U-Pb ages of detrital and volcanic zircons of the Toro Negro Formation, northwestern Argentina: Age, provenance and sedimentation rates

William H. Amidon a,*, Patricia L. Ciccioli b, Sergio A. Marensi b, Carlos O. Limarino b, G. Burch Fisher c, Douglas W. Burbank d, Andrew Kylander-Clark d

a Geology Department, Middlebury College, Middlebury, VT, 05753, USA
b Departamento de Ciencias Geológicas, IGeBA, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires-CONICET. Pabellón 2, 1er piso, Ciudad Universitaria, C1428EA Buenos Aires, Argentina
c Jackson School of Geosciences, University of Texas at Austin, Austin, TX, 78712, USA
d Earth Research Institute, University of California, Santa Barbara, CA, 93106, USA

A R T I C L E   I N F O

Article history:
Received 13 November 2015
Received in revised form 23 May 2016
Accepted 26 May 2016
Available online 28 May 2016

Keywords:
Tephra
Vinchina
Fiambala
Bermejo
Famatina
U-Pb
Zircon
Precordillera
Valle Fertil

A B S T R A C T

The Toro Negro Formation is a foreland sequence in western La Rioja province, Argentina, which records the late-stage tectonic evolution of the Vinchina Basin. Together with the underlying Vinchina Formation, these two units represent one of the thickest and longest continually exposed foreland sections in northwest Argentina. The Vinchina basin is uniquely situated between the Toro Negro and Umango blocks of the Western Sierra Pampeanas to the north and south, the Precordillera to the west, and the Sierra de Famatina to the east. New U-Pb dating of volcanic tephra provides improved age constraints on the pace of sedimentation, and U-Pb ages of detrital zircons serve to strengthen existing provenance interpretations. We show that deposition of the Toro Negro Formation spans roughly 6.9 to 2.3 Ma: Late Miocene to Early Pleistocene. A high-relief, erosional unconformity with the underlying Vinchina Formation developed sometime between 9.3 and 6.9 Ma, although stratigraphic considerations suggest it spanned only the later part of this time interval (perhaps 7.5–6.9 Ma). Above this unconformity, undecompressed sedimentation rates are remarkably high at ~1.2 mm/yr, slowing to ~0.3 mm/yr after ~6 Ma. An unconformity in the upper part of the section is constrained to occur sometime between 5.0 and 3.0 Ma, probably beginning not long after 5.0 Ma. The timing of both unconformities broadly matches the timing of inferred tectonic events in the Sierra Famatina (~50 km to the east, the Fiambalá basin to the north, and the Bermejo basin to the south), suggesting they may record regional tectonism at these times. Provenance interpretations of detrital zircon spectra are consistent with previous interpretations based on sediment petrography. They show that provenance did not change significantly during the course of Toro Negro deposition, precluding major tectonically-induced drainage reorganization events. Sediments were derived primarily from the north (Toro Negro Block) and west (Precordillera). The data are consistent with a subtle increase in sediment supply from the Precordillera beginning around 6.5 Ma.

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1. Introduction

Foreland basin sediments are important recorders of the tectonic and climatic evolution of mountain ranges. Such stratigraphic successions have proven especially useful in unraveling the tectonic evolution of the eastern Andes, where the structural style changes rapidly and precise age control is commonly available from tephrochronology. For example, foreland sequences in northern Argentina have been critical to distinguishing regions of in-sequence thrust progradation, such as the Subandean belt, from regions of out-of-sequence thrusting that are more characteristic of the Sierras Pampeanas and Santa Barbara System (Strecker et al., 2007). Foreland sediments are also valuable records of terrestrial climate and vegetation, presenting an additional impetus for understanding their age, provenance, and depositional setting (e.g. Mulch et al., 2010).

The Bermejo basin of NW Argentina is a world-class example of
a foreland basin that has evolved by a mixture of thin- and thick-skinned deformation (Beer and Jordan, 1989; Collo et al., 2011; Jordan et al., 1993, 2001; Milana et al., 2003). The classic model of Jordan et al. (2001) involves a transition from an initially “simple foreland” that is subsequently divided into sub-basins by the rise of mountain ranges along deep-seated basement thrusts to create a “broken foreland.” In this model, the simple foreland stage from (~20-8 Ma) is primarily a flexural response to shortening in the Frontal Cordillera and Precordillera to the west. By ~6.5 Ma, uplift of the Sierras Pampeanas fragments the Bermejo foreland into more localized depocenters (Jordan et al., 2001). As additional studies have focused on these localized depocenters, it has become clear that some of the basement uplifts, particularly those in the north, such as the Vinchina Basin, are older and record a complex interplay of thin- and thick-skinned deformation throughout the Miocene (e.g. Davila and Astini, 2007; Ciccioli et al., 2011, 2013a; Marenssi et al., 2015). Thus, many questions remain about the precise spatio-temporal pattern with which the broken foreland evolved, and how it was controlled by pre-existing structures and changes in the Pacific-South America plate dynamics.

