Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2010, v. 80, 750–762
Research Article
DOI: 10.2110/jsr.2010.064

UPPER OLIGOCENE CONGLOMERATES OF THE ALTIPLANO, CENTRAL ANDES: THE RECORD OF DEPOSITION AND DEFORMATION ALONG THE MARGIN OF A HINTERLAND BASIN

ANDREW L. LEIER,[1] NADINE McQUARRIE,[2] BRIAN K. HORTON,[3] AND GEORGE E. GEHRELS[4]
[1]*Department of Geoscience, University of Calgary, Calgary, Alberta T2N 1N4, Canada*
[2]*Department of Geosciences, Princeton University, Princeton, New Jersey 08544, U.S.A.*
[3]*Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, 78712 U.S.A.*
[4]*Department of Geosciences, University of Arizona, Tucson, Arizona 85721 U.S.A.*
e-mail: aleier@ucalgary.ca

ABSTRACT: **The Altiplano Plateau is a high-elevation, internally drained basin located in the hinterland of the Central Andean fold-thrust belt of Bolivia. Cenozoic strata exposed along the margins of the basin provide a unique record of deposition and deformation in this region and can also be applied to understanding synorogenic sedimentation in other fold-thrust belts. We examined Oligocene conglomerate units deposited along the margin of the nascent Altiplano in an effort to better understand how this large hinterland basin has evolved, and examine the relationship between upper crustal deformation and sedimentation in the interior of the Central Andean fold-thrust belt. Facies associations indicate initial deposition occurred in alluvial-fan and braidplain settings, and growth strata in these units record syndeformational deposition. Facies associations in overlying units contain a greater proportion of fine-grained material and were deposited in isolated fluvial channels surrounded by well drained-floodplain deposits. These units are less deformed relative to the alluvial-fan and braidplain deposits, suggesting that deformation waned as deposition continued. Clast counts and paleocurrents indicate that much of the Oligocene sediment was locally derived from Paleozoic strata and deposited in semi-isolated basins located between major thrusts and folds. Uranium-lead ages of detrital zircons from the conglomerate beds correspond to those from surrounding Paleozoic strata, supporting the hypothesis that most of sediment in the Oligocene conglomerate beds were derived directly from these older units. The youngest population of detrital zircon ages in the conglomerate beds are identical to the inferred ages of the deposits themselves. Collectively, the data indicate that the eastern margin of the Altiplano during Oligocene time was dominated by active upper crustal deformation, with alluvial-fan and braidplain deposition occurring in topographic lows. As deformation waned, deposition shifted from alluvial fans to isolated fluvial channels surrounded by extensive floodplains. In the regional setting, Upper Oligocene sediments exposed along the eastern margin of the Altiplano represent the remnants of a feeder zone to large fluvial distributary systems that occupied and infilled the center of the Altiplano.**

INTRODUCTION

Large hinterland basins are an important and increasingly recognized subset of sedimentary basins (Horton in press). Located in the elevated interior of fold-thrust belts, these basins provide an unparalleled record of sedimentation, tectonics, magmatism, and surface uplift in convergent orogens. Examples of these basins can be found around the world, in both modern (e.g., Inter-Andean Valley of Ecuador; Magdalena Valley Basin of Columbia; Horton in press) and ancient settings (e.g., Bowser Basin of Canada; Evenchick et al. 2007). Despite the unique and important sedimentary record in these basins, the formation and evolution of these areas remain poorly understood.

The Altiplano Plateau in the Central Andes is arguably the best example of a hinterland basin (Fig. 1). Although referred to as a plateau owing to its high elevation (~ 4 km) and low relief (Isacks 1988), in terms of sedimentary dynamics the Altiplano is more aptly characterized as a large basin. A significant (~ 200 km) eastward jump in thrust-belt activity in the Central Andes at ca. 40 Ma effectively segmented the existing foreland basin and created the nascent Altiplano as a large, internally drained basin within the fold-thrust belt (McQuarrie et al. 2005). During most of the Cenozoic Era, this area, which is today bordered on the west by a modern volcanic arc and on the east by deformed Paleozoic rocks of the Central Andean fold-thrust belt, has been a repository for synorogenic sediments. Cumulative thicknesses of Cenozoic strata in some areas of the Altiplano exceed 12 km (Horton et al. 2001).

In this paper we describe the sedimentology, stratigraphy, provenance, and basin history of upper Oligocene conglomerate units that were deposited along the eastern margin of the Altiplano in response to upper crustal deformation (Fig. 2). Interpretations are based on detailed measured sections, paleocurrent measurements, newly mapped stratigraphic and structural relationships, and provenance data, including ~ 1000 conglomerate clast counts and > 1000 detrital zircon U-Pb ages. Our results indicate that sediments were derived from a series of west-verging folds and thrust faults (backthrust belt) that created the eastern topographic barrier of the Altiplano Plateau and divided the internally drained plateau from the foreland basin to the east (Fig. 1). The sediments are generally coarse grained (pebble to boulder conglomerate beds) and were deposited in localized alluvial fans and fluvial braidplain settings in semiarid environments. Growth strata in several of the exposures indicate syndeformational deposition, and provenance analysis

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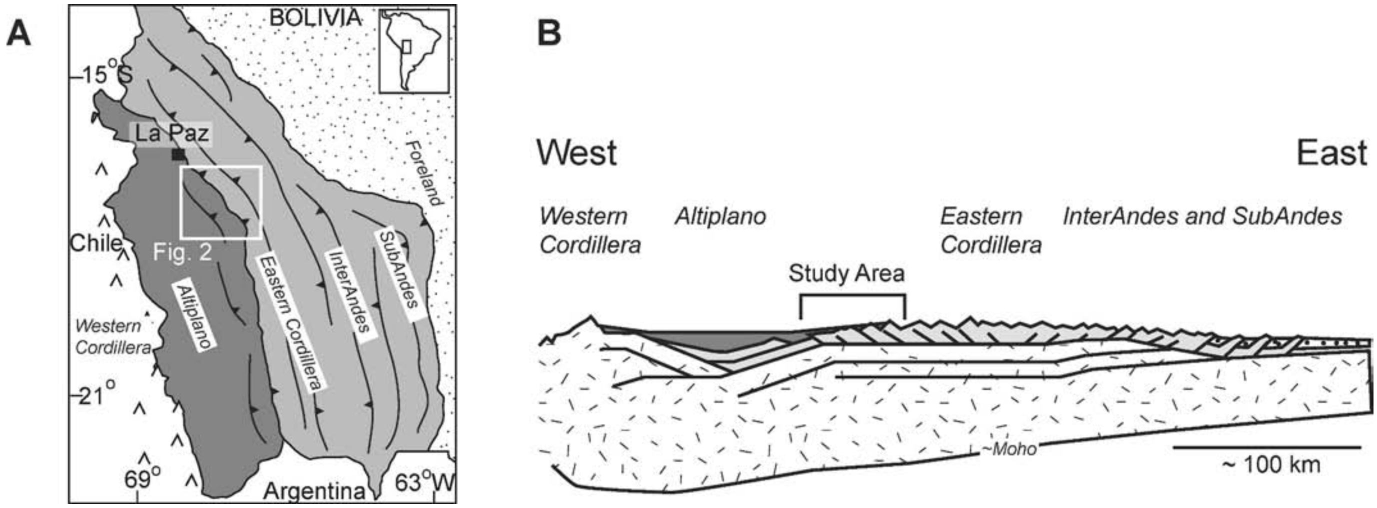


FIG. 1.—Location map and tectonic zones of the Central Andes. **A)** Location map of study area showing the tectonic zones discussed in text. The Altiplano is shown in dark gray, the fold-thrust belt is in light gray, and the foreland in white. Location of Figure 2 is shown with a white box. **B)** Schematic crustal-scale cross section through the Central Andes. The Altiplano is located between the Western Cordillera (modern arc) and the Huarina backthrust belt (west-vergent structures) of the Eastern Cordillera.

indicates that sediments were derived from Paleozoic-age units exposed in hanging walls of adjacent thrust faults. Instead of a spatially continuous zone of deposition, the sediments were deposited in a series of semicontinuous minibasins situated between thrust faults and folds. The sedimentary strata in these basins represent the proximal portion of a larger sedimentary system wherein clastic material was derived from topography in the east, transported to the west, and deposited in the central Altiplano by fluvial distributary fans.

REGIONAL GEOLOGY

Tectonic and Structural Setting

The Altiplano is one of several tectonomorphic zones in the Central Andes (Fig. 1). From west to east, the Central Andes can be divided into the Western Cordillera (magmatic arc), the Altiplano (high-elevation plateau and basin), the Eastern Cordillera (interior portion of the fold-thrust belt), and the Interandean and Subandean zones (younger, currently active portions of the fold-thrust belt). Deformation began in the Central Andean retro-arc fold-thrust belt by Late Cretaceous time (Coney and Evenchick 1994; Sempere et al. 1997; DeCelles and Horton 2003; McQuarrie et al. 2005) and migrated cratonward (eastward) such that by late Eocene time folding and thrust faulting were occurring in areas of the Eastern Cordillera (Horton 1998; DeCelles and Horton 2003). From ca. 15 Ma to the present, shortening in the Central Andes of Bolivia has been accommodated primarily by crustal deformation in the Subandean zone, with additional minor deformation occurring in the Altiplano between ca. 15 and 10 Ma (Lamb and Hoke 1997; McQuarrie et al. 2005).

