that suggests Quaternary stress partitioning still exists in the Western United States (Jordan and Allmendinger 1986). These basement blocks have been uplifted and tilted during the past 8.5 Myr (Ramos et al. 2002) and their morphostructural evolution has been linked with the development of the Pampas flat-slab and with the Andean building ever since, thus involving Quaternary deformation more than 600 km away from the trench. These blocks commonly are bounded by west-verging reverse faults that dip 30°-55°E. Such marginal faults are usually located along the western hillslopes and constitute the Neogene uplifted front of the ranges. Quaternary deformation has been reported along many of them (Massabie 1987, Costa 1999, Costa et al. 2000a, and many others).

It is commonly understood that these typical intraplate faults have long recurrence intervals. However, recent studies have suggested that prehistoric earthquakes have ruptured to the surface, probably with coseismic vertical slip larger than 1 m (Costa and Vita Finzi 1996, Costa et al. 2001).

Thus, the seismic capability of these faults seems to be much more relevant than suggested by the seismic catalog.

**THE CENTRAL ANDES SOUTH OF 33°S**


During the Quaternary, deformation has been partitioned into two states of stress south of 32°S (Lavenu and Cembrano 1999, Lavenu et al. 2000). In the fore-arc sliver (Costal Cordillera, Central Depression, and part of the Main Cordillera), compressive deformation along N-S trends, is recorded by reverse faults (San José de Maipo, Esperanza, and Victoria faults east from Santiago and southeast from Concepción) (Lavenu et al. 2000, 2002, this volume).

At the intra-arc, the Liquiñe–Ofqui fault system (Hervé 1976, Hervé and Thiele 1987, Cembrano et al. 1996) is at the southern Central Andes a prominent neotectonic feature that suggests Quaternary stress partitioning (Fig. 5). Trans-pressive NE-SW deformation occurred during the Pleistocene along this fault system (Lavenu and Cembrano 1999, Lavenu, this volume).

Local changes from transpressive to trans-tensive regimes along its trace have been reported on the basis of the trend of reactivated faults (Lavenu, this volume). The northern growth of this fault system into the eastern Andean slope in Argentina has been proposed by Folguera et al. (2004), thus constituting the modern orogenic front between 36°S and 38°S (the Antiíte–Copahue fault zone of the Guanacocos fold-and-thrust belt) (Fig. 5).

This part of the Andes generate the largest
instrumentally recorded earthquake in the world (the Mw 9.5, 1960 Chilean Earthquake); although with an offshore epicenter this event determined uplift and subsidence along large parts of south-central Chile (Saint-Amant 1963, Plafker and Savage 1970, Atwater et al. 1992, Gisueñtes 1989, and many others). Even forty years after this event, GPS measurements indicate that the crust is still adjusting to this sudden strain release (Kendrick et al. 1999).

This and other ancient mega-thrust earthquakes have left their imprints in coastal terraces rather than as noticeable onshore ruptures. However, the role of uplifted terraces in illuminating the record of previous earthquakes has proved to be elusive. The complications related to differential preservation of evidences and temporary reversals in the sense of movement have been addressed by Atwater et al. (1992) and Vita Finzi (1996).

Rock-avalanches and landslides seem to be the remaining evidence of secondary and off-fault effects of large prehistoric earthquakes that were not necessarily associated with surface ruptures in the Andes between 36°S and 38°S (González Díaz et al. 2006, Hermanns et al. 2003, Costa and González Díaz, in press).

QUATERNARY DEFORMATION AT THE SOUTHERN ANDES (46° 30’S-55’S)

The southern Andes extend south of the Triple Junction that links the subduction of the Chile rise with the interaction of the South America, Nazca, and Antarctic plates (Figs. 1 and 6). Little is known about the Quaternary tectonics between the Gulf of Penas (46°30’S) and the Tierra del Fuego. The rugged terrain and dense forest cover on the western slope have so far prevented paleoseismic research other than image interpretation and general reconnaissance surveys. Neogene deformation is partitioned through strike-slip structures at the forearc and a fold-and-thrust belt along the eastern foothills of continental South America, where Neogene deformation has been documented (Ramos 1989, Kraemer 1993) but no Quaternary structures have been specifically studied.

In the Fueguian Andes at the southern tip of South America, a striking change in the pattern of Quaternary deformation is caused by the interaction of the South American and Scotia plates, giving rise to a dominance of strike-slip faulting on Tierra del Fuego Island (Winslow 1982, Winslow and Prieto 1991, Klepeis 1994, Lodolo et al. 2003, Smalley et al. 2003). Two Ms 7.8 earthquakes that occurred on December 17th, 1949, caused surface ruptures along the Fagnano-Magallanes fault (Fig. 6), which is considered to be the onshore expression of this plate-transform boundary.

Geologic investigations (Schwartz et al. 2001, 2002, Costa et al. this volume) near Fagnano Lake have documented 1-2 m of normal coseismic slip with an undetermined (submetric) amount of left-lateral movement. The secondary strike-slip component fits the interpretation that Lago Fagnano is in a transtensive section of this major fault system (Lodolo et al. 2003).