This study seeks to better understand the history of the Toro Negro Formation, a clastic foreland sequence deposited in the Vinchina depocenter (the modern Bolson de Jagüe basin) at the northern end of the Bermejo Basin near 28.5°S (Fig. 1). The Vinchina basin is a classic example of a localized depocenter, because it is bounded to the north, south, and east by basement-cored uplifts (Fig. 2). The Toro Negro block to the north and the Umango-Espinal arch to the south are both part of the Western Sierras Pampeanas, whereas the Sierra de Fatamina to the east and Sierra de Narváez to the northeast are part of the Fatamina System. To the west, the Vinchina depocenter is bound by the Frontal Cordillera and the northernmost extent of the Precordillera (Figs. 1 and 2). The Frontal Cordillera is composed of metamorphic basement, Late Paleozoic to Triassic granitoids, and young Cenozoic volcanics (Caminos, 1972; Caminos et al., 1979; Caminos and Fauquè, 2001). Farther east, the Precordillera is a thin-skinned fold-and-thrust belt, creating a series of north-south oriented mountain ranges immediately west of the Jagüe basin. The Vinchina depocenter also sits ~50 km north of a major basement structural lineament known as the Valle Fértil lineament, which is interpreted to be an important basement structure whose Miocene reactivation exerted a strong control on partitioning of the Bermejo Basin (Ciccioli et al., 2011, 2013a). The Toro Negro Formation is thus well situated to record both uplift of basement blocks in the Western Sierras Pampeanas, as well as thrust activity in the northern Precordillera (Ciccioli, 2008; Ciccioli et al., 2014a).

The sedimentology of the Vinchina depocenter has been well studied over the past 10 years (e.g. Tripaldi et al., 2001; Limarino et al., 2001; Ciccioli, 2008; Ciccioli and Marenssi, 2012; Ciccioli et al., 2011, 2013b, 2014a; Marenssi et al., 2015). In particular, the modal composition of sandstones and conglomerates has proven an effective means to establish source areas and to explore the relation between shifts in compositional framework and changes in watershed configuration (Ciccioli, 2008; Ciccioli et al., 2014a). Sandstone composition does not, however, depend exclusively on the source rocks: it may be affected by the physiography and chemical weathering in the source area, by reworking and abrasion of the sediments during transportation and sedimentation, by recycling of older sediments, and by diagenetic effects (Amorosi and Zuffa, 2011; Dickinson and Suczek, 1979; Espejo and López-Gamundi, 1994). Additionally, uncertainty regarding the age of the Toro Negro Formation has prevented sedimentological observations from being interpreted in a well-dated regional framework. Age estimates for the Toro Negro Formation have ranged from Plio-Pleistocene (Reynolds, 1987; Tabbutt et al., 1989; Re and Barredo, 1993) to late Miocene-early Pliocene (Ciccioli et al., 2005; Collo et al., 2011). In the absence of better time control, significant uncertainty persists concerning the timing and pace of Toro Negro deposition.

This study presents eight, new U/Pb zircon ages on volcanic tephra from the La Troya section. These new dates refine the age of the Toro Negro Formation to approximately 6.87 to 2.37 Ma (Late Miocene-earliest Pleistocene). We also combine existing petrographic and clast-count data with U-Pb dating of detrital zircons from eight sites to better constrain provenance changes. These results demonstrate that the Toro Negro Formation is somewhat younger than previously thought, they define four-fold changes in sediment-accumulation rates, and they support the conclusions of Ciccioli et al. (2014a) that these sediments are derived primarily from the north and west with only minor changes in provenance over time.

2. Geologic setting

The bedrock geology in the study area is a mosaic of accreted terranes intruded by igneous rocks that record nearly every stage of Andean margin evolution. The geologic evolution is briefly reviewed here to provide a context for interpretation of detrital U-Pb ages. During Grenville time (~1300–1050 Ma), the margin of the Rio de la Plata craton was sutured with Laurentia as part of the supercontinent Rodinia (Ramos and Folguera, 2009). Numerous granitoids were intruded and sedimentary rocks accreted, which are now preserved as high-grade schists and gneisses exposed in basement blocks throughout the Western Sierras Pampeanas, e.g., the Maz, Espinal, and Umango ranges (Casquet et al., 2008; Colombo et al., 2009; Martina et al., 2005; Ramos and Folguera, 2009; Rapela et al., 2010). Spatially significant meta-sedimentary units include the dominantly quartz schists and gneisses of the El Espinal and Tambillito Formations (Turner, 1964), and the dominantly pelitic schists and gneisses of the Sierra de Maz, El Zaino, and El Taco Groups (Kilmurray, 1971).