In this study we focus on the boundary between the folds and thrust faults of the Eastern Cordillera and the muted topography of the adjacent Altiplano (Figs. 1, 2). Whereas the Eastern Cordillera as a whole contains east-verging folds and thrust faults, the folds and faults in our study area are typically west-vergent, and constitute what is called the Huarina backthrust belt (Sempere et al. 1990). The Huarina backthrust belt deforms Paleozoic-age shale and sandstone with lesser amounts of Mesozoic-age sandstone and limestone (Roeder 1988; Sempere et al. 1990; McQuarrie and DeCelles 2001; Gillis et al. 2006). Based on thermochronology data, structural relationships, and the age of overlapping undeformed strata, deformation in the Huarina backthrust belt is thought to have begun by Eocene time and ceased by early to middle Miocene time (MacFadden et al. 1985; Sempere et al. 1990; McQuarrie 2002; Gillis et al. 2006). Upper Oligocene and Miocene strata contain evidence of syndepositional and postdepositional deformation; however, reconstructions of the Huarina backthrust belt indicate that most of the upper crustal deformation occurred prior to late Oligocene time (Sempere et al. 1990; McQuarrie and DeCelles 2001).

Stratigraphy

Paleogene conglomerate beds are exposed in multiple locations in the eastern portion of the Altiplano and the western margin of the Eastern Cordillera (Figs. 1, 2). These units are variously named the Luribay Conglomerate, the Peñas Conglomerate, and the Bolivar Formation, among others (Sempere et al. 1990; Marshall et al. 1992; Geobol 1997; Horton et al. 2001). To avoid confusion, we will refer to these beds collectively as "Oligocene conglomerate units" unless otherwise necessary. The Oligocene depositional age assigned to these units is based on Ar-Ar and magnetostratigraphy ages of ca. 29 Ma from beds in conformably overlying strata (MacFadden et al. 1985; McRae 1990; Kay et al. 1998; Gillis et al. 2006).

Oligocene conglomerate units overlie an unconformity, beneath which lie strata that range in age from Cretaceous to Ordovician (Figs. 2, 3). Jurassic and Cretaceous strata are present locally and together are 100 to 500 m thick. Jurassic strata consist of an eolianite sandstone unit, whereas the Cretaceous strata consist of mudstone, local sandstone units, and shallow marine limestone beds (Geobol 1997). Carboniferous and Permian strata are generally limited to the western portion of the study area near Coro Coro, and consist of approximately 300 m of siltstone, sandstone, and minor limestone. The greater part (> 7 km) of the Paleozoic strata consist of Ordovician, Silurian, and Devonian units, which are dominantly mudstone, siltstone, and thin beds of very fine- to fine-grained sandstone (McQuarrie and DeCelles 2001). The Devonian strata also contain a distinct fine- to medium-grained red sandstone unit called the Villa Villa Formation (Geobol 1997).

Oligocene conglomerate units in multiple locations display growth strata (Fig. 3), indicating syndepositional deformation (e.g., Riba 1976). However, these conglomerate beds are conformably overlain by relatively

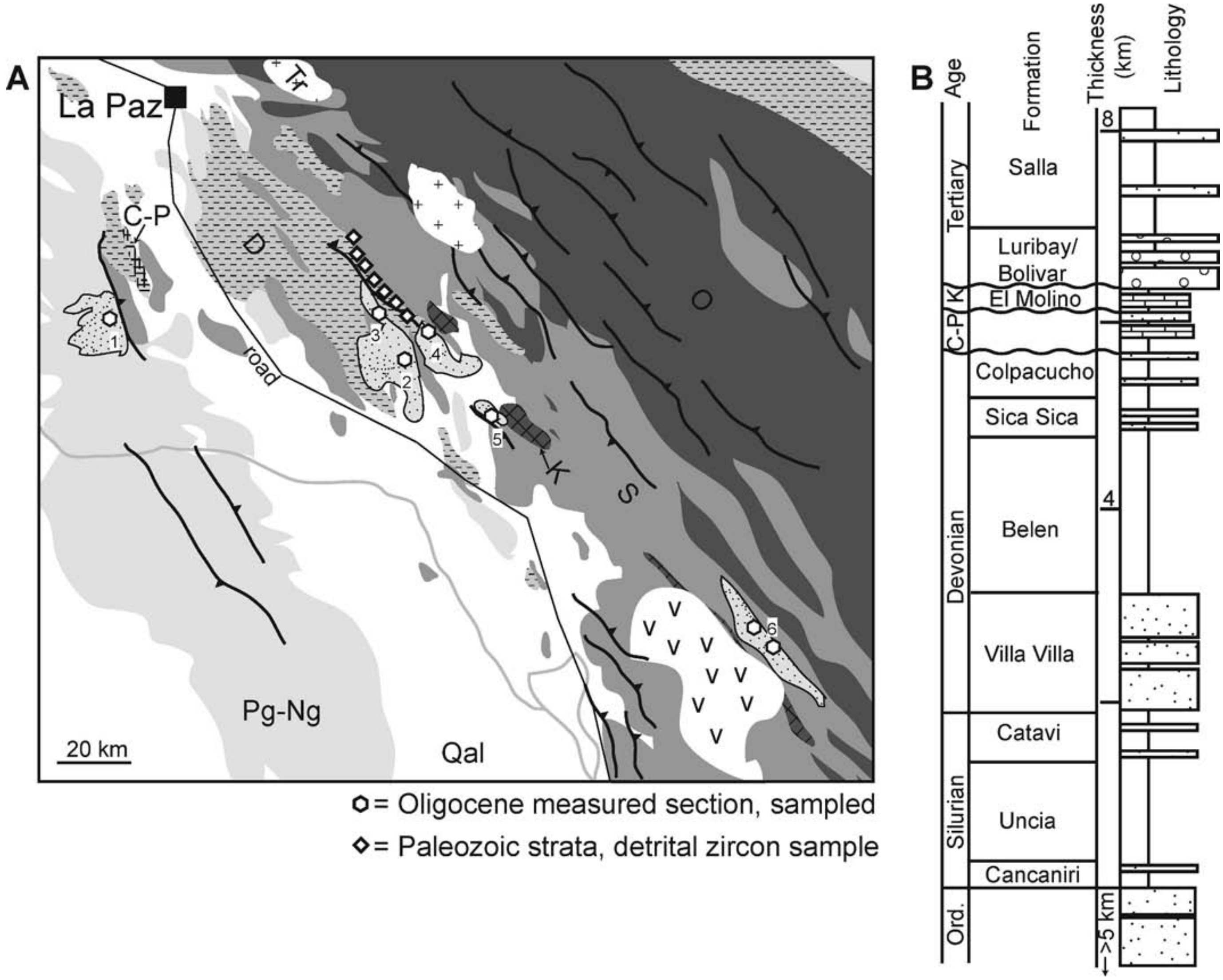


FIG. 2.—Geology of the study area and stratigraphy in the region. **A)** Simplified geologic map of the study area showing lithologic units and prominent structural features. White hexagons mark specific study locations, and diamonds mark locations where samples of Paleozoic strata were sampled. Upper Oligocene exposures are denoted by Pg-Ng and have black outlines. Locations: 1 = Coro Coro, 2 = Salla, 3 = Luriaby, 4 = North Puchuni, 5 = South Puchuni, 6 = Bolivar. Qal = Quaternary alluvium; Pg-Ng = Paleogene–Neogene sedimentary strata; V = Cenozoic volcanic strata; K = Cretaceous sedimentary strata; Tr = Triassic granite; C-P = Carboniferous–Permian sedimentary strata; D = Devonian sedimentary strata; S = Silurian sedimentary strata; O = Ordovician sedimentary strata. **B)** Stratigraphy in the region with general thickness and lithology. Stippled pattern = sandstone; white = mudstone; brick = limestone; large circles = conglomerate.

undeformed mudstone and sandstone beds, such as those of the Salla Beds (Fig. 3; MacFadden et al. 1985; McRae 1990). These finer-grained units, which are ca. 24–29 Ma in age, postdate most of the upper-crustal deformation in the region (MacFadden et al. 1985; Sempere et al. 1990; Geobol 1997).

METHODOLOGY

This study focuses on six locations: the Coro Coro, Salla, Luribay, North Puchuni, South Puchuni, and Bolivar areas (Fig. 2). Each location contains several specific study sites, where sections were measured and the geology of the region mapped at 1:25,000 scale. To simplify the presentation of the data we will typically refer to the general locations, rather than individual sites, unless information from a specific study site is noteworthy.

