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Vestiges of an Ordovician west-vergent thin-skinned Ocloyic thrust belt in the Argentine Precordillera, southern Central Andes

William A. Thomas [a,*], Ricardo A. Astini [b]

[a] *Department of Earth and Environmental Sciences, University of Kentucky, 101 Slone Building, Lexington, KY 40506-0053, USA*
[b] *Cátedra de Estratigrafía y Geología Histórica, Universidad Nacional de Córdoba, X5016GCA Córdoba, Argentina*

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Abstract

Collision of the down-going, Laurentia-derived Argentine Precordillera terrane with the Gondwanan margin drove the Ordovician Ocloyic orogeny, including subduction volcanism, metamorphism, and top-to-west shearing east of the Precordillera. In the Precordillera, above passive-margin carbonates (Lower Ordovician San Juan Limestone and older carbonates), a Middle to Upper Ordovician westward-prograding synorogenic clastic wedge of black shale (Gualcamayo Shale) and coarser clastic sediment (Las Vacas Conglomerate and Trapiche Formation) fills a peripheral foreland basin. New research has identified vestiges of a west-directed thin-skinned Ocloyic foreland thrust belt that has been fragmented by east-directed Andean thrusting. The El Corral thrust sheet, with hanging-wall detachment in the San Juan Limestone, extends over a west-directed footwall frontal ramp and extensive flat to low-angle footwall cutoff in the Gualcamayo and Las Vacas formations. Las Vacas conglomerates in the footwall include olistoliths (10-m scale) exclusively of San Juan Limestone and Gualcamayo Shale; the beds in some olistoliths are folded. The advancing El Corral thrust sheet successively supplied and overrode the stratigraphically restricted olistoliths. In the El Corral footwall, tight west-vergent folds and faults within an anticlinorium in the San Juan Limestone and Gualcamayo Shale suggest a deeper (unexposed) thrust fault, the Los Celestitos fault. West of the anticlinorium, easterly dip (restored to remove Andean deformation) beneath an angular unconformity between Las Vacas and Trapiche beds is consistent geometrically with the trailing limb of a west-vergent fault-propagation anticline in the hanging wall of the subsurface Los Celestitos fault. The same angular unconformity truncates the El Corral fault and hanging-wall strata. In the Trapiche Formation, contrasting sedimentary facies from sandy turbidites westward to limestone-clast megabeds and olistoliths suggest another frontal ramp from a stratigraphically deeper detachment in a break-forward sequence. None of these observations separately defines an Ocloyic thrust belt. Taken together, however, these vestiges of thrust-belt style indicate the consistent geometry of an Ordovician west-vergent thin-skinned Ocloyic thrust belt.

Keywords: Precordillera; Ocloyic orogeny; Ocloyic thrust belt; Ordovician; thin-skinned thrust belt

1. Introduction

The Middle to Late Ordovician Ocloyic orogeny is interpreted to reflect collision of the down-going, Laurentia-derived Argentine Precordillera terrane with an upper-plate segment of the pre-Andean margin of Gondwana (e.g., Astini et al., 1995; Thomas and Astini, 1996). The present structure of the Precordillera, in the eastern foothills of the Andes in northwestern Argentina, is dominated by the frontal Andean thrust faults (Fig. 1) (e.g., Ramos, 1988; Ramos et al., 2004). Grenville-age basement rocks and a Cambrian–Ordovician carbonate platform record the early history and paleogeographic affinities of the Precordillera (Astini and Thomas, 1999). In the eastern Precordillera, a diachronous, southwestward prograding, upward transition from passive-margin platform carbonates (San Juan Limestone) to black shale (Gualcamayo Shale) indicates initial subsidence of a foreland basin from Arenig to

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[*] Corresponding author. Tel.: +1 859 257 6222; fax: +1 859 323 1938.
E-mail addresses: geowat@uky.edu (W.A. Thomas), raastini@efn.uncor.edu (R.A. Astini).

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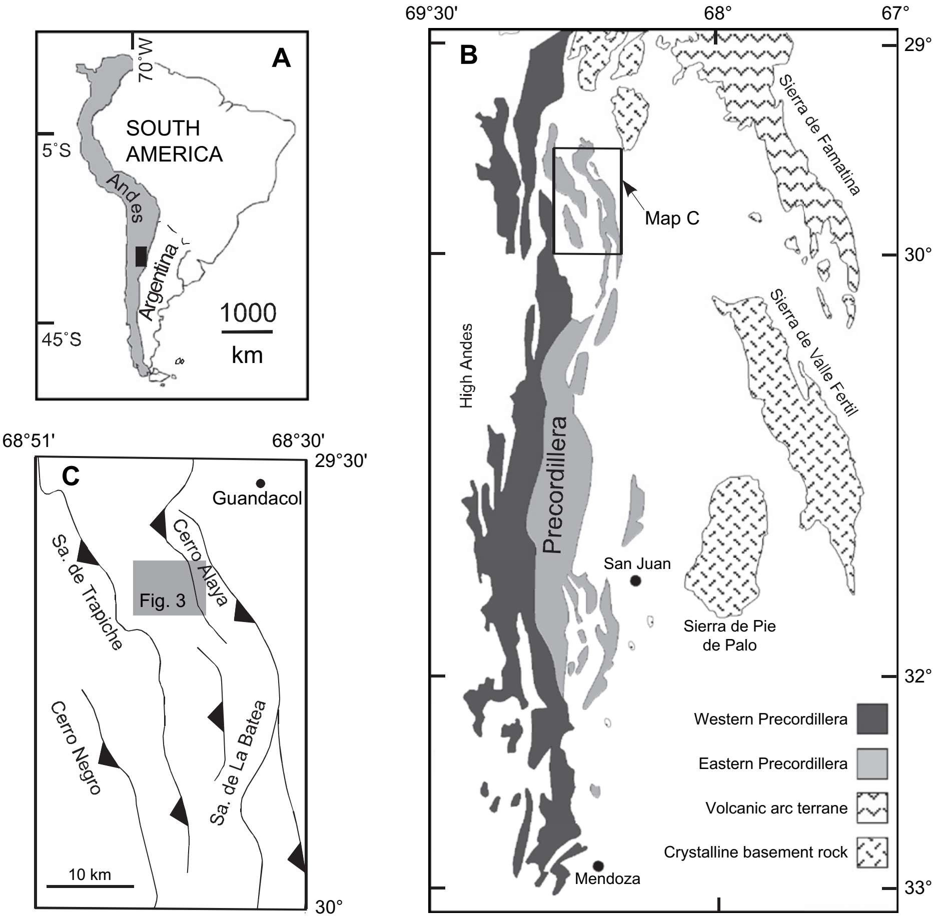

Fig. 1. Location maps: (A) location within frontal Andes; (B) location of Precordillera, and basement uplifts and volcanic terrane east of the Precordillera; (C) location of Andean thrust faults and area of Fig. 3.

Llanvirn (Ordovician) time (Astini et al., 1995). Above the black shale, coarser clastic sediment (Las Vacas Conglomerate and Trapiche Formation) filling the foreland basin includes extrabasinal igneous and quartzite clasts and intrabasinal limestone and shale olistoliths. Flexural subsidence is linked to tectonic loading as the Precordillera entered an eastward dipping subduction zone beneath the western margin of Gondwana (Astini et al., 1995). The Ordovician Famatina volcanic arc (Fig. 1), east of the Precordillera, is interpreted to be a continental-margin arc associated with eastward subduction, which ended when the continental crust of the Precordillera collided with the Gondwanan margin (Pankhurst et al., 1998, 2000; Quenardelle and Ramos, 1999). Bentonite (volcanic ash) beds within the interval of upward transition from carbonate to black shale in the Precordillera are temporally and geochemically linked to Famatina (Huff et al., 1997). Ordovician east-directed thrusting and folding characterize the backarc east of Famatina (Dávila et al., 2003). In addition to magmatism/volcanism and deformation in Famatina (Saavedra et al., 1998; Astini and Dávila, 2004; Dahlquist et al., 2005), metamorphic ages of ~460 Ma are associated with top-to-west shear zones in the Sierra de Pie de Palo and Sierra de Valle Fertil (Casquet et al., 2001; van Staal et al., 2002, 2005; Ramos, 2004; Vujovich et al., 2004) in the internides of the Ocloyic orogen east of the Precordillera (Fig. 1). Despite these clear indications of an Ordovician orogenic event associated with accretion of the Precordillera to Gondwana, no certain Ocloyic thrust-belt structures have been recognized in the orogenic foreland in the Precordillera, and the lack of a preserved west-vergent Ocloyic thrust belt on the lower plate has been cause to question the hypothesis of Ordovician accretion of the Argentine Precordillera. In this article, we will explain how several independent observations can be integrated to indicate disrupted vestiges of a west-vergent, thin-skinned Ocloyic thrust belt, now overprinted by east-vergent Andean thrust faults. Where successive orogenic events have overprinted the same foreland, the structures of a foreland thin-skinned thrust belt may be the least commonly preserved or recognized documentation of the early orogenic events. For example, in the southern Appalachians, a foreland clastic wedge and internal metamorphic and plutonic rocks document the Ordovician Taconic orogeny (Drake et al., 1989); however, no foreland thrust-belt structures have been recognized through the overprint of the late Paleozoic Alleghanian orogeny. Some of the principles used in this article may prove useful in other multi-phase orogenic belts.

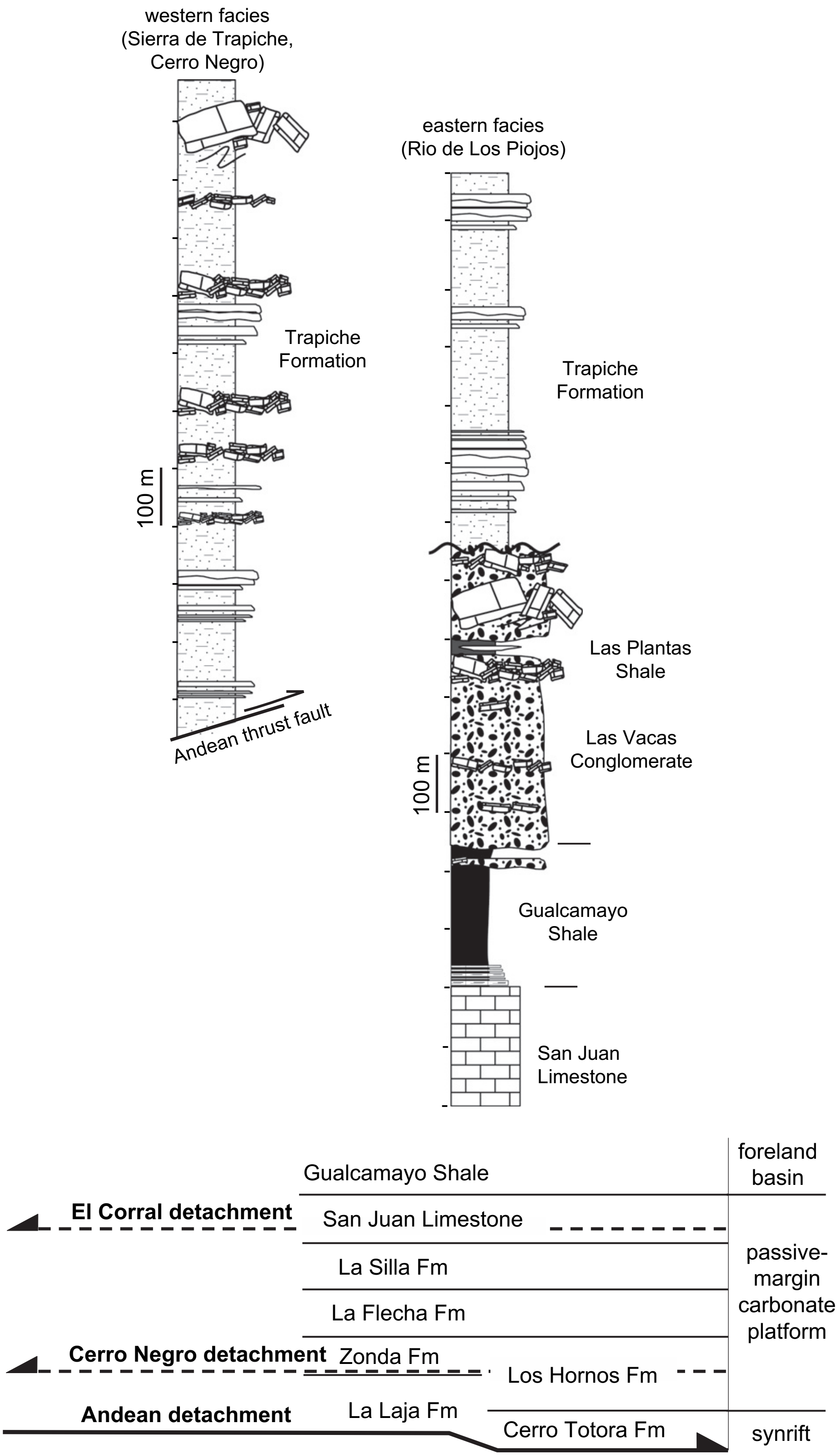

Fig. 2. Stratigraphic diagram for northeastern Precordillera, showing thrust detachments with respect to stratigraphic subdivisions in Cambrian–Ordovician carbonate platform strata, and stratigraphic successions in Ordovician clastic wedge.

2. Stratigraphy

A classic passive-margin carbonate succession of Early Cambrian to Early Ordovician age documents the platform of the Precordillera (Fig. 2) (Keller et al., 1994; Astini et al., 1995). The oldest Paleozoic strata exposed in the hanging walls of Andean thrust sheets belong to a redbed, carbonate, and evaporite succession in the Lower Cambrian Cerro Totora

Formation (Astini and Vaccari, 1996). Interbedded fine clastic and carbonate rocks of the lower La Laja Formation are overlain by a succession of peritidal to subtidal platform limestones and dolostones of the upper La Laja, Zonda, and laterally equivalent Los Hornos, and the La Flecha and La Silla Formations, which characterize the Precordillera carbonate bank (Fig. 2). At the top of the platform succession, the San Juan Limestone includes abundantly fossiliferous, open-shelf limestones.

A diachronous upward transition from San Juan Limestone to black shale of the Gualcamayo Shale indicates initial subsidence of a foreland basin in response to tectonic loading (Astini et al., 1995). Deposition of the black shale began in middle Arenig time and progressed diachronously westward and southward onto the platform through Llanvirn time (Astini, 1994a; Astini et al., 1995). Conglomerate beds of the Las Vacas Conglomerate record progradation of coarser clastic sediment (Astini, 1998a); the upward transition is marked by lenses of Las Vacas Conglomerate within the upper part of the Gualcamayo Shale (Fig. 2). Large blocky olistoliths of the San Juan Limestone and Gualcamayo Shale are mixed locally with bouldery detritus from extrabasinal orogenic sources in the Las Vacas conglomerate beds. Above the coarse Las Vacas conglomerates, quartzose sandstone turbidites characterize the Trapiche Formation. In contrast, in the more westerly part of the foreland basin in the Sierra de Trapiche and Cerro Negro (Fig. 1C), carbonate-boulder megabeds and olistoliths are interlayered with otherwise finer turbidites of the Trapiche Formation (Fig. 2). The sources and transport processes of the mixture of clast sizes and compositions have important implications for the tectonic evolution of the foreland basin.

The clastic wedge is truncated at the top, obscuring the record of the later stages of evolution of the foreland basin. In the northern Precordillera, Late Carboniferous strata unconformably overlie the Ordovician clastic units. Farther south, unconformity-bounded units of Silurian and Devonian strata intervene between the Ordovician and late Paleozoic beds.

3. The El Corral thrust fault

The eastern side of the Sierra de La Batea and Cerro Alaya in the northeastern Precordillera consists of steeply dipping and deformed, thrust-imbricated carbonate rocks of the La Flecha to San Juan succession (Fig. 1). Like other frontal Andean faults, the west-dipping frontal ramps are relatively steep (30–60°), and the ramps evidently rise from a detachment near the base of the Paleozoic cover succession (Allmendinger et al., 1990; Zapata, 1996; Zapata and Allmendinger, 1996; Cristallini and Ramos, 2000). West of the frontal west-dipping Andean thrust faults, in the valley of the Rio de Los Piojos, an east-dipping, west-vergent thrust fault has a hanging-wall detachment in the San Juan Limestone (locality 1, Figs. 3–5). A relatively steeply east-dipping (35°) footwall frontal ramp cuts up section to the west from Gualcamayo Shale to folded lowermost Las Vacas Conglomerate in the immediate footwall (Figs. 3–5). The stratigraphically highest beds preserved on the present land surface in the footwall are the lowermost Las Vacas conglomerate beds, which are folded into an overturned west-facing syncline. Although the east-dipping, west-vergent fault might be an Andean back thrust, additional map relationships indicate instead that the west-vergent thrust fault and associated folds are part of a west-vergent Ocloyic thin-skinned thrust belt.

The east-dipping thrust fault, here called the El Corral thrust fault, has been mapped into the hills both north and south of the Rio de Los Piojos (Fig. 3) (Astini, 1991). Along the northern escarpment of the valley of the Rio de Los Piojos, the map trace shows that the fault dip decreases westward to subhorizontal, and the subhorizontal fault surface extends westward to the tributary Quebrada del Corral (Figs. 3, 4). The hanging-wall detachment persists within the San Juan Limestone, indicating a hanging-wall flat within the extent of the exposure (locality 3, Figs. 3, 4, 6). In the footwall, the El Corral fault cuts obliquely at a very low angle up section to the west from the Gualcamayo Shale into the Las Vacas Conglomerate and, farther west, at a higher angle in the Las Vacas Conglomerate (Fig. 4). Indeed, because of the flat-on-flat geometry of San Juan Limestone over Gualcamayo Shale, the El Corral fault contact was interpreted originally to be a stratigraphic contact with the then-inferred-to-be younger San Juan Limestone above the Gualcamayo Shale (Furque, 1963). Similarly, south of the valley of the Rio de Los Piojos, a hanging-wall flat in the San Juan Limestone is emplaced over a low-angle footwall cutoff that cuts up section to the west from the Gualcamayo Shale into the lower Las Vacas Conglomerate. A sinuous map trace illustrates that the fault surface is subhorizontal (Fig. 3).

The west-vergent El Corral fault differs in geometry and style from the Andean thrust faults in the same sierra. The east-vergent Andean faults are steep frontal ramps that cut upward from a décollement low in the Paleozoic stratigraphy, and the frontal ramps cut up section to the present erosion surface. In contrast, the west-vergent El Corral fault has an extensive hanging-wall detachment flat in the San Juan Limestone (stratigraphically >2000 m above the Andean décollement) and an extensive flat to low-angle footwall cutoff in the Middle Ordovician clastic succession (Gualcamayo Shale and Las Vacas Conglomerate). The east–west (cross-strike) extent of the hanging-wall flat of the El Corral fault in the San Juan Limestone contrasts both in style and in detachment level with the Andean frontal ramps, as does the flat footwall cutoff.

At the presently preserved leading edge of the El Corral thrust sheet (Fig. 3), on the east side of the canyon of the Quebrada del Corral, the map trace of an angular unconformity below the beds of the Trapiche Formation truncates the footwall beds, fault, and hanging-wall beds (locality 9, Figs. 3, 4), indicating that the El Corral fault pre-dates deposition of the Trapiche Formation. The age of thrusting is constrained between the middle-late Caradoc (early Late Ordovician, according to the most recent revision of the Ordovician time scale) age of deposition of the Las Vacas Conglomerate and the early Ashgill age of deposition of the Trapiche Formation above the unconformity (Astini, 1998b).

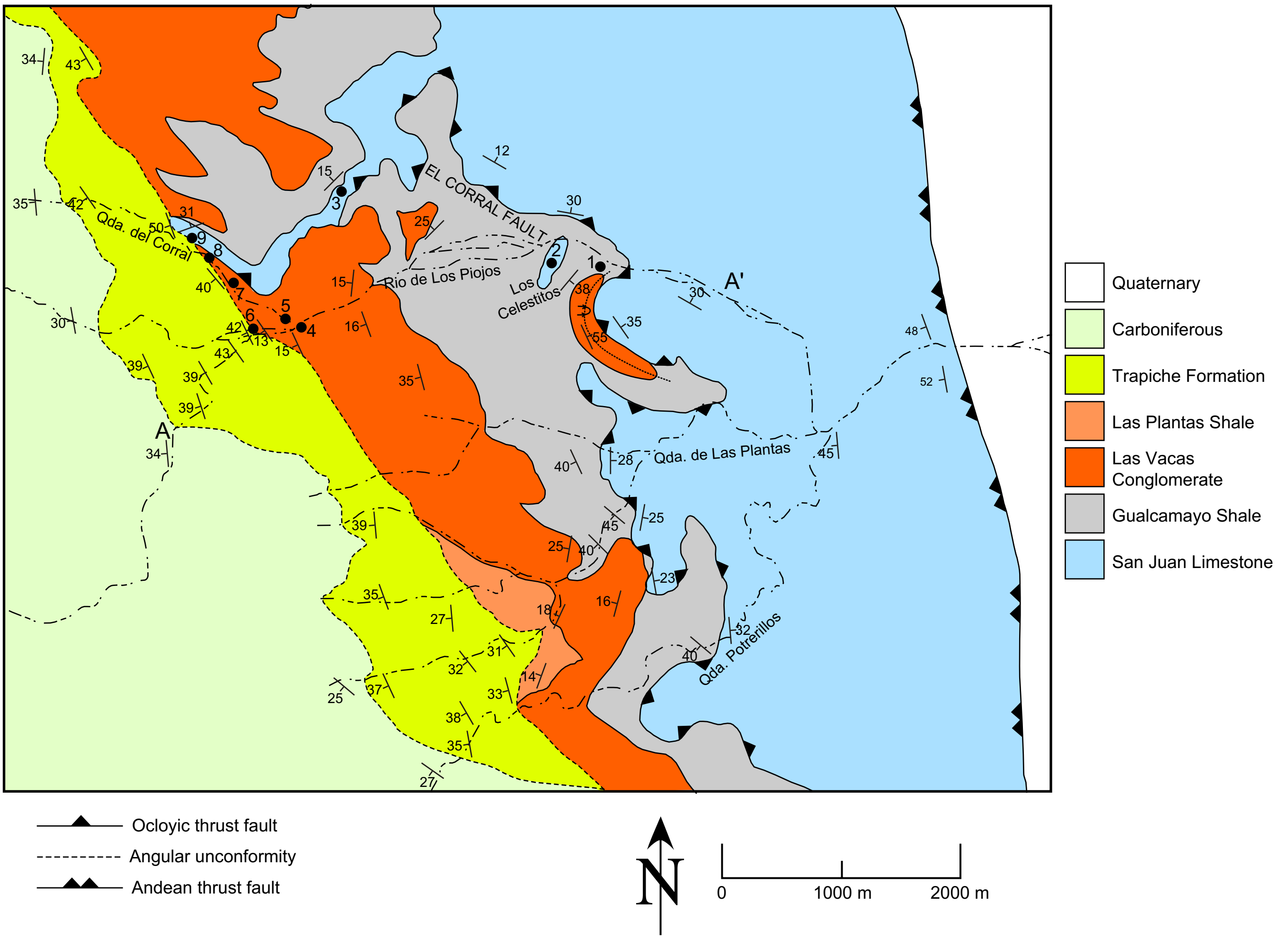

Fig. 3. Geologic map of Ocloyic structures along the valley of the Rio de Los Piojos (modified from Astini, 1991). Localities discussed in text are identified by number (numbers increase from east to west, not in order of discussion in the text). End points A–A′ show line of cross section of Fig. 4.

4. The Los Celestitos fault

Two outcrops in the footwall of the El Corral fault suggest an underlying thrust fault at a deeper level within a west-directed thin-skinned thrust belt. The inferred subsurface fault, here called the Los Celestitos fault, is geometrically similar to the El Corral fault with an extensive flat-on-flat geometry (Fig. 4).

At Los Celestitos along the Rio de Los Piojos, a train of west-vergent tight folds and small-magnitude thrust faults dominates a low-amplitude anticlinorium of complexly deformed lower Gualcamayo Shale and uppermost San Juan Limestone (locality 2, Figs. 3, 4, 7). The anticlinorium may be a fault-bend fold (ramp anticline) related to a footwall frontal ramp, thrust splays, or a fault-propagation fold rooted in the subsurface Los Celestitos fault (Fig. 4). The anticlinorium is surrounded at the present outcrop level by Gualcamayo Shale, ductile deformation of which evidently absorbed the deformation that is recorded in the San Juan Limestone. The anticlinorium and overlying Gualcamayo Shale are in the footwall of the east-dipping footwall ramp of the El Corral thrust fault and are structurally below the west-facing syncline in the Las Vacas conglomerate in the immediate footwall of the El Corral thrust fault (Fig. 4).

Along the valley of the Rio de Los Piojos west (upstream) of the mouth of the tributary Quebrada del Corral, an angular unconformity between beds of the Trapiche Formation and coarser clastic strata of the Las Vacas Conglomerate (locality 6, Figs. 3, 4, 8) clearly indicates pre-Trapiche folding or tilting of the older Las Vacas strata. The surface of the angular unconformity presently dips ~42° west, parallel with beds in the overlying Trapiche. The Las Vacas beds now dip ~13° west, and the angular discordance is ~29° (Figs. 4, 8). The present dip is largely a result of folding associated with Andean thrusting, and it may include other post-Trapiche deformation (possibly Silurian, Devonian, Carboniferous, and/or Triassic). Regardless of the time(s) of post-Trapiche folding, after palinspastic restoration to restore the Trapiche depositional geometry, the Las Vacas beds below the unconformity dip eastward. The restored (pre-Trapiche) angle of dip in the Las Vacas beds is consistent with the trailing limb of a west-vergent fault-propagation fold. A fault-propagation fold at this location may mark the tip of the Los Celestitos fault, which is inferred to have a detachment in the San Juan

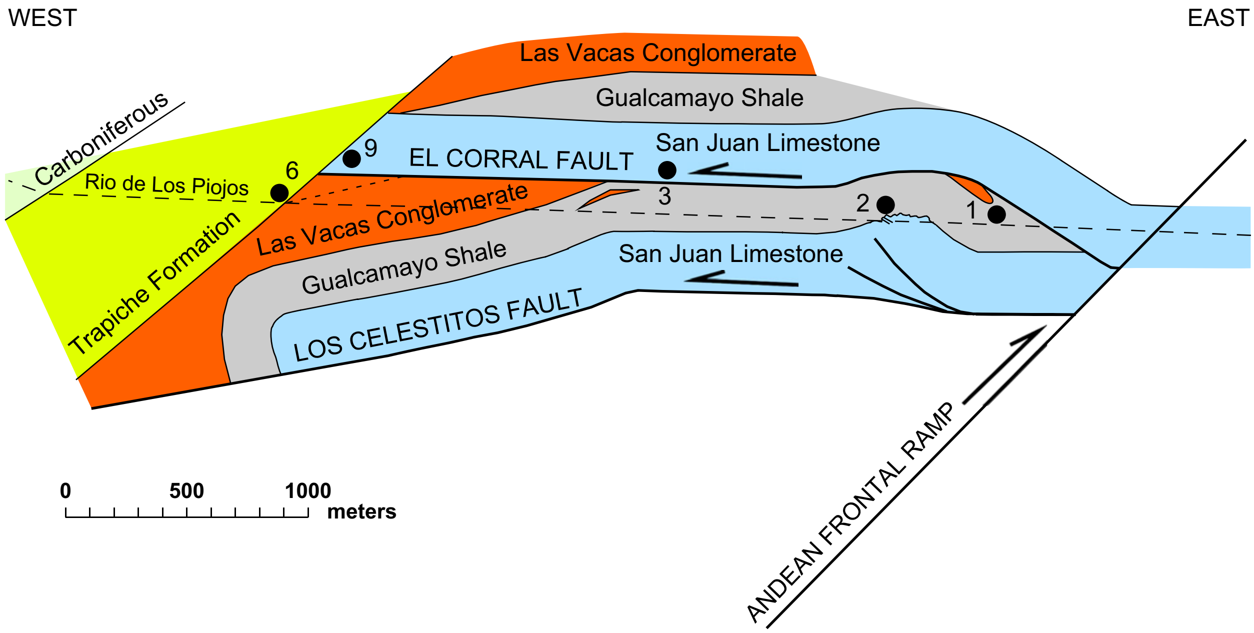

Fig. 4. Interpretative structural cross section along the valley of the Rio de Los Piojos. Long-dashed line shows bottom of the valley of the Rio de Los Piojos. Short-dashed line shows bedding in upper part of Las Vacas Conglomerate unconformably below Trapiche Formation. Cross section based on (1) outcrops along