By the early Cambrian (~535 Ma), a subduction margin was established, followed shortly by accretion of the Pampa Terrane during the middle Cambrian. Granitoids and meta-sedimentary rocks of this age are widely exposed in the Eastern Sierras Pampeanas, but are less common near the study area (Pankhurst et al., 1998). Subduction was reestablished by the early Ordovician accompanied by voluminous plutonism and intrusion of the Fatamina granitoid belt from ~465 to 490 Ma and by compression during the ensuing Ocloyic orogeny (Pankhurst et al., 1998, Rapela et al., 1998, Rubiolo et al., 2002). Fatamian granites are widely exposed in the Sierra de Fatamina and Sierra de Narváez (Fatamina System), and sparsely exposed in the Sierra de Umango (Western Sierras Pampeanas), with ages from ~464–481 Ma (Pankhurst et al., 2000; Rapela et al., 1999; Rubiolo et al., 2002; Varela et al., 2000, 2011). Ordovician Fatamian arc volcanism was accompanied by deposition of siliciclastic and volcaniclastic sedimentary rocks in a back-arc basin (Bahlburg and Hervé, 1997; Sims et al., 1998). A thick (~3200 m) succession of Ordovician sediments exposed in the Fatamina System includes siliciclastic, rocks such as the Negro Peinado, Suri, Las Planchadas, Río Bonete, Achival, La Escondida, and Ingá Formations (Acenolaza and Toselli, 1981; Aecenolaza et al., 1996; Astini et al., 2003; Mangano and Droser, 2003; Turner, 1967; among others).

During the latest Ordovician and Silurian, the Precordillera (Cuyania) Terrane docked and sutured a crustal fragment with an overlying shelf sedimentary sequence during the Ocloyic orogeny (Ramos et al., 1986; Rapela et al., 1998). The strictly defined Cambro-Ordovician Precordillera terrane is exposed to the south of the Vinchina region, including the Las Vacas, Trapiche, Yerba Loca,
and many other formations (Fig. 7). However, we use the broader term of Precordillera to refer to the thin-skinned fold-and-thrust belts exposed immediately west of our field area, which includes the Ordovician Chuscho and Rio Bonete formations overlain by the younger Carboniferous-Permian formations described below (Fig. 2).

After Cambro-Ordovician thickening, significant topography likely characterized the western margin of South America. The late Paleozoic was characterized by sedimentation into basins flanking this topography, including the Río Blanco Basin in our study area (Limarino et al., 2006; López Gamundi, 1987; Scalabrini Ortiz, 1973). Associated sedimentary units include the latest Devonian Jagüel and Punilla Formations, which are unconformably overlain by the Carboniferous Punta del Agua and Río del Peñón Formations (Gulbranson et al., 2010, 2015; Henry et al., 2008; Net and Limarino, 2006). Sparsely preserved early Permian clastic sequences are also present, including the Patquía/De la Cuesta Formations (Caselli and Limarino, 2002). Volcanism continued into the Early Carboniferous, as evidenced by granites, such as the Potrerillos and Las Tunas Plutons exposed immediately west of the Jagüé Basin (Dahlquist et al., 2006; Grosse et al., 2009; Rapela et al., 1982; Varela et al., 2011). Early Carboniferous rhyolite and andesite intervals (335–348 Ma) are also exposed in the north and west of the study area, some of which were initially mapped as Ordovician (Gulbranson et al., 2010; Martina et al., 2011).

By mid-Permian time, widespread subduction and arc volcanism were again affecting the region, as recorded by at least two classes of igneous rocks. First, arc-type granitoids were intruded, often referred to as the Frontal Cordillera Plutons or Elqui Complex, and have been dated to ~267–254 Ma (Llambías and Sato, 1992; Nasi et al., 1985). The Colanguil batholith is the largest intrusion of this age in the study area, exposed about 100 km to the southwest. A second phase of plutonism is recorded by the batholiths of the Ingaguas Complex, which were emplaced from ~260 to 192 Ma and are exposed in Montosa–El Potro batholith ~150 km to the northwest, well outside of the modern watershed (Mpodozis and Kay, 1992). These rocks are roughly equivalent to the Choiyoi plutons that are widely exposed between ~30 and 34° S.
Fig. 2. Detailed Geological map of the study area including regional stratigraphy as discussed in section 2 of the text. Modified from Ciccioli (2008).
During the Mesozoic, scarce volcanism and continental sedimentation took place to the west and south of the study area as recorded in the Santo Domingo and Ciénaga de Río Huaco Formations (Caminos et al., 1995; Coughlin, 2000; Caminos and Fauqué, 2001; Limarino et al., 2005; Tedesco et al., 2007). These extensional depocenters were developed due the breakup of Gondwana along previous basement lineaments in the northwest of Argentina.