Sedimentology and Paleocurrent Data

Detailed sections were measured at each study site, where observations of sedimentary features were made and samples collected. In addition, paleocurrent data were obtained in order to reconstruct sediment provenance, sediment pathways, and paleogeography. Paleocurrent data consist of measurements taken on *a–b* planes of imbricated clasts in conglomerate beds. All data were rotated to horizontal using standard stereonet techniques.

Analysis of Detrital Zircons

We collected four samples from Oligocene conglomerate beds and seven from Paleozoic strata in the surrounding area for detrital-zircon uranium-lead (U-Pb) geochronology (Fig. 2). Individual samples were

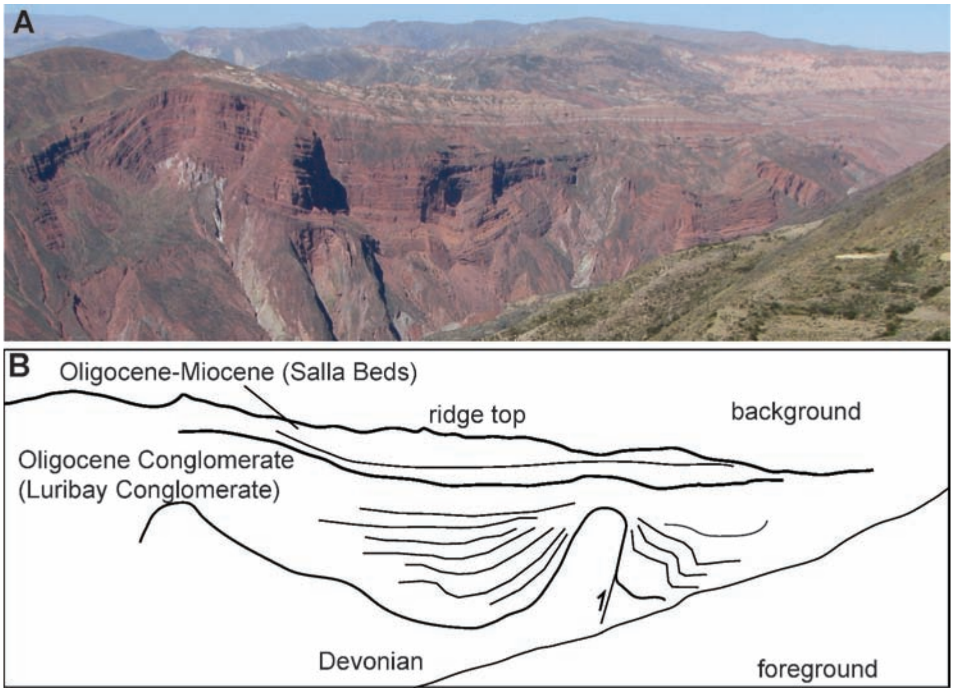


FIG. 3.—Cenozoic strata in the study location. **A)** Photo of Oligocene conglomerate units, including growth strata in the lower portion of the succession. Overlying Salla Beds are less deformed than the lowermost strata. **B)** Pencil drawing of the above photo, highlighting features.

processed with standard crushing and pulverizing procedures followed by density and magnetic separation. Uranium-lead geochronology of detrital zircons extracted from the samples was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the University of Arizona LaserChron Center. The analyses involve ablation of zircon with a laser using a spot diameter of 10–50 microns. Detailed descriptions of the processing and analytical methods are presented in the Appendix (See Acknowledgments section for URL.)

Clast Counts

Nearly 1000 clasts were described and recorded at ten stratigraphic sites. At each site, approximately 100 clasts were selected using a 10 cm by 10 cm grid. Several of the potential source units for the clasts have similar lithologies; therefore, clasts were initially divided into categories based on descriptive properties. However, several clast types have characteristics that can be attributed to specific formations (e.g., red sandstone of the Devonian Villa Villa Formation), and in such cases the interpreted provenance unit was identified. Provenance interpretations were further supported by the identification of potential source units made during geological mapping of the area.

SEDIMENTOLOGY, STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS

Facies

Clastic strata in the Oligocene conglomerate units are divided into nine facies, which are described and interpreted in Table 1. The following paragraphs focus on three genetically related facies associations that can be interpreted in the context of depositional systems.

Facies Associations

Matrix-Supported and Clast-Supported Conglomerate; Description.— The matrix-supported and clast-supported conglomerate facies association consists of beds of matrix-supported conglomerate, clast-supported conglomerate, and minor massive sandstone and mudstone (Fig. 4). The matrix-supported conglomerate beds have pebble- to cobble-size clasts and rare boulder-size clasts, all of which are typically in a muddy-sandstone matrix (Facies G4). Clast-supported conglomerate beds have pebble- to cobble-sized clasts that are poorly sorted and generally randomly oriented (Fig. 4; Facies G3). Rare, poorly developed horizontal stratification is present in these beds at some locations. Clasts in both the matrix-supported and clast-supported conglomerate are typically angular to subangular (Table 1). Sandstone and mudstone beds are rare, but where present are massive, poorly sorted, and commonly contain isolated pebbles and granules (Facies S4, F1). Traction-transport structures in the conglomerate, sandstone, and mudstone beds are absent. Bedding thicknesses in this facies association vary but are commonly between 0.5 and 2.0 m, and individual beds have non-erosional bases and tabular geometries.

With respect to the larger-scale architecture and stratigraphic relationships, the matrix-supported and clast-supported facies association is present in limited locations, where present these deposits are located at the base of the Oligocene succession, unconformably overlying Paleozoic strata (Fig. 3). The matrix-supported and clast-supported conglomerate facies association is occasionally interstratified with the clast-supported conglomerate and sandstone facies association (described below). Growth strata in this facies association occur in several locations (Fig. 3).

Matrix-Supported and Clast-Supported Conglomerate; Interpretation.— The matrix- and clast-supported conglomerate facies association is interpreted as deposits of debris flows and high-sediment-concentration water flows in an alluvial-fan setting (e.g., Blair and McPherson 1994). The matrix-supported conglomerate beds are interpreted as debris-flow deposits based on the matrix-supported clasts, which suggests a cohesive-plastic flow (Nemec and Steel 1984), and the absence of basal scours, suggesting laminar flow (Table 1). The clast-supported conglomerate beds are interpreted as deposits of high-sediment-concentration flows. These beds display clast support and are better organized than the aforementioned matrix-supported conglomerate beds, but they lack structures and stratification indicating fluid traction transport. Flows with high sediment concentration (i.e., hyperconcentrated flow) transport clasts by buoyancy forces, dispersive pressure, and traction shear stresses,

TABLE 1.—*Table of facies, their description, and paleoenvironmental interpretation. Individual facies are also described in the context of facies associations in the text.*

Facies	Lithology/Bedding	Structures	Additional	Processes/Environment
F_1	Red, pink, tan, muddy siltstone. Bedding thickness varies from 0.1 m to > 2 m.	Massive; root traces; horizons of different colors; occasional mottled texture.	Occasional calcium carbonate nodules present.	Relatively low-energy, subaerial setting with vegetation. Interpreted as a paleosol. Precipitation likely less than 60 cm/yr.
S_1	Red- to buff-colored very fine- to fine-grained, moderately well sorted sandstone. Beds typically between 3 cm and 10 cm thick.	Asymmetric ripples and ripple cross-lamination.		Unidirectional current. Lower-flow-regime conditions. Migration of ripples.
S_2	Red- to buff-colored very fine- to coarse-grained, moderately well sorted sandstone. Beds typically between 5 cm and 1 m thick.	Plane-parallel lamination. Rare bioturbation in the upper part of some beds.	Rare granule-size material in the beds.	Unidirectional current. Plane-bed, critical flow.
S_3	Red- to buff-colored fine- to very coarse-grained, moderately to poorly sorted sandstone. Beds typically between 0.1 and 1 m thick.	Trough-cross stratification.	Granule and pebble-size material common.	Unidirectional current. Migration of 3-D dunes.
S_4	Red- to buff-colored very fine- to very coarse-grained, moderately to very poorly sorted sandstone. Beds between 5 cm and 0.5 m thick.	Massive. Unidentifiable bioturbation common.	Occasional faint, partial, laminations present. Rare granule and pebble-sized material in some beds.	Original bedding and sedimentary structures destroyed by bioturbation. Indicates periods of no sedimentation when organisms reworked deposits. Beds with granule- and pebble- size material may be deposits of high-sediment-concentration flows.
G_1	Red-, brown-, buff-colored clast-supported pebble to cobble conglomerate. Beds between 0.2 and 1 m thick.	Clasts are imbricated and bedding is well defined. Rare discontinuous lenses of very coarse- or granule-sandstone interbedded.	Slight normal grading in occasional beds. Irregular scours at the base of some beds.	Deposited under traction transport by low-relief gravel bedforms or as lag deposits. Rare, discontinuous sandstone lenses suggest fluctuations in flow conditions.
G_2	Red-, brown-, buff-colored clast-supported pebble to cobble conglomerate. Beds between 0.5 and 2 m thick.	Trough cross-stratification. Rare planar cross-stratification. Occasionally contains imbricated clasts. Rare, discontinuous sandstone interbeds.	Irregular, erosional scours at the bases of the beds. Occasional normal grading.	Deposited under unidirectional flow and traction transport by migrating 3-D (trough cross-strata) and rare 2-D (planar cross-strata) gravel bedforms.
G_3	Variably colored pebble to cobble clast-supported conglomerate. Beds between 0.2 and 2 m thick.	Deposits are occasionally crudely bedded, commonly disorganized with clasts randomly oriented. Rare boulder-size clasts.	Typically no grading. Beds are generally laterally continuous with little evidence of erosion at base.	Noncohesive, clast-supported debris-flow or high-sediment- concentration-flow deposits. Possible traction-transport deposit (fluid flow) under relatively rapid sedimentation rates. Possible gravity-density deposit partially reworked by subsequent flows.
G_4	Red-, brown-, buff-colored matrix-supported pebble to cobble conglomerate. Beds between 0.5 and 2 m thick.	Clasts randomly oriented. Matrix composed of muddy-sandy material. Rare boulder-size clasts.	No grading. Beds have little to no evidence of erosion at bases.	Cohesive-debris-flow deposit.

