Quaternary Science Reviews 80 (2013) 143–168

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Timing and nature of alluvial fan and strath terrace formation in the Eastern Precordillera of Argentina

Kathryn Hedrick [a,*], Lewis A. Owen [a], Thomas K. Rockwell [b], Andrew Meigs [c], Carlos Costa [d], Marc W. Caffee [e], Eulalia Masana [f], Emilio Ahumada [d]

[a] Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA
[b] Department of Geological Sciences, San Diego State University, San Diego, CA 92182, USA
[c] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
[d] Department of Geology, Universidad Nacional de San Luis, 5700 San Luis, Argentina
[e] Department of Physics, Purdue University, West Lafayette, IN 47907, USA
[f] Department Geodinamica ia Geofisica, Universitat de Barcelona, Spain

ARTICLE INFO

Article history:
Received 7 January 2013
Received in revised form
25 April 2013
Accepted 7 May 2013
Available online 6 October 2013

Keywords:
Terrestrial cosmogenic nuclide dating
Optically stimulated luminescence dating
Climate change
Tectonics
Erosion rates

ABSTRACT

Sixty-eight ^{10}Be terrestrial cosmogenic nuclide (TCN) surface exposure ages are presented to define the timing of alluvial fan and strath terrace formation in the hyper-arid San Juan region of the Argentine Precordillera. This region is tectonically active, and numerous fault scarps traverse Quaternary landforms. The three study sites, Marquesado strath complex, Loma Negra alluvial fan and Carpintería strath complex reveal a history of alluvial fan and strath terrace development over the past ~225 ka. The Marquesado complex $Q3_m$ surface dates to ~17 ± 3 ka, whereas the Loma Negra $Q1_{ln}$, $Q2_{ln}$, $Q3_{ln}$, $Q4_{ln}$, and $Q5_{ln}$ surfaces date to ~24 ± 3 ka, ~48 ± 2 ka, ~65 ± 13 ka, ~105 ± 21 ka, and ~181 ± 29 ka, respectively. The Carpintería complex comprises eight surfaces that have been dated and include the $Q1_c$ (~23 ± 3 ka), $Q2_c$ (~5 ± 5 ka), $Q3a_c$ (~25 ± 12 ka), $Q3b_c$ (~29 ± 15 ka), $Q4_c$ (~61 ± 12 ka), $Q5_c$ (~98 ± 18 ka), $Q6_c$ (~93 ± 18 ka), and $Q7_c$ (~212 ± 37 ka). ^{10}Be TCN depth profile data for the Loma Negra alluvial fan complex and Carpintería strath terrace complex, as well as OSL ages on some Carpintería deposits, aid in refining surface ages for comparison with local and global climate proxies, and additionally offer insights into inheritance and erosion rate values for TCNs (~10×10^4 ^{10}Be atoms/g of SiO_2 and ~5 m Ma^{-1}, respectively). Comparison with other alluvial fan studies in the region show that less dynamic and older preserved surfaces occur in the Carpintería and Loma Negra areas with only younger alluvial fan surfaces preserved both to the north and south. These data in combination with that of other studies illustrate broad regional agreement between alluvial fan and strath terrace ages, which suggests that climate is the dominant forcing agent in the timing of terrace formation in this region.

1. Introduction

Alluvial fans are one landform of a continuum – including strath terraces and talus slopes – related to mountain range-proximal erosion and deposition. Alluvial fans are pervasive and commonly well-preserved landforms that form in dynamic landscapes in a wide variety of geomorphic and climatic settings, and they are especially widespread in tectonically active regions (Blair and McPherson, 1994; Harvey et al., 2005). Factors controlling alluvial fan and strath terrace formation are complex and the efficacy and relative contributions of different geomorphic processes may vary from one region to the next. In addition, the dominant depositional processes at work often change temporally and spatially on alluvial fans, resulting in complex deposits that may be difficult to interpret. The importance of determining the timing and rate of alluvial fan formation lies in their utility to be used for paleoenvironmental, tectonic and landscape studies. Determining the main driver of deposition might also allow for mountain-proximal landforms to be used as a proxy for major tectonic or climatic events.