Throughout much of the Cenozoic, the region existed as a relatively quiescent retro-arc environment to the east of the main volcanic axis. As the Andean orogeny got underway at about 20 Ma, significant shortening was accommodated in the Frontal Cordillera and Precordillera, causing development of the Bermejo Basin (Jordan et al., 2001). By about 20 Ma, flat-slab subduction was initiated (Kay et al., 1987), and by 10 Ma, flat-slab subduction began affecting the eastern Andes between the latitudes of ~27°–33°S (Jordan et al., 1983). This low-dip subduction largely extinguished volcanism to the south of the study area (Kay and Abbruzzi, 1996), and ultimately accelerated deformation. Because the study area sits at the transition from flat-slab subduction (south) to regular subduction (north), late Cenozoic volcanics are abundant to the northwest of the study area, but sparse to the southwest (Goss et al., 2013; Kay et al., 2013) (Fig. 1B).

3. Previous work

3.1. Stratigraphy of the Vinchina depocenter

At least four major Upper Paleogene and Neogene formations have been deposited in the Vinchina depocenter: the Vallecito, Vinchina, Toro Negro, and El Corral (Fig. 2). In the La Troya depocenter to the south of the study area, the pre-Miocene Puesto la Flecha and Vallecito formations have a combined thickness of ~1100 m and are composed of lacustrine facies and cross-beded eolian sandstones, respectively (Borrello and Cuerda, 1967; de la Fuente et al., 2003; Tripaldi and Limarino, 2005).

The rapidly deposited Miocene Vinchina Formation is ~5100 m thick and is composed mostly of reddish sandstones and shales deposited in fluvial and lacustrine environments (Ramos, 1970; Turner, 1964; Tripaldi et al., 2001). Recent U-Pb ages estimate the formation to span roughly 15.6–9.2 Ma (Ciccioli et al., 2014b; Collo et al., 2011). The fluvial sandstones of the Lower Member of the Vinchina Formation are interpreted to herald the initiation of uplift in the Sierra Espinal/Maz arch and the Sierra del Toro Negro, due to the interplay of two transpressional faults: the Tucuman and Valle in the Sierra Espinal/Maz arch and the Sierra del Toro Negro, due to formation to span roughly 15.6 Ma (Turner, 1964; Tripaldi et al., 2001).

3.2. Provenance of the Toro Negro formation

Ciccioli et al. (2014a) combine sandstone petrofacies, conglomerate lithic identification, and paleocurrent analysis to show that sediments in the Toro Negro Formation are primarily derived from the north (Toro Negro Range), with periods of increased contribution from the west (Frontal Cordillera and Precordillera). For example, DSII shows notable north-south facies changes from fluvial conglomerates and coarse-grained sandstones in the north (Los Pozuelos section) to fine-grained successions deposited in a playa lake in the south (Del Yeso section). Preserved strata do not record material derived from the east (Sierra de Famatina) or south (Sierra de Umango). Although overall provenance changes are minor, subtle changes in provenance are summarized here and in Fig. 3.

The Toro Negro sandstones can be divided into three sandstone petrofacies: plutonic-metamorphic, volcanic and mixed. The plutonic-metamorphic petrofacies (PMP) is defined by (K-feldspar/plagioclase) > 1, (high-grade metamorphic lithics/volcanic lithics) > 1, and >60% of clasts derived from crystalline rocks. The volcanic petrofacies (VP) is defined by > 60% of volcanic components and a (K-feldspar/plagioclase) < 1. Finally, the mixed petrofacies (MP) shows a variable (K-feldspar/plagioclase) ratio and a relative decrease in volcanic groundmasses, quartz and crystalline rock clasts in relation to the PMP. The lower beds of DSII are dominated by the plutonic-metamorphic petrofacies, grading upward into the mixed petrofacies towards the top of DSII (Fig. 3). Conglomerate clasts support this succession, showing a predominance of high-grade metamorphic basement clasts near the base of DSII, with secondary amounts of volcanic and sedimentary clasts and a lack of slates and phylites (Ciccioli et al., 2014a). This composition suggests material derived primarily from basement exposures of the Western Sierras Pampeanas, most likely the Toro Negro Range, based on north-south paleocurrents and the decrease of grain size toward the south (Ciccioli, 2008; Ciccioli and Marenssi, 2012; Ciccioli et al., 2014a).

The lower part of the DSII returns to the plutonic-metamorphic petrofacies (Fig. 3) based on abundant schist, gneiss and metavolcanic fragments, as well as different types of simpleclites (Ciccioli et al., 2014a). Towards the top of DSII, a shift back towards mixed petrofacies is revealed by the increased abundance of
volcanic components. Conglomerate clasts at the top of DSII also show an increase in volcanic and sedimentary components. This increase in volcanic components towards the top of DSII suggests an enhanced sediment supply from Silurian-Carboniferous volcanic rocks of the Precordillera, perhaps combined with Cenozoic volcanic rocks of the Frontal Cordillera (Ciccioli et al., 2014a).