which yield massive or crudely stratified deposits (Nemec and Steel 1984; Costa 1988). The poorly sorted, massive sandstone and mudstone facies are interpreted as high-sediment-concentration flows. The lack of channel forms or scours at the bases of beds indicates unconfined flow, and the angularity of the clasts suggests small transport distances. Collectively, these features indicate an alluvial-fan depositional setting. The presence of growth strata in this facies association indicates that deposition of these stratigraphic units was coeval with upper crustal deformation (Fig. 3).

Clast-Supported Conglomerate and Sandstone; Description.—The clast-supported conglomerate and sandstone facies association consists of clast-supported pebble- to cobble-conglomerate beds and medium- to very coarse-grained sandstone units (Fig. 4). Conglomerate beds are characterized by well-defined bedding, moderate sorting, imbricated clasts, and rare normal grading (Facies G1). Clasts are typically subangular. Bedding surfaces commonly truncate the upper portions of underlying beds. Individual conglomerate beds are normally < 0.75 m thick, extend laterally for tens to hundreds of meters, and commonly have broadly lenticular geometries. Poorly developed trough cross stratification is present in rare beds (Facies G2); clast-supported conglomerate beds with non-imbricated clasts are present at several locations (Facies G3). Clast compositions and angularity vary between locations (see provenance below). The conglomerate beds are associated with moderately well-sorted to poorly sorted, medium- to very coarse-grained sandstone beds with trough cross stratification (Facies S3) and plane-parallel lamination (Facies S2). These beds are commonly lenticular, laterally discontinuous, and truncated by the basal scour surfaces of the overlying beds. Localized laminae of granule- and pebble-size material in the sandstone beds are common.

This facies association is present in almost all of the study sites and in this regard is the most common of the facies associations. In terms of its stratigraphic position in the Oligocene succession, the clast-supported conglomerate and sandstone facies association commonly overlies the matrix-supported and clast-supported conglomerate facies association (described above) and is in turn overlain by the conglomerate lenses and mudstone facies association (described below). Thicknesses of this facies association vary considerably but

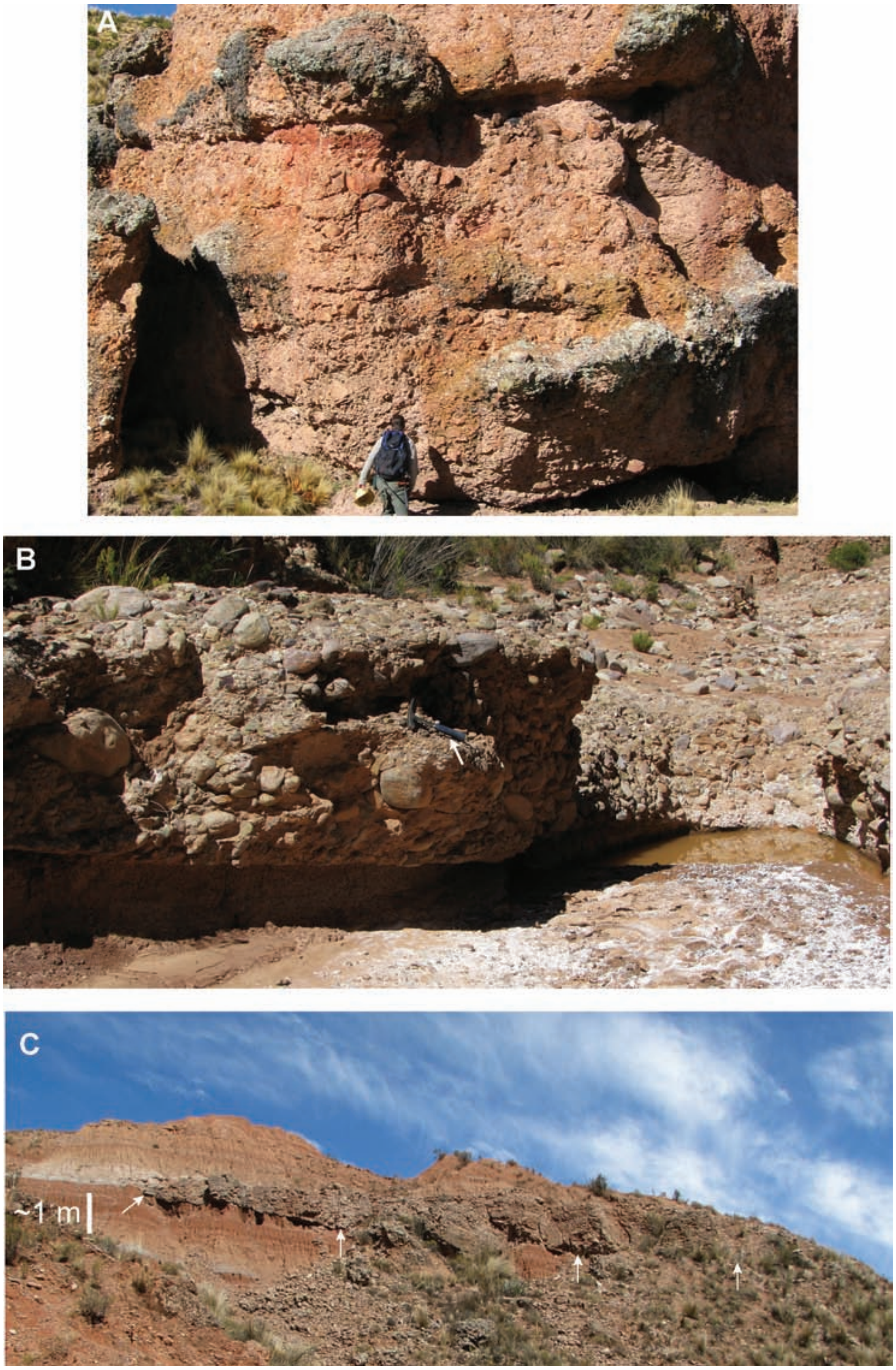
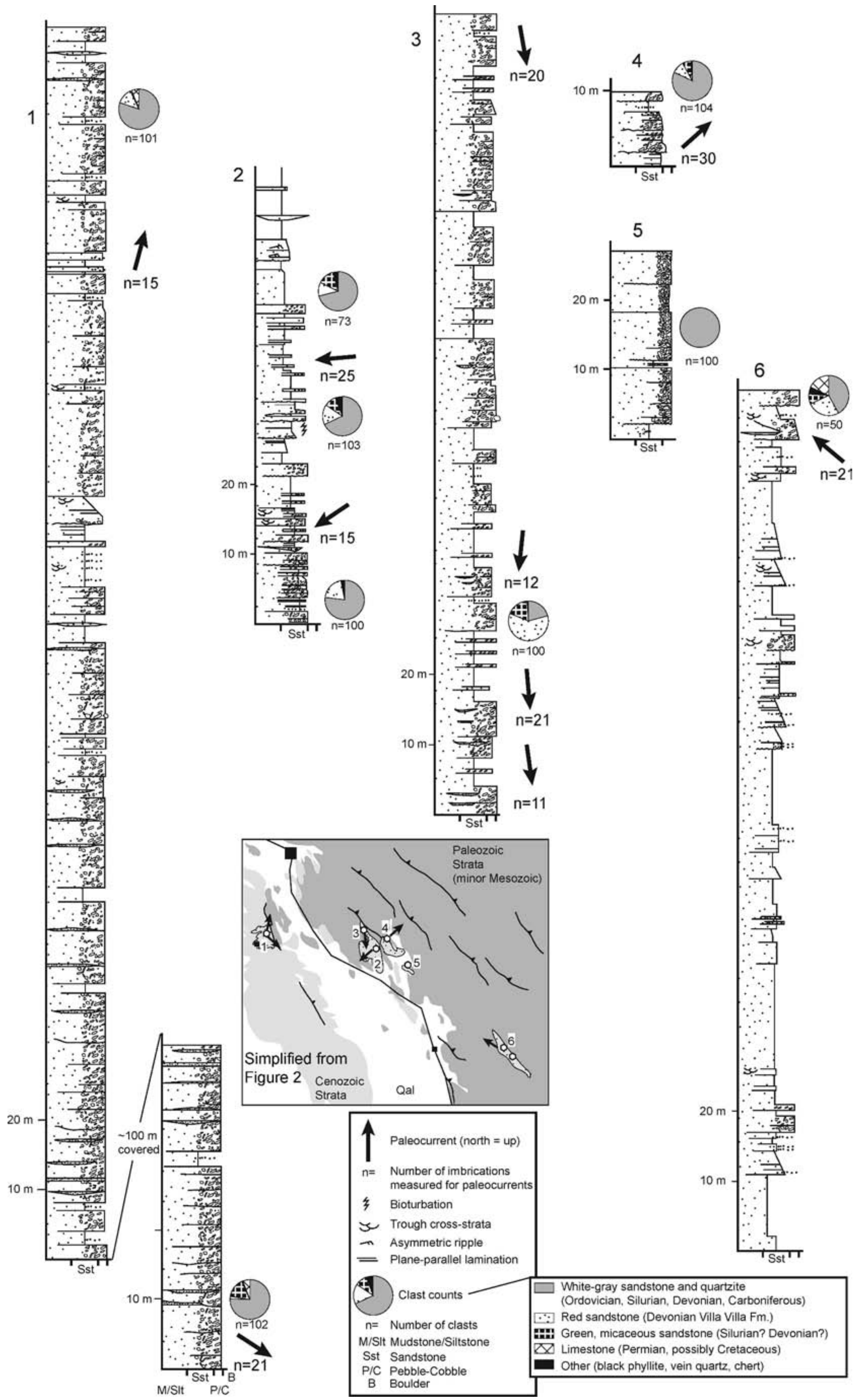