Influences on the timing of alluvial fan surface formation is greatly debated, with some studies emphasizing that tectonics is the dominant forcing factor while other studies suggest climate dominates (Wells and McFadden, 1987; Frostick and Reid, 1989; Bull, 1991; Blair and McPherson, 1994; Ritter et al., 1995; Harvey et al., 1999a,b; Harvey and Wells, 2003). In addition, many

* Corresponding author.
E-mail address: kate.hedrick@gmail.com (K. Hedrick).

0277-3791/$ – see front matter
http://dx.doi.org/10.1016/j.quascirev.2013.05.004

environments include other factors which may affect the timing of alluvial fan surface formation; for example, Trowbridge (1911), Church and Ryder (1972) and Church et al. (1989) suggest that paraglacial processes are important factors in alluvial fan formation, whereas Williams (1973), Wasson (1977), and Dorn (2009) emphasize the importance of periglacial processes in cold environments. However, recent studies of Quaternary alluvial fan sequences suggest that although tectonics is significant in providing conditions suitable for alluvial fan development, climatic events may be more important in determining the timing and rate of alluvial fan surface formation (Ritter et al., 1995; c.f. Harvey et al., 2005). The current lack of understanding of the timing and nature of alluvial fan formation represents a noteworthy gap in the scientific knowledge which may be filled by quantitative studies of the timing of alluvial fan formation.

Although alluvial fans are common landforms worldwide, the best places to study alluvial fans are usually in arid or hyper-arid environments where alluvial fan surfaces are more readily preserved and the lack of vegetation helps makes them easy to study. Extensive research has been undertaken on alluvial fans worldwide for many years (Denny, 1965; Boothroyd and Nummendal, 1977; Bull, 1977; Kesel and Spicer, 1985; Kostaschuk et al., 1986; Kochel, 1990), however many of the previous studies have relied on relative dating techniques (e.g. surface characteristics, geomorphology of terraces, soil development) to define the ages of alluvial fan surfaces because the most common numerical dating method—radiocarbon geochronology—cannot generally be applied due to the paucity of organic material in arid or hyper-arid alluvial fans. In addition, another common numerical dating method, optically stimulated luminescence (OSL), although well-suited for the dating of sand, cannot always be readily used due to the coarse grained nature of most alluvial fan deposits. Recently, however, the development of terrestrial cosmogenic nuclide (TCN) surface exposure dating has allowed alluvial fans to be dated more readily (e.g. Owen et al., 2006; Frankel et al., 2007; Hall et al., 2008; Spelz et al., 2008; Frankel et al., 2011; Hall et al., 2012).

To explore the nature and timing of alluvial fan formation in a hyper-arid region, and to assess the relative importance of forcing factors for alluvial fan development, a series of alluvial fans and strath terrace surfaces in the foreland of the Eastern Precordillera of Argentina on the western outskirts of San Juan, ~150 km north of Mendoza were examined. For the purposes of this paper we define the terms alluvial fan and strath terrace as follows: alluvial fans are a fan-shaped landform comprising thick (>2 m) sedimentary deposits and/or a lack of visible bedrock, whereas strath terraces are defined as landforms covered in thin (<2 m) sedimentary deposits or with visible underlying bedrock which lack the characteristic alluvial fan shape.

Fans and strath terrace deposits are well preserved in the forelands of the Eastern Precordillera. Determining the timing and mode of formation of alluvial fans and terraces in this region is important for both tectonic and paleoenvironmental studies. We map and date, using ^{10}Be TCN and OSL dating methods, multiple surfaces on three different alluvial fan-strath terrace complexes along the eastern front of the Sierra Chica de Zonda range near San Juan. Our study is compared to other alluvial fan and terrace studies in the Precordillera (Siame et al., 1997; Colombo et al., 2000; Siame et al., 2002; Schmidt et al., 2011, 2012) to explore whether climatic or tectonic events are most important in their formation along the Eastern Precordillera.