The lower part of DSIII is characterized by a mixed sandstone petrofacies (Fig. 3) associated with a predominance of high-grade crystalline clasts, with secondary sedimentary, volcanic, and low-grade metamorphic clasts (Ciccioli et al., 2014a). This composition suggests a persistent source of basement rocks from the Toro Negro Range to the north, with secondary contributions from the west (Ciccioli et al., 2014a). In middle DSIII, this petrofacies transitions upward to a volcanic assemblage due to the addition of intrabasinal glassy volcanic sand components, suggesting a growing neo-volcanic source to the northwest during this time. The existence of young volcanics in the headwaters is supported by the occurrence of two thick tephra beds in this part of the section, and numerous eruptive centers of this age (Figs. 1 and 3). The uppermost DSIII is marked by a shift back to plutonic-
metamorphic petrofacies due to an increase in high-grade crystalline lithics coupled with sedimentary, slate, and phylite fragments (Ciccioli et al., 2014a). Conglomerate clasts show a similar trend; sedimentary and low-grade metamorphic clasts also become more abundant towards the middle and top of DSIII, collectively suggesting an increasing contribution from the Precordillera and Frontal Cordillera to the west (Ciccioli et al., 2014a).

In summary, the main source of sediment to DSII and III appears to be from the Toro Negro Range to the north with a growing contribution from the Precordillera and/or Frontal Cordillera by the middle/late DSII and DSIII.

4. Methods

Field samples for U-Pb dating were placed in the stratigraphic context of Ciccioli et al. (2014a) using GPS coordinates combined with original field notes and imagery. U-Pb dating was applied to tephra for stratigraphic age determination and to detrital samples for provenance analysis. Detrital zircon samples were collected from 8 freshly exposed roadcuts extending medium-grained sandstone to pebble conglomerate deposits along the La Troya section (Table S1). Bulk material was exhumed, hand crushed, and sieved to <500 μm in the field. Eight volcanic ash samples were collected as intact fragments in the field and crushed in the lab. In the lab, all samples were wet sieved to <210 μm, rinsed to remove clay-sized particles, and zircons were separated following standard magnetic and heavy liquid procedures. Zircons were then mounted in epoxy, and polished parallel to the c-axis for analysis by laser ablation — inductively coupled plasma mass spectrometry (LA-ICPMS).

Zircon analyses were performed at the UCSB LASS facility using a Photon Machines Analyte 193-nm excimer laser and Nu Instruments Plasma MC-ICPMS, following the methods described in Kylander-Clark et al. (2013). Analyses targeted the rims of zircons free of cracks or inclusions using a spot size of 30 μm and a repetition rate of 4 Hz. Results were standardized using the 91,500 zircon reference material (Wiedenbeck et al., 1995). Standards GJ1 (601.7 ± 1.3 Ma; Jackson et al., 2004) and Plesovice (337 ± 0.37 Ma: Slama et al., 2008) were used for secondary quality control, yielding mean 206Pb/238U ages of 599.3 ± 4.5 (n = 22; MSWD = 1.4) and 337.9 ± 3.6 Ma (n = 27; MSWD = 1.1).

All tephra ages are based on 206Pb/238U ages corrected for initial Pb and secular disequilibrium. Most analyses are slightly discordant, which we attribute to minor amounts of common Pb (Fig. S1: Table S2). We correct for this by assuming concordance, calculating a 207-corrected 206Pb/238U age using ISOPLOT (Ludwig, 1991), and assuming a common 204Pb/206Pb ratio of 0.84 (Stacey and Kramers, 1975). The magnitude of this age correction varies by sample, with a few grains reaching up to 50% (e.g. ash 7), but for the majority of ages, corrections are only a few percent (Fig. S1). A second correction accounts for the exclusion of 238Th during crystallization, causing a period of disequilibrium in the 238U/206Pb decay series and a resultant age underestimate. This correction follows Schraer (1984) as described in Schoene (2013) and assumes a Th/U ratio of 3.2 based on an average value of Mio-Pliocene ignimbrites in the Incapillo region (Fig. 1B).

For detrital zircons, cores of crack-free zircons were targeted using a spot size of 15 μm and were ablated at a rate of 4 Hz. Given the increasing possibility of Pb loss with age, 207-corrected 238U/206Pb ages are used for <1200 Ma grains, and 204Pb/206Pb ages are used for >1200 Ma. Grains that showed greater than 15% discordance between 207U/206Pb and 238U/206Pb ages were rejected, except for grains <10 Ma, which were all utilized. Detrital zircon results are displayed using kernel density estimate (KDE) plots with smoothing kernels of 0.5 Ma for ages < 50 Ma and of 4 Ma for ages > 50 Ma.