FIG. 4.—Photos of lithologies in the upper Oligocene succession. **A)** Massive beds of matrix-supported and clast-supported conglomerate beds typical of the lowermost beds in the Oligocene succession. Person for scale. **B)** Clast-supported cobble conglomerate beds dipping gently into the photo and to the right. These beds are common throughout the succession. Hammer is highlighted by arrow for scale. **C)** Conglomerate lens in muddy siltstone. Arrows highlight the base and edge of the conglomerate lens. Surrounding finer-grained deposits are interpreted as paleosols.

are typically between 20 and 150 m. The thickest continuous section of this facies association occurs in the Coro Coro area (Fig. 5). Whereas individual beds in the clast-supported conglomerate and sandstone facies tend to be laterally discontinuous, outcrops of the overall facies association persist for distances > 2 km.

Clast-Supported Conglomerate and Sandstone; Interpretation.—The clast-supported conglomerate and sandstone facies association is interpreted to have been deposited by migrating bedforms in wide, relatively shallow, fluvial channels in a braidplain setting (e.g., Blair and McPherson 1994). The imbrication, clast support, and rare sedimentary structures in the pebble–cobble conglomerate beds indicate traction transport of gravel in barforms (Costa 1988). The trough cross-stratified sandstone beds were deposited by migrating 3-D dunes, and the plane-parallel-laminated beds were deposited under upper flow regime conditions (e.g., Paola et al. 1989). The erosional bases and lenticular geometry of the beds in this facies association suggest turbulent, channelized flow. The high width/thickness ratios of the sandstone units and the absence of significant relief along basal scour surfaces suggest wide, shallow channels. Moderate to poor sorting, coarse clasts, and lack


1
n=101
n=15
20 m
10 m
Sst
~100 m covered
10 m
n=102
n=21
M/Slt
Sst
P/C
B
2
n=73
n=25
n=103
20 m
n=15
10 m
n=100
Sst
3
n=20
n=12
n=100
20 m
n=21
10 m
n=11
Sst
4
10 m
n=104
n=30
Sst
5
20 m
n=100
10 m
Sst
6
n=50
n=21
20 m
10 m
Sst
Paleozoic Strata (minor Mesozoic)
Simplified from Figure 2
Cenozoic Strata
Qal
Paleocurrent (north = up)
n= Number of imbrications measured for paleocurrents
Bioturbation
Trough cross-strata
Asymmetric ripple
Plane-parallel lamination
Clast counts
n= Number of clasts
M/Slt Mudstone/Siltstone
Sst Sandstone
P/C Pebble-Cobble
B Boulder
White-gray sandstone and quartzite (Ordovician, Silurian, Devonian, Carboniferous)
Red sandstone (Devonian Villa Villa Fm.)
Green, micaceous sandstone (Silurian? Devonian?)
Limestone (Permian, possibly Cretaceous)
Other (black phyllite, vein quartz, chert)

of grading in several beds suggests that some of the sediments were deposited rapidly, possibly during flood events (e.g., DeCelles et al. 1991).

Conglomerate Lenses and Mudstone; Description.—The conglomerate lenses and mudstone facies association consists of clast-supported pebble-cobble conglomerate and minor sandstone units, both of which are enveloped in mudstone. The conglomerate beds typically contain imbricated clasts (Facies G1) with rare cross-stratification (Facies G2) and normally graded beds. Sandstone beds are most commonly associated and interbedded with conglomerate units. The sandstone beds consist of medium to very coarse grains and often include granule and pebble horizons. Sedimentary structures in the sandstone units include plane-parallel laminae (Facies S2) and trough cross stratification (Facies S3). Rarely, thin to medium thickness sandstone beds are interstratified with mudstones. In such locations, the sandstone beds are typically medium- to fine-grained, contain ripple cross laminae (Facies S1), or are bioturbated and massive (Facies S4). Mudstone units are typically clayey siltstone, red to tan in color, and massive, and contain calcium carbonate nodules and rhizoliths (Facies F1).

The conglomerate lenses and mudstone facies association commonly constitutes the uppermost portion of the Oligocene succession and grades conformably into the finer-grained overlying deposits (e.g., the Salla Beds; Fig. 3). Conglomerate and associated sandstone units in this facies association are lensoid in shape and surrounded by mudstone. The coarse-grained intervals overlie irregular erosional surfaces that truncate beds in the underlying mudstone. Lateral margins of the conglomerate units can be steep, and vertical and lateral boundaries between the conglomerate beds and the surrounding mudstone beds are sharp (Fig. 4). Unlike the matrix-supported and clast-supported conglomerate facies association at the base of the succession, which contain growth strata, the beds of the conglomerate lenses and mudstone facies association are largely undeformed (Fig. 3).

Conglomerate Lenses and Mudstone; Interpretation.—The conglomerate lenses and mudstone facies association is interpreted as fluvial deposits, with the conglomerate and associated sandstone beds interpreted as deposits of paleochannels and the mudstone units interpreted as deposits of floodplain environments where pedogenic processes occurred. We interpret the sedimentology and two-dimensional fluvial architecture of this facies association as recording a fluvial system that was characterized by cut-and-fill processes. The sharp, erosional boundary at the bases and sides of the conglomerate and sandstone units, the pronounced change in grain size between the interpreted channel fills and the surrounding mudstone, and the absence of deposits typically associated with leveed paleoenvironments suggest that the channels were incised into the surrounding finer-grained material. The lack of lateral accretion sets in the conglomerate and sandstone units indicate non-migrating channels that had to have been infilled largely through vertical aggradation. The mudstone-surrounded, lensoid shape of the interpreted channel deposits indicate single channels with ribbon-like geometries (e.g., Schuster and Steidtmann 1987). With this interpretation, the channels would have initially been incised into the clays and silts of the floodplain environment and then infilled by the relatively coarse-grained sediment, followed by abandonment or avulsion to an alternative channel. Pedogenic carbonate nodules in the paleosols suggest that the region experienced semiarid conditions with precipitation < 500 mm/yr (Birkeland 1999). The flow of water in the interpreted channels may have been ephemeral, but this cannot be determined conclusively from the available data.

Summary of Deposition from Facies Analysis

The vertical arrangement of facies associations in the Oligocene conglomerate succession reflects an evolution of depositional settings through time. The matrix-supported and clast-supported conglomerate facies association and the clast-supported conglomerate and sandstone facies association, in the lowermost portion of the Oligocene succession, indicate that deposition was initially dominated by alluvial fans and braidplain systems. The fact that the matrix-supported and clast-supported conglomerate facies associations are not present at every study site suggests the alluvial fans were localized or removed by subsequent erosion. Growth strata in these deposits indicate that sedimentation was synchronous with active upper crustal deformation.

The change to the conglomerate lenses and mudstone facies association in the upper portion of the Oligocene conglomerate succession indicates that the alluvial fans and braidplain systems that initially dominated the area gave way to a depositional environment dominated by floodplains and rare fluvial channels. Additionally, the relatively undeformed nature of the beds in the upper portion of the succession suggest that the floodplain sediments and isolated gravel channels were deposited after most of the upper crustal deformation had ceased.