EXTRA ANDEAN SOUTH AMERICA

Except for some areas in Brazil, Quaternary deformation along this intraplate region (which is larger than the entire Andean Cordillera) is poorly studied and not well documented. Neogene structures, particularly those with Quaternary activity or the capacity for future movement, have long recurrence intervals (5 kyr to 100 kyr or more). This is because they do not reflect direct plate interaction, but instead reflect low-strain rate reactivation of previous anisotropies and structures (sometimes very old) under the present stress regime after a long cycle of stress loading.

As demonstrated in other “stable” continental regions, surface deformation can occur at unexpected locations, even those without noticeable seismicity and/or late Quaternary faulting (Crone et al. 1997, 2003). In these regions, Quaternary rates of deformation are considerably lower (and probably well below 0.1 mm/yr) than prevailing erosion or deposition rates, thus resulting structures have only a slight chance of imposing their geomorphic signatures into the landscape assemblages as a result of faulting. Macroscale and even regionally continuous linear features in cratonic and pericratonic areas may result from the passive imposition of long-lived structures commonly enhanced by fluvial systems. Conversely, subtle linear features and anomalies in river patterns in Quaternary basins might evolve from the ongoing propagation of brittle subsurface structures with slip rates much lower than the sedimentation rate. The interpretation as to whether or not these features have Quaternary activity is often a matter of controversy due to the lack of diagnostic data (Peulvast et al. IN PRESS) datable materials, or natural exposures.

For continental extra-Andean South America, Riccomini and Assumpção (1999) have divided it into the Brazilian and Patagonian platforms, the former being composed of Archean to Proterozoic cratons, Neoproterozoic orogenic belts, and Phanerozoic sedimentary basins. The latter includes extra-Andean Patagonia as well as the Pampean and surrounding regions cored by the Pampa craton.

In the Brazilian platform, several examples...
of Quaternary tectonics have been reported, particularly in the past two decades (Riccomini et al. 1989, Assumpção 1992, Saadi 1993, Bezerra et al. 1998, 2001, 2005, this volume, Saadi et al. 2002, 2005, Bezerra and Vita-Finzi 2000, and many others). These cases include not only surface ruptures but also for development of liquefaction features and geodetic anomalies. Structures affecting Quaternary deposits often correspond to reactivated fault planes with a long history of both reactivation phases and stress regimes. The contemporary continental stresses result in E-W to WNW-ESE shortening along the Atlantic coast, although several changes in stress regimes have been documented during the Quaternary (Riccomini and Assumpção 1999, Saadi et al. 2002). Also, recent apatite fission-track dating suggests a significant rate of crustal uplift since the Miocene (Nóbrega et al. 2005).

A record of Quaternary deformation is present in several craton-related basins, such as the Amazonas, Pantanal and Paraná basins (Iriondo and Sugüío 1981, Riccomini and Assumpção 1999, Saadi et al. 2002, 2005). However, the two areas where Quaternary deformation has been well documented are the Borborema region in northeastern Brazil and along the Serra do Mar rift system (São Paulo and Rio de Janeiro States). In the state of Rio Grande do Norte in northeastern Brazil, raised marine terraces record coastal uplift and submergence during the Quaternary. Tectonic differential coastal uplift and subsidence, in excess of that predicted by glacioisostatic models, have been suggested (Barreto et al. 2002) because part of the data can not be explained by eustatic variations alone. Liquefaction features in Quaternary alluvial gravel and gravelly sediment have been described at the Potiguar basin area. These features are linked to historical earthquakes as well as to paleoseismicity, accounting for palaeomagnitudes of about M 6.8 (Bezerra and Vita-Finzi 2000, Bezerra et al. 2005, this volume). Among the most significant faults in terms of Quaternary deformation, the Jundiaí and Boa Cica faults (Fig. 7) record Holocene displacements, the former having a cumulated vertical slip of approximately 260 m on Miocene deposits (Barreiras Formation) (Bezerra and Vita-Finzi, 2000, Bezerra et al. 2001, this volume). The trace of the NE-trending Samambaia fault (Fig. 7) shows prominent seismicity near the village of João Câmara (Takeya et al. 1989, Bezerra et al., this volume), illustrating one of the few cases where a fault is imaged by seismicity in intraplate areas.

Figure 6: Location of the Jundiaí and Boa Cica faults, which affect Neogene sedimentary units; (C) epicenters that illuminate the Samambaia fault.

Figure 7: Map of NE Brazil and location of faults discussed in text: a) Map of the west part of the Potiguar basin and main faults; b) location of the Jundiaí and Boa Cica faults, which affect Neogene sedimentary units; c) epicenters that illuminate the Samambaia fault.
At the Serra do Mar, several Quaternary structures have been described as affecting the Cenozoic basins related to the continental rift (Riccomini et al. 1989, and many others cited in Riccomini and Assumpção 1999). These structures mainly represent the reactivation of previously active structures having a general NE-SW trend. They record different stress regimes acting during the Quaternary in that region. The few reports on Quaternary deformation on the Pampean plains and in extra-Andean Patagonian regions have commonly noted local features having only secondary evidence or tectonic origins (Quattrocchio et al. 1994, Sagripanti et al. 1999, Brunetto 2005, 2006, Mon et al. 2005, and Rosello et al. 2005).