5. Discussion

5.1. Tephra ages and the pace of sedimentation

Tephra ages for the Toro Negro Formation range from 6.87 to 2.37 Ma (Fig. 4 and Table S2), indicating that sedimentation took place from Messinian (Late Miocene) to Galerian (earliest Pliocene) times. Each of the eight tephra beds yielded a distribution of U-Pb zircon ages reflecting differing degrees of contamination by zircons derived from pre-eruption country rock and reworking (Table S2). We assign eruptive ages based on the weighted mean age of the youngest cluster of zircons that overlap each other within 1σ uncertainty. This approach is justified by the fact that young zircons are unlikely to have experienced significant Pb loss that would lead to anomalously young ages, yet are virtually certain to have begun crystallization hundreds of thousands of years prior to eruption (Brown and Fletcher, 1999).

The new tephra ages place constraints on the maximum duration of the basal unconformity to be less than 2.4 Myr with bracketing ages of ~9.3–6.9 Ma. The DSII-DSIII unconformity lies between 6.8 and 6.2 Ma, whereas the DSIII-III unconformity is bracketed by ages of 5.0–3.0 Ma (Fig. 5). The basal unconformity is constrained by ash 1 located ~100 m above the unconformity, combined with a 9.34 ± 0.03 Ma ash from the Los Pozuelos section sitting ~125 m below the unconformity (Fig. 1; Ciccioli et al., 2014b). However, because up to 1000 m of the upper part of the Vinchina Formation has been eroded from the Los Pozuelos section, the actual duration of the unconformity is likely to be significantly shorter. Extrapolating the mean Vinchina sediment-accumulation rate (~0.61 mm/yr) through the existing and eroded overlying section (1125 m) suggests that the unconformity is more likely to span a time interval closer to ~7.5 to 6.9 Ma. Note that this refined age estimate is strongly dependent on the assumed sedimentation rate and the amount of eroded section lost from the upper Vinchina formation.

The DSI and II unconformity is bracketed by ash 1 and 5 (Figs. 3 and 5) and appears to have been relatively short lived based on the sedimentation rates discussed below. The DSII-DSIII unconformity is constrained by ash 9 (5.0 Ma) and the youngest grain in sample AV-10. Given that the unconformity occurs just above ash 9 and that sample AV-10 is ~300 m higher in the section, the actual depositional hiatus probably occurred shortly after ash 9: during the early Pliocene. Based on a downward extrapolation of the DSII accumulation rate (Fig. 5), the unconformity at its base is likely to span ~1 Myr. Our data also constrain the timing of an apparent unconformity between the top of the Toro Negro Formation and the overlying Pleistocene gravels to span ~2.4–1.4 Ma. This constraint comes from the age of ash 12 and the youngest detrital zircon in sample V-25, which sits only ~20 m above it (Fig. 5).

Undecomposed sedimentation rates show striking variability: 1.2 mm/yr from ~6.9–6.1 Ma, slowing to a rate of ~0.3 mm/yr from ~6.1 to 5.0 Ma, and then accelerating back to ~0.6 mm/yr from ~3.0 to 2.4 Ma (Fig. 5). These intervals were chosen based on natural breaks in tephra-constrained sedimentation rate, which spans the DSII-III unconformity and the uppermost unconformity. Because the duration of the DSI-II unconformity is apparently quite short, we compute a long-term sedimentation rate that spans this hiatus.

The most striking implication of this revised chronology is the newly discovered nature of deposition and erosion in the Late Miocene: prior to ~7.5 Ma, the Vinchina Formation aggraded at an average rate of ~0.61 mm/yr (Ciccioli et al., 2014b); about 1000 m of erosion occurred between 7.5 and 6.9 Ma; and then the sedimentation rate accelerated to ~1.2 mm/yr at ~6.9 Ma as deposition of the Toro
Negro Formation began (Fig. 5). This succession of changes implies that between 7.5 and 6.9 Ma, the area experienced a drop in relative base level that triggered significant erosion and was then followed by a period of rapid subsidence (or basin isolation) that caused rapid sedimentation from ~6.9 to 6.1 Ma.

The timing of the Toro Negro basal unconformity is very similar to an unconformity observed between the Santo Domingo and El Durazno Formations in syn-orogenic strata of the eastern flank of the Sierra del Famatina ~50 km to the east (Avila). This synchrony suggests that the two events may be genetically linked: for example, by uplift along basement thrusts and/or motion on basement lineaments that uplifted the Sierra del Famatina. In this regard, Limarino et al. (2010) proposed that uplift of the Sierra Famatina produced accelerated subsidence and increased accommodation in areas proximal to the Sierra de Famatina, thus driving incision of the Vinchina Formation sitting upstream of the subsidence. During post-tectonic times, subsidence and accommodation rates proximal to the Sierra Famatina decreased (Limarino et al., 2010), triggering renewed aggradation and a return to basin filling conditions in the Toro Negro region.