SEDIMENT PROVENANCE

Clast Counts

Coro Coro.—Conglomerate clasts at the Coro Coro location (location 1 of Figs. 2 and 5) are composed mainly of white-gray sandstone and lesser red sandstone and green micaceous sandstone. The red sandstone is interpreted to have been derived from the Devonian Villa Villa Formation, and the green micaceous sandstone is interpreted to be from either Silurian or Devonian strata (Fig. 5). Clasts in the Coro Coro location are notable for containing a population of carbonate lithologies, which are interpreted to have been derived from Permian units exposed in an adjacent thrust sheet to the east (Fig. 2).

Salla Area.—Conglomerate clasts in the Salla area are varied and consistent with Silurian and Devonian strata exposed in the immediate area (location 2 of Figs. 2 and 5). The majority of the clasts consist of white-gray, well-indurated sandstone, with lesser populations of red sandstone (interpreted to be from the Devonian Villa Villa Formation), and green micaceous sandstone (interpreted to be from Silurian or Devonian units).

Luribay.—Conglomerate beds in the Luribay location (location 3 of Figs. 2 and 5) are dominated by clasts of red sandstone, interpreted to have been derived from the Devonian Villa Villa Formation. The Villa Villa Formation is exposed in the hanging wall of a thrust fault located approximately 1 km to the east of the studied outcrop (Fig. 2; Geobol 1997).

Puchuni Area, North.—Conglomerate clasts in the northern part of the Puchuni area (location 4 of Figs. 2 and 5) are similar to those in the Salla area. The major constituent consists of white-gray sandstone and lesser

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FIG. 5.—Upper Oligocene measured sections, clast-count results, and paleocurrent measurements. Numbers refer to the locations on the inset map and are the same as those in Figure 2. Vertical scale is the same for all sections. Likely source lithologies for clasts are shown in parenthesis in the legend inset.

red sandstone and green micaceous sandstone clasts. These clast lithologies are consistent with the Silurian and Devonian units that are exposed in the vicinity.

Puchuni Area, South.—The conglomerate clasts in outcrop exposures south of the Puchuni area (location 5 of Figs. 2 and 5) consist entirely of white, well-indurated fine-grained sandstone, which are interpreted to have been derived from Silurian strata exposed in the hanging wall of a nearby thrust fault (Fig. 2; Geobol 1997).

Bolivar.—The conglomerate strata in the Bolivar area (location 6 of Figs. 2 and 5), contain several, evenly distributed clast populations. Similarly to the other locations, many of the clasts are white-gray sandstone, red sandstone, and green micaceous sandstone. Limestone clasts are abundant in the conglomerate units and were derived from either Permian or Cretaceous strata.

Paleocurrents

Paleocurrent measurements indicate that sediment transport directions were either parallel or perpendicular to the northwest–southeast structural trend (Fig. 5). In the Coro Coro, Luriaby, and Bolivar locations, the paleocurrent directions are parallel to the ~ north–south strike of the adjacent thrust faults and folds. The measurements in the Coro Coro area are directed to the southwest near the base of the succession and toward the northwest near the top. Paleocurrents in the Luribay area are consistently directed to the south–southeast, and the paleocurrent directions in the Bolivar area are directed to the northwest. In contrast, measurements in the Salla and North Puchuni areas are directed to the west and east, respectively, and perpendicular to the structural trend.

Based on the paleocurrent measurements, we reconstruct the Oligocene sediment transport pattern in the region to have been composed of axially flowing systems, which were fed by localized transverse-flowing systems. The transverse-flowing systems likely emanated from topography associated with upper crustal deformation, and debouched into the axially flowing systems, similarly to the pattern seen in many modern contractional areas (e.g., Jackson et al. 1996). The axially flowing systems would presumably have emptied into larger systems that would have flowed westward into the Altiplano basin (Hampton and Horton 2007).

Analysis of Detrital Zircons

Four samples from the Oligocene conglomerate units and 7 from Paleozoic strata in the Huarina backthrust belt were collected for provenance analysis using detrital-zircon U-Pb ages (Fig. 2). Detailed descriptions of the methodology used and all analytical data are reported in the Appendix. The U-Pb ages are shown on relative age-probability diagrams (Fig. 6) using the algorithms of Ludwig (2003).

Source-Area Samples

Potential sediment source units were sampled in the region and divided into three groups based on age and lithology: Upper Silurian–lowermost Devonian strata, the Devonian Villa Villa Formation, and uppermost Devonian and Carboniferous strata. The detrital-zircon ages in all of the sample groups are very similar (Fig. 6). Each group contains three prominent peaks of ca. 475, 520–590, and 620–650 Ma (Fig. 6). An additional peak of ca. 1050 Ma is also present in each of the samples. For complete zircon age data, please see the Appendix.

Oligocene Conglomerate Units

Oligocene conglomerate units contain several detrital-zircon age populations. All of the samples have peaks at ca. 460–480, 520–540, 620–640, and 1050 Ma (Fig. 6), which coincide with those from the underlying Paleozoic units. In addition, several of the samples contain populations with ages between 240 and 280 Ma. The sample from the Salla area contains the youngest zircons, and based on these yields a maximum depositional age of 28.3 ± 0.6 Ma (at 2-sigma, MSWD = 0.4). The sample from the Bolivar location contains detrital zircons with ages of 120–150 Ma. The sample from the Coro Coro location contains a population of detrital zircons with ages of ca. 1380 Ma, which are largely absent from the other locations. For the complete list of individual zircon age data, please see the Appendix.

Interpretations

The robust correlation between the age populations of detrital zircons from Paleozoic units with those from the Oligocene conglomerate units suggests that locally exposed Paleozoic strata were being eroded and the sediment redeposited during Oligocene time. This interpretation is consistent with the conglomerate clast counts (above), which also indicate that Paleozoic strata were an important sediment source during Oligocene time. Detrital zircon age populations of ca. 240–280 Ma from the Oligocene conglomerate units indicate that sediment was also derived from a Permo-Triassic source. Permo-Triassic plutons are located throughout the Cordillera of Bolivia, but whether the grains in the Oligocene strata are derived from these plutons directly or were recycled via post-Triassic strata cannot be determined at this time. Gillis et al. (2006) determined that significant exhumation occurred in some of these plutons during Eocene time, indicating that it is possible that the Permo-Triassic plutonic rocks were at the surface by Oligocene time. The sample from the Bolivar location contains a population of detrital zircons with ages between 120 and 150 Ma, which corresponds to Late Jurassic–Early Cretaceous igneous activity. The ca. 120–150 Ma detrital zircons in the Oligocene strata are interpreted to have been derived from Upper Jurassic–Lower Cretaceous strata and igneous units in the surrounding area (Geobol 1995).

The 28 Ma peak (composed of > 3 grains) from the Luribay Conglomerate in the Salla area is equal to its interpreted depositional age. These relatively young detrital zircons are likely derived from Oligocene plutonic rocks exposed in the immediate area or from volcanogenic sources (Gillis et al. 2006). Combining Ar-Ar ages and magnetostratigraphy, Kay et al. (1998) determined the Salla Beds, which conformably overlie the Luribay Conglomerate, were deposited between 29 and 24 Ma. This implies the uppermost portion of the Luribay Conglomerate was deposited at ca. 29 Ma. The detrital zircon peak at 28 Ma and the 29 Ma age at the base of the Salla Beds is virtually indistinguishable and any difference reconcilable when considering the inherent uncertainties in the geochronological techniques used. The lithology and depositional setting of these conglomerate units often makes it difficult to constrain their depositional ages. The close relationship between the inferred depositional age of the conglomerate beds in the Salla area and the youngest detrital-zircons ages in the conglomerate beds suggest that detrital zircon geochronology may be an effective tool for constraining the age of these units elsewhere.