CONCLUDING REMARKS

Quaternary deformation in South America is concentrated along the Andean Cordillera and adjacent regions, whereas deformation has been sparsely documented in the extra-Andean regions. The inherited structural discontinuities and ongoing plate interactions are the main controls on the distribution, geometry, and kinematics of Quaternary deformation. At both ends of continental South America, major Quaternary structures have formed principally from plate interactions with strike-slip regimes, whereas Quaternary deformation along the Central Andes (4°S-46°30’S) is basically compressional and related to subduction of the Nazca plate. The influence of the style and distribution of structures with Quaternary activity is strongly influenced by the subduction angle and the resulting interaction with the overriding South American plate.

Quaternary structures along the Northern Andes are the most continuous and of continental scale. Most of these faults have slip rates higher than 1 mm yr⁻¹ and are commonly associated with shallow crustal seismicity. Through a complex geometric and kinematic framework, these structures accommodate and transfer ongoing stresses resulting from the interaction of the Caribbean and South America plates. These structures have strike-slip movement (i.e. Oca-Ancón, San Sebastián, Los Bajos El Soldado and Boconó fault in Venezuela, Chingual and Pallatanga faults in Ecuador), transpressive, and even compressive types of movements (the Eastern Cordillera frontal fault system in Colombia).

Along the Central Andes, the traces and distribution of structures with Quaternary activity are less continuous and less well organized. The Pacific coastal region and the western Andean piedmont are the closest areas to large offshore subduction earthquakes. However, Quaternary deformation is not represented by prominent fault zones (except for the Atacama fault in Chile), but rather through emerging or subsiding areas instead.

The style and characteristics of Quaternary tectonics at the surface are mainly the consequences of different geometries of the subducting angle of the Nazca plate. Therefore, along the Central Andes, particularly north of 33°S, the subducting plate can be grouped into different segments. At the Peruvian flat-slab segment (4°S-14°S) both normal and reverse faulting have been documented, some of them as short traces with associated historical ruptures and others as main bounding structures of high mountain ranges such as the Cordillera Blanca fault.

At the normal subduction segment of the Andes between 14°S and 27°S Quaternary faulting has been described along the Peruvian and Chilean coastal areas, where the Atacama fault system stands out. Quaternary deformation is represented across the Andes by high-angle normal faults at the Puna and Altiplano plateaus; high-angle reverse faults along the Cordillera Oriental, and thin-skinned thrusts at the sub-Andean zone.

The Pampean flat-slab segment of the Central Andes (27°S-33°S) concentrates Quaternary deformation along the orogenic front at the eastern foothills of the Precordillera. This deformation is also distributed across the Andean foreland through block uplifts of the Sierras Pampeanas where most of their bounding reverse faults have undergone activity during the Quaternary. Except for a few structures, the Quaternary deformation south of 33°S is poorly documented. In southernmost South America at Tierra del Fuego island, the Magallanes-Fagnano fault is an onshore E-W-trending transform boundary between the South America and Scotia plates. It constitutes a well expressed linear feature on a regional scale, with left-lateral motion predicted from modern plate kinematics and documented by GPS studies.

For extra-Andean South America, much progress in neotectonics has been made during the last two decades, particularly at the coastal regions in Brazil. Here, Quaternary activity has been documented on faults that have reactivated previous discontinuities or fault zones, as well as the discovery of secondary phenomena related to Quaternary faulting. Structures in these type of stable continental settings commonly have short traces compared with Andean structures and are commonly linked to Mesozoic rift zones or even older crustal weaknesses.

Except for the primary Quaternary faults in the Northern Andes of Venezuela and Colombia, most Quaternary structures in continental South America are developed within an intraplate domain. Here, inherited discontinuities and their relations with the present stress regime seem to influence the time span of their seismic cycles much more than do distant interplate interactions. Due to the long recurrence intervals inherent in the seismic cycles of intraplate structures (10⁴-10⁵ years), they may not be imaged by seismicity, but still have proven seismogenic capability. The recent devastating earthquake in Gujarat, India (almost 20,000 deaths), the 1812 New Madrid earthquakes in the USA, and lesser but illustrative surface-faulting earthquakes in Australia (Crone et al. 2003) show that many stable continental interior regions are not so stable. Thus, information on Quaternary faulting and surface deformation would add significant data for expanding the record of historical and instrumental seismicity and for developing more realistic assessments of the seismic capability posed by a structure. This in turn, would help to a better understanding on the likely spatial and temporal distribution of future damaging earthquakes.

ACKNOWLEDGEMENTS

We thank all the colleagues that collaborated with the ILP Project "World Map of
Major Active faults. We are also indebted to V. Ramos and M. Sébrier for constructive reviews. O. Pedersen, H. Cisneros and E. Ahumada helped with the graphics.

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An overview of the main quaternary deformation of South America


Recibido: 30 de junio, 2006
Aceptado: 15 de noviembre, 2006