Uplift in the Famatina and/or Vinchina regions at this time (roughly 7.5–6.9 Ma) is consistent with coeval uplift of isolated basement blocks elsewhere in the Bermejo Basin. Jordan et al. (2001) proposed that the Bermejo Basin transitioned from a simple to a broken foreland at ~7.3 Ma: a transition that is interpreted to signal activation of basement structures, such as the northern Valle Fertil Lineament. In addition, Coughlin et al. (1998) showed that exhumation in the Sierra de Valle Fertil likely began at about the same time, between 10 and 5 Ma. However, other basement blocks were uplifted earlier in the Miocene. For example, the Vinchina basin was already receiving sediments from the Toro Negro basement uplift as early as 15 Ma (Marenssi et al., 2015) and the Sierra de Famatina to the east had already experienced uplift during the early and middle Miocene (Davila and Astini, 2007). It is thus conceivable that the deep localized incision of the Vinchina formation (the basal unconformity) was driven by uplift along basement structures in the immediate vicinity of the Vinchina basin.

The early Pliocene (shortly after 5 Ma) timing of the DSII-III unconformity is also coincident with regional tectonism. Johnson et al. (1986) infer an eastward jump in Sierra de Huaco deformation (San Juan province) at 4.8 Ma, similar in timing to a major
Fig. 6. Detrital U-Pb zircon spectra shown as kernel density estimates using a 4-Myr smoothing kernel for ages >50 Ma and a 0.5-Myr smoothing kernel for ages <50 Ma. Open circles represent individual grain ages (with no uncertainties).
A period of deformation from ~5.3 to 4.0 Ma in the Fiambalá basin about 100 km to the north (Carrapa et al., 2008).

5.2. Attribution of U-Pb age peaks

U-Pb age distributions of detrital zircons contain an impressive range of U-Pb ages, which are consistent with the expected contributions from regional bedrock units based on previous studies (Abre et al., 2012; Alvarez et al., 2011; Gleason et al., 2007; Casquet et al., 2008; Collo et al., 2009; and Rapela et al., 2007 (Figs. 6 and 7; Table S3). Here we identify seven age intervals and discuss their possible source regions. These intervals are loosely based on the major stages of geologic evolution described in Section 2 and in some cases are representative of specific source regions, but a given source more commonly contains ages from multiple age intervals. Despite recognition that zircons can also be sourced from recycled Neogene or older strata, our provenance attribution considers only direct bedrock sources.

First, Mesoproterozoic ages from (~1400-900 Ma) are the largest population, constituting ~25-50% of grains in each sample (Figs. 8 and 9). Grains of this age are dominant in the spectra of Grenville-aged basement rocks of the Western Sierras Pampeanas, e.g., the El Zaino Fm., as well as in sedimentary units of the Precordillera and the Frontal Cordillera (Fig. 7). Interestingly this population is only weakly expressed in the Cambro-Ordovician units of the Famatina System (Rapela et al., 2007; Collo et al., 2009). This minor population is consistent with the idea that these units were deposited prior to the arrival of the Precordillera terrane(s), which are rich in Proterozoic zircons.

Second, Neoproterozoic-Cambrian ages (~900-490 Ma) represent about 10–22% of grains in each sample (Figs. 8 and 9). This population is important in the spectra of the Frontal Cordillera (El Transito Complex) and the Famatina System (Suri, Achevial, and Negro Peinado Formations), but more weakly expressed in the Precordillera and Western Sierras Pampeanas (Fig. 7).

Third, Ordovician-Silurian ages (~490-415 Ma) are also common, constituting roughly 14–34% of grains in a sample (Figs. 8 and 9).

Fig. 7. Compilation of detrital U-Pb zircon ages from bedrock units within ~200 km of the study area. Although the El Taco Formation has been interpreted as Neoproterozoic, its detrital zircon spectra suggests this unit was deposited in the Middle to Late Paleozoic.
This population is mostly present in the younger metasediments of the Famatina System and the Frontal Cordillera, yet is by definition absent from older Grenville-aged basement rocks of the Western Sierras Pampeanas (Fig. 7). Although we do not have spectra for the Middle-Late Paleozoic (Silurian-Permian) units exposed immediately west of the study area (Precordillera), it is likely that those...
rocks are also rich in this population, because they sourced sediments from the eroding Famatinian arc. Of course, zircons of this age can also be sourced directly from granitoids currently exposed in the Famatinian System, although our methods do not allow discrimination of first-vs. second-cycle zircons.

The remaining four age intervals represent minor, but persistent components of the zircon spectra (Figs. 8 and 9). They are all <360 Ma and, thus, can only be sourced from the western part of the study area. Early Carboniferous zircons (∼360–320 Ma) are sourced from the Carboniferous-Permian strata directly north and west of the study area, which includes numerous volcanicogenic intervals from ∼348 to 340 Ma (Fig. 1). Permian-Triassic ages (∼305–238 Ma) are a minor, yet persistent component that can only be sourced from western batholiths, such as the Colangulí Batholith or Montosa–El Potro complex (Fig. 1B) and probably from Del Penón-Santo Domingo area (Caminos, 1972; Caminos et al., 1979; Coughlin, 2000). Likewise, Cretaceous-Paleocene ages (∼75–55 Ma) can only be sourced from volcanic rocks exposed near the crest of the Frontal Cordillera and the western part of Precordillera (Santo Domingo area; Caminos et al., 1979). Finally, Late Cenozoic ages from ∼38 to 1 Ma are sourced from the northwestern part of the study area, where they are widely exposed today (Goss et al., 2013; Kay et al., 2013).