REGIONAL DEPOSITIONAL HISTORY AND BASIN EVOLUTION

Localized Depocenters

It is tempting to interpret the age equivalence and regional distribution of the Oligocene conglomerate units as indicating that the area was once covered by an extensive, sheetlike, gravel-fluvial system. However, the data presented in this study indicate that the Oligocene conglomerate units were derived from local source areas and deposited in relatively isolated depocenters (Fig. 7). The interpretation of multiple, approximately coeval, but localized depocenters is based on the regional-scale

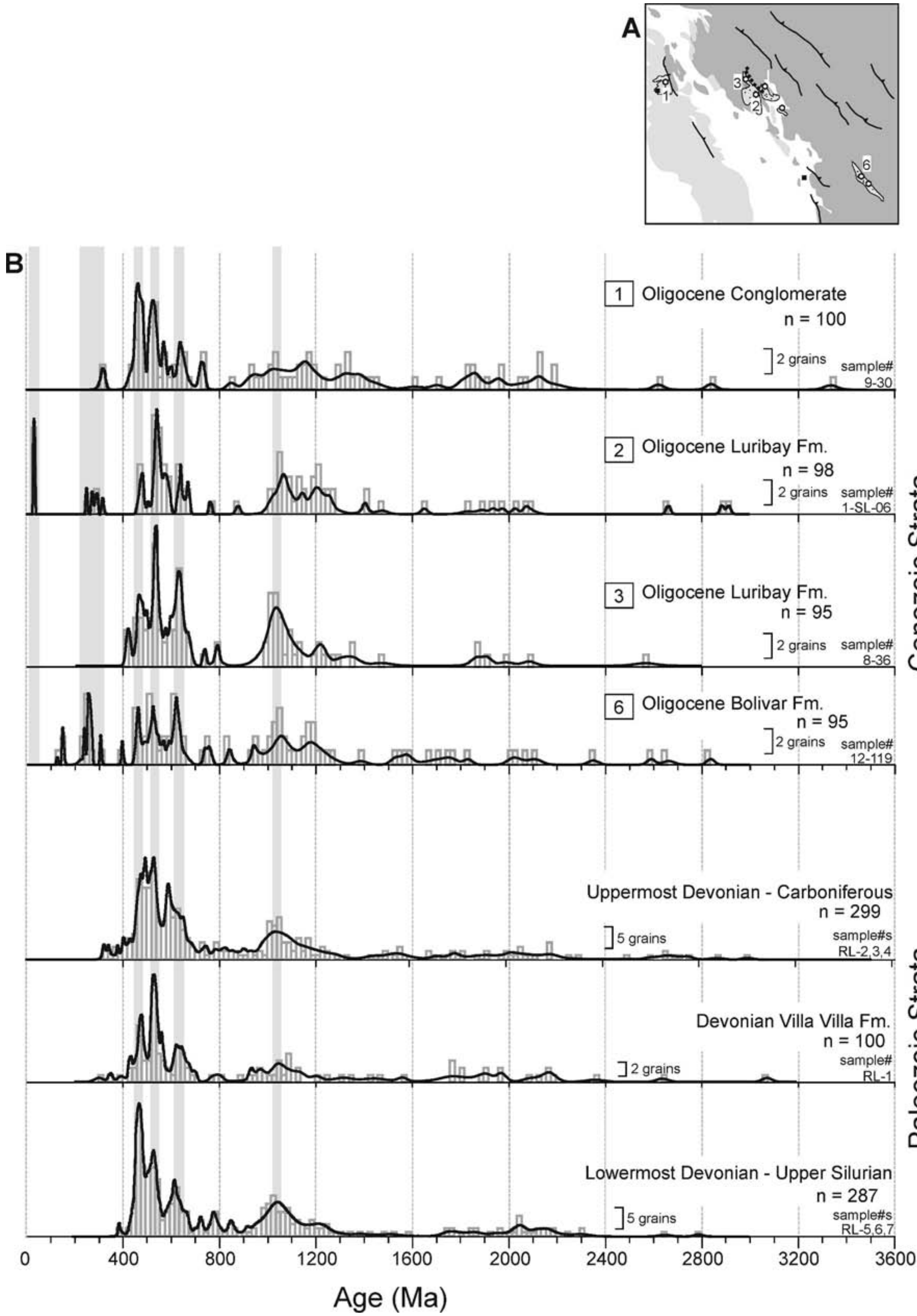

FIG. 6.—Detrital-zircon data. **A)** Map showing location of samples. Numbers are the same as in Figure 2. **B)** Detrital-zircon data from Oligocene conglomerate beds and underlying Paleozoic stratigraphic units. Horizontal scale is age of zircons, vertical scale of individual graphs is number of grains (shown with bracket and number of grains). Bin size used is 20 million years. The line on each graph shows the relative probability distribution. The gray bands highlight common detrital-zircon age populations.

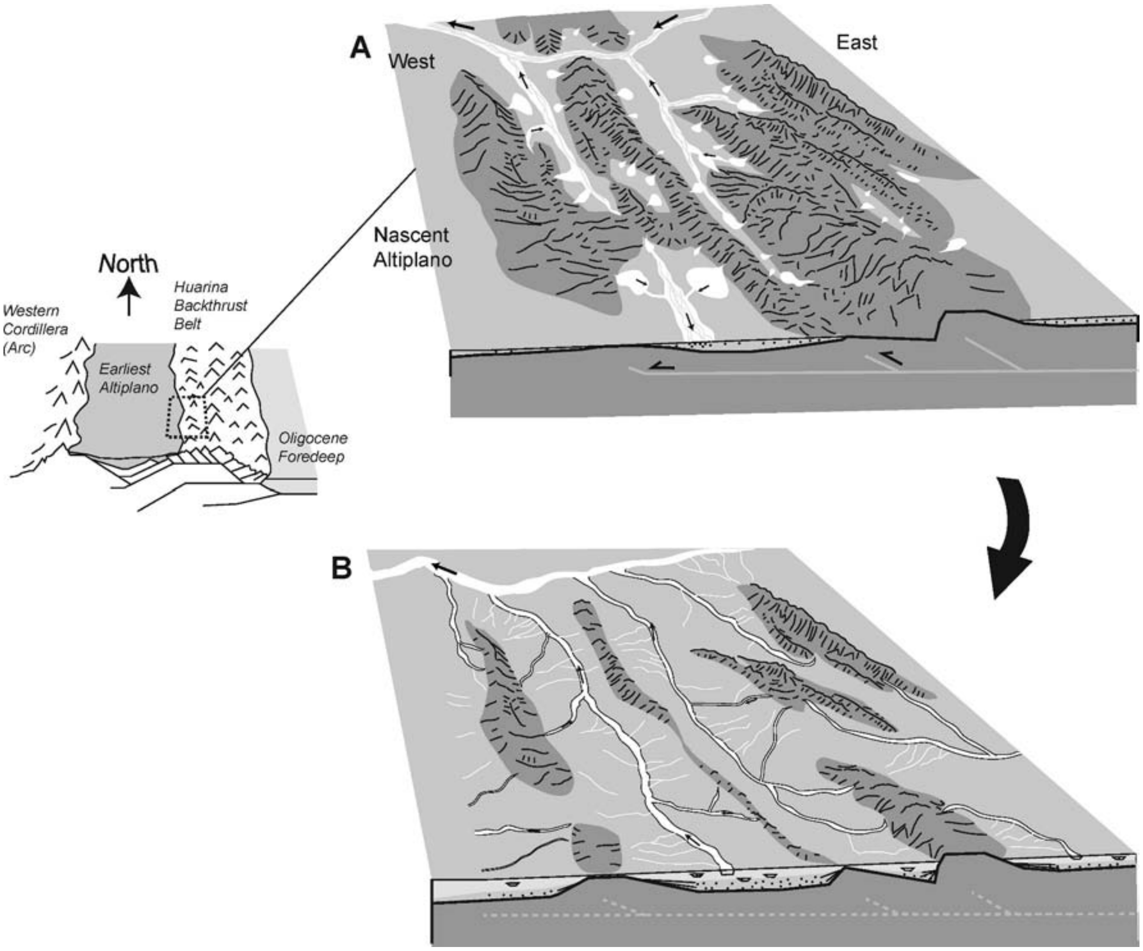

FIG. 7.—Generalized reconstruction of deposition and deformation in the study area. Figure at the left shows the tectonic setting. **A)** Initial deposition occurred in alluvial fans and braidplains in isolated or semi-isolated basins situated between thrust faults and folds. Growth strata in these deposits indicate that deposition was coeval with upper crustal deformation. Arrows schematically depict paleocurrent directions. **B)** Deposition in the upper portion of the Oligocene succession occurred in fluvial channels and extensive floodplains (e.g., Fig. 4C). Deformation during this time had decreased or ceased and many of the subbasins in the area were infilled.

architecture of the units, paleocurrent data, and sediment provenance information.

Clast populations at all sites share first-order characteristics; however, the differences between areas suggest that the deposits at each location were derived from the erosion of strata exposed in nearby folds and thrust-fault hanging walls. Similarities between locations are interpreted to be due largely to the fact that similar Paleozoic and Mesozoic strata are exposed all along the Eastern Cordillera (Geobol 1997; McQuarrie and DeCelles 2001). Thus, deformation during Oligocene time would have exposed similar rocks to erosion and subsequent redeposition. Differences in clast populations between locations correlate with differences in the pre-Cenozoic strata surrounding these areas (e.g., Luribay area versus the Coro Coro area; Figs. 2 and 5). Localized sediment provenance is further supported by large and frequently subangular clasts (Fig. 4), suggesting relatively limited transport distances. Facies indicating deposition on alluvial fans, which rarely exceed 15 km from the source area (e.g., Blair and McPherson 1994) also support localized depocenters.

Paleocurrent data vary greatly between locations ($\sim 90^\circ$) and in close proximity, suggesting more localized deposition (Fig. 5) and support deposition in localized depocenters. The variability in these data reflect differences in transport-related parameters (e.g., slope orientation) that existed between small distances (< 10 km; Figs. 5, 7). Similar paleocurrent patterns are present in younger fold-thrust-belt systems where localized depocenters form between topography associated with structures (e.g., Jackson et al. 1996).