2. Regional setting

San Juan province is situated in the northwest-central region of Argentina and forms a portion of the western border with Chile, located above the southern Pampean flat-subduction segment of the Andes (Ramos et al., 2002). The province contains a wide variety of geomorphic settings with the tall, glaciated mountains of the High Andean Cordillera (Cordillera Principal and Cordillera Frontal), rising up to the peak of El Mercedario 6770 m above sea level (asl), which take up approximately the western third of the province. This is followed eastward by the significantly lower-elevation (<3000 m asl) of the Precordillera before finally flattening along its eastern border into the Sierras Pampaneas broken foreland (Jordan et al., 1983; Ramos et al., 1986; Mpodozis and Ramos, 1989; von Gosen, 1992; Ramos et al., 2002), which are expressed as generally flat plains with isolated, fault-bounded mountains that rise up to 2500 m asl, but generally with a relative relief of <700 m above the valley floor surrounded by bajada and strath surfaces. One such isolated mountain is Pie de Palo (~3300 m asl), which borders the northeastern edge of San Juan city. The detailed study areas are located entirely within the eastern piedmont of the Eastern Precordillera, where the Quaternary Andean thrust front is located (Costa et al., 2000; Ramos et al., 2002; Costa et al., 2006; Meigs et al., 2006; Vergés et al., 2007).

Our field areas abut this portion of the Eastern Precordillera, which comprise the Sierra de Villicum (Marquesado alluvial fan) and the Sierra Chica de Zonda (Loma Negra and Carpintería alluvial fans). These ranges are bounded by the west-verging Villicum-Pedernal thrust fault, which trends approximately north-south along the western edge of both the Sierra de Villicum and the Sierra Chica de Zonda (Costa et al., 2000).

Alluvial fans and strath terraces form an extensive bajada along Chica de Zonda, stretching for ~150 km from San Juan to Mendoza (Fig. 1). Study areas were chosen near the city of San Juan on the backlimb of the Villicum-Pedernal thrust (Fig. 1). Previous studies of alluvial fans in this region include those of Siame et al. (1997), Siame et al. (2002) and Colombo et al. (2000) ~60 km to the north, ~10 km north and ~15 km northeast of our study areas, respectively. Schmidt et al. (2011) and Schmidt et al. (2012) also conducted studies on alluvial fans ~80 km and ~130 km to the south.

The region is tectonically active and has experienced many large earthquakes, notably Argentina's most disastrous earthquake: the 1944 San Juan M_W7 earthquake, which destroyed ~80% of San Juan and surrounding areas (Bastías and Henríquez, 1984; Perucca and Paredes, 2002; Alvarado et al., 2007; Meigs and Nabelek, 2010) ~20 km to the northeast of our study area. The Sierras Pampeanas to the east are affected by active east- and west-verging reverse faults with a thick-skinned origin (Kandinsky-Cade et al., 1985; Fielding and Jordan, 1988; Ramos et al., 2002; Costa et al., 2006; Meigs and Nabelek, 2010), whereas the central Precordillera to the west comprises thin-skinned east-vergent thrust faults (von Gosen, 1992). The eastern Precordillera acts as a transition zone (Fielding and Jordan, 1988; Zapata and Allmendinger, 1996) between these two tectonic environs and is characterized by thin-skinned west-verging thrust faults shallower than ~5 km depth (von Gosen, 1992) and reverse fault seismicity deeper than 40 km (Smalley et al., 1993). Studies undertaken by many researchers suggest that the crust beneath both the Eastern Precordillera and the Sierras Pampeanas is affected by active planar reverse faults below 5 km depth (Kandinsky-Cade et al., 1985; Smalley et al., 1993; Meigs et al., 2006; Gimenez et al., 2010; Meigs and Nabelek, 2010), whereas other researchers suggest that these deeper structures are secondary to fault movement (Vergés et al., 2007).

San Juan and the nearby study areas are located within the South American Arid Diagonal (Bruniard, 1982; Morales et al., 2009), a region believed to have been climatically sensitive to the shifts of the Pacific and Atlantic anticyclones from the late Pleistocene through the Holocene (Abraham et al., 2000). For the period of 1940–2007, mean annual precipitation in San Juan was 93 mm