5.3. Changes in U-Pb spectra over time

Based on the persistent presence of the <360-Ma age populations described above, a major conclusion is that the Toro Negro Formation had a continuous source of sediment from the north and west. This provenance determination supports the conclusions of Ciccioli et al. (2014a) that sediments were primarily derived from the Toro Negro Range and Frontal Cordillera-Precordillera (Fig. 1). No age populations in the zircon spectra require a sediment supply from the east or south, although they do not preclude contributions from these areas given strongly overlapping age spectra between the source regions. Although all spectra have important Ordovician-Silurian “Famatinian” peaks, it is likely that these peaks are derived from the ubiquitous Silurian-Ordovician meta-sedimentary and Late Paleozoic sedimentary units to the north and west of the basin. A second conclusion is that the first-order lithologic makeup of the source area has remained relatively constant over time. There are few major changes in the zircon spectra that require the addition or subtraction of unique source areas, although this consistency does not preclude the growth and erosion of thrust sheets or basement blocks.

Despite the lack of major changes, subtle shifts in the proportions of age populations (Figs. 6 and 8) support the idea of an increasing contribution from the Precordillera and Frontal Cordillera (Fig. 1A) during DSII and III. For example, DSII (samples V7 and V9) is distinguished from DSII (V11-V17) by relatively smaller proportions of Mesoproterozoic, Early Carboniferous, and Permo-Triassic zircons, which have important sources in the Precordillera and Frontal Cordillera to the west (Martina et al., 2011). Interestingly, the Early Carboniferous age peak seems to get systematically older with time, perhaps recording the progressive erosional unroofing of a volcaniclastic succession spanning roughly 325–355 Ma in age. Several unusual Cambrian age peaks in DSII (V7–V9) from 490 to 535 Ma are not found in younger DSII or III samples; although their source is unclear, they probably come from the Toro Negro region to the north. Similar ages were obtained by Grissom et al. (1998) for a mafic–ultramafic complex in the Fiambalá range. Likewise, the DSII spectra contain a unique “shoulder” of Latest Silurian to Earliest Devonian zircons (∼420–406 Ma), whose origin is unclear, but are likely associated with the Paleozoic strata of the northern Precordillera, e.g., the Punilla and Jagüé formations.

6. Conclusions

This study presents new U-Pb zircon ages on volcanic tephra that constrain the duration of previously described unconformities in the Toro Negro Formation of NW Argentina. The basal unconformity likely occurred during the latter portion of an interval spanning a 9.4–6.9 Ma (Late Miocene) window, followed by a period of very rapid sedimentation rates (∼1.2 mm/yr) from 6.9 to 6.1 Ma, which occurred as the Toro Negro sediments rapidly filled paleo-valleys carved in the underlying Vinchina Formation. The basal unconformity is synchronous with an unconformity in synorogenic strata of the Sierra de Famatina about 50 km to the east, suggesting they may record a common tectonic forcing mechanism, such as reactivation of regional basement structures. In contrast, the DSII-II unconformity occurred between ~6.9 and 6.2 Ma and must have been short lived based on the extremely rapid sedimentation rate through this interval. Sedimentation rates then dropped nearly 5 fold to ∼0.3 mm/yr from ~6.1 to 5.0 Ma, followed by the DSII-III unconformity, which occurred during the earlier portion of the 5.0–3.0 Ma (Early Pliocene) window and likely spans ~1 Myr. The uppermost Toro Negro Formation accumulated rapidly (∼0.6 mm/yr) and is capped by Pleistocene gravels. These units are separated by an unconformity whose age lies between ~2.4 and 1.4 Ma.

Detrital U-Pb zircon ages from the Toro Negro Formation reveal a diverse combination of age populations consistent with the wide range of source rocks exposed in the region. The detrital zircon spectra support previous observations that sediments are primarily derived from the north and west, and that there are no major changes in sediment provenance within the entire Toro Negro Formation. Slight increases in Mesozoic, Permo-Triassic, Devonian and Carboniferous age populations are consistent with enhanced contributions from the west (Frontal Cordillera and Precordillera) during latest Miocene to earliest Pleistocene deposition (DSII and DSIII).

Acknowledgments

This research was supported by grants from the National Science Foundation (EAR-1148233, 1148268) as well as Argentine grants: UBACyT GC-3858A (Universidad de Buenos Aires), PICT 727/12, PICT 1963/14 (ANPCyT) and PIP 252 (CONICET). Thanks to Drew Gorin, Perri Silverhart, and Louise McCarren for field, lab, and nutritional assistance.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2016.05.013.

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