Regional stratigraphic-thickness trends suggest that although the Oligocene conglomerate units were deposited over a broad area and at approximately the same time, it is likely that these sediments were focused in localized areas. The Oligocene conglomerate units are present over a large area, but the specific exposures are of a limited extent. Whereas it is highly likely that postdepositional erosion has affected the current distribution of the conglomerate units, this explanation fails to account for all irregularities in distribution. At multiple locations, thicknesses of the Oligocene conglomerate units are demonstrably thinner near thrust faults and folds despite uniform thicknesses in overlying strata (Fig. 3). These relationships suggest that paleotopography impacted spatial accommodation patterns leading to the development of subbasins.

Relationship between Deformation and Sedimentation

Deformation in the Huarina backthrust belt occurred between ca. 40 and 25 Ma, based on thermochronology and crosscutting relationships (Sempere et al. 1990; McQuarrie and DeCelles 2001; Gillis et al. 2006). However, only sedimentary units younger than ca. 28 Ma were preserved in the specific study areas, indicating that either the sediments deposited between ca. 40–28 Ma were removed prior to deposition of the Oligocene

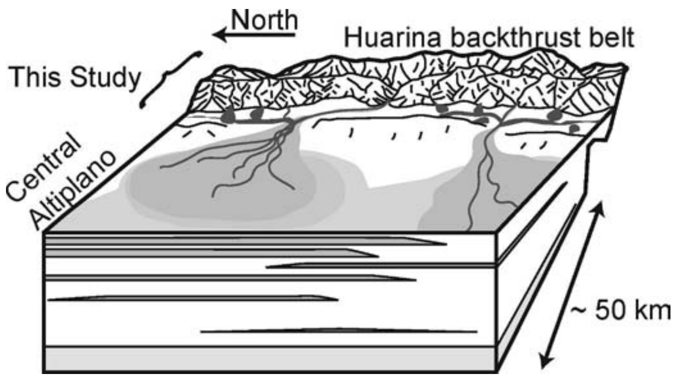

FIG. 8.—Oblique view of the Altiplano and Eastern Cordillera, looking east. The sediments examined in this study are interpreted as being part of a larger depositional system. Sediment was derived from Paleozoic and Mesozoic strata in the Eastern Cordillera, transported to the west, and deposited in the Altiplano in fluvial distributary fans. The Oligocene sediment examined in this study represents the proximal feeder zones to these distributary systems.

conglomerate units, or no sediments were ever deposited during this time period. It is impossible to be certain of the history of material that is now absent or may never have been present, but we postulate that is it likely sedimentation did occur between 40 and 28 Ma and that most of this material was removed during upper crustal deformation. The Huarina backthrust belt propagated from east to west (McQuarrie et al. 2005), likely cannibalizing synorogenic sediments deposited along its western margin, similarly to other advancing fold-thrust belts (e.g., Royse 1993). This scenario is supported by the fact that areas in the central Altiplano basin, where Huarina backthrust activity did not occur, contain complete successions of Oligocene and Eocene sedimentary rocks (Horton et al. 2001). Along the margins of the Altiplano, it was only as deformation rates decreased in the Huarina backthrust belt that synorogenic sediments could be preserved.

The diminishment of thrust-fault activity in the Huarina backthrust belt correlates with a general change in depositional facies in the region, from localized alluvial-fan deposition at the base of the succession to floodplain-dominated fluvial deposits near the top. Evidence of waning tectonic activity includes the difference between the amount of deformation in the beds at the base of the Oligocene succession versus those near the top (Fig. 3) and is further supported by thermochronologic data that record decreased exhumation by this time (Gillis et al. 2006). Paleogeographically, deposition changed from localized alluvial fans and axially flowing fluvial systems to isolated coarse-grained channels surrounded by well-drained soils forming in mud-sized sediment (Fig. 4). The conglomerate and mudstone strata eventually grade into the fine-grained, undeformed strata of the Salla Beds (MacFadden et al. 1985). The hypothesis that changes in the sedimentary systems resulted from climate and other factors cannot be ruled out entirely, but the correlation between the timing and degree of deformation and the characteristics of the depositional systems suggests that deformation exerted a strong influence on the deposits.

ROLE IN ALTIPLANO BASIN INFILLING

The muted relief of the Altiplano is due in no small part to the large volume of sediment that has been deposited in the area (e.g., McQuarrie and DeCelles 2001; Elger et al. 2005). The Altiplano contains up to 12 km of strata that were deposited during formation of the Central Andes (Horton et al. 2001). Since at least Oligocene time the region has been receiving sediment from both the Western Cordillera (volcanic arc) to the west and the Eastern Cordillera to the east (Horton et al. 2002).

The conglomerate units described in this paper can be combined with previous studies to provide a more complete picture of the Oligocene sedimentary system that is partially responsible for the infilling of the Altiplano basin. Eocene through Oligocene age strata exposed in areas 50 km west-southwest of the locations outlined in this paper indicate that by late Oligocene time the central portion of the Altiplano was an internally drained basin occupied by large fluvial distributary systems (Hampton and Horton 2007). Sedimentary units in these locations are up to 6 km thick and were deposited by unconfined sheetflood processes in overbank floodplains, playa lakes, and poorly defined channels (Hampton and Horton 2007). Sandstone petrography (Horton et al. 2002) and paleocurrent data (Hampton and Horton 2007) indicate that by late Oligocene time flow was east to west and sediment in the central Altiplano basin was derived primarily from the Eastern Cordillera.

We propose that the Oligocene conglomerate units described in this study represent the depositional remnants of a proximal feeder zone that supplied sediment to the fluvial distributary systems that occupied the central Altiplano basin during late Oligocene time (Fig. 8). Distributary fluvial systems like those interpreted by Hampton and Horton (2007) consist of distal distributary networks, medial zones of channels and floodplains, and coarse-grained proximal areas that supply sediment to the overall system (Kelly and Olsen 1993; Nichols and Fisher 2007). Employing this model, the Huarina backthrust belt would have been the primary sediment source for fluvial distributary fans in the Altiplano. The strata described in this paper represent the coarser-grained sediments deposited in the upstream portion of these systems (Fig. 8).

SUMMARY AND CONCLUSIONS

A major cratonward jump in fold-thrust-belt activity in the Central Andes occurred at ca. 40 Ma (McQuarrie et al. 2005), partitioned the existing foreland basin, and created a broad, internally drained region in the interior of the fold-thrust belt. This region would eventually evolve into the present day Altiplano, which is one of the largest plateaus on Earth and arguably one of the best examples of a large intermontane basin located in the hinterland of a fold-thrust belt. The upper Oligocene conglomerate beds examined in this study were deposited along the eastern margin of the Altiplano as the eastern topographic boundary of the Altiplano was still being constructed via upper crustal folding and thrusting. Thus, these sediments provide not only a record of sedimentation in this region, but also a unique window into the dynamics of plateau formation.

Deposition in the area initially occurred in alluvial-fan and braidplain settings in a series of disconnected or semiconnected basins located between thrust faults and folds of the Huarina backthrust belt. The sediments were derived primarily from Paleozoic strata, which were exposed in thrust sheets in the immediate vicinity. Growth strata in these rocks indicate that deposition of alluvial fans and braidplains occurred coevally with upper crustal deformation.

The upper portion of the Oligocene conglomerate units are less deformed than the beds near the base of the succession and display little to no evidence of syndepositional deformation. These beds contain higher percentages of sandstone and mudstone and have facies that indicate that deposition in the region had changed from alluvial-fan and braidplains, to single-channel fluvial environments complete with well-drained floodplains. Clasts and detrital-zircon data indicate sediment continued to be derived primarily from localized sources.

The Altiplano contains $>$ 10 km of Cenozoic strata and has been an internally drained basin for tens of millions of years (Horton et al. 2001). The ultimate source of the vast volume of sediment that has infilled the region is the magmatic arc to the west and the Paleozoic and Mesozoic strata exposed in the fold-thrust belt to the east (Fig. 1). The Oligocene conglomerate beds examined in this study are interpreted as the proximal remnants of fluvial distributary systems that delivered sediment from the fold-thrust belt and into the Altiplano. These reconstructions explicitly show that eroded clastic material from the fold-thrust belt was not delivered to the foreland basin, but instead was sequestered within the interior of the fold-thrust belt.

ACKNOWLEDGEMENTS

This research was supported by a grant from the National Sciences and Engineering Research Council of Canada. Additional funds were provided by the Princeton University Department of Geosciences. We thank C. Garzione and B. McFadden for helpful discussions of regional stratigraphy. Field work was facilitated by logistical assistance from S. Tawackoli and C. Ossio. We would like to thank the outstanding drivers of Imbex and R. Villegas. We gratefully acknowledge S. Long and T. Cecil-Cockwell for their tremendous help and work. We thank T. Dixon and T. McCartney for their help. The manuscript was greatly improved by thorough and very helpful comments from M. Rygel, and reviewers B. Carrapa and B. Bluck. We also thank Editor P. McCarthy for the helpful comments. The Appendix is available at: http://www.sepm.org/jsr/jsr_data_archive.asp.

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Received 14 September 2009; accepted 18 February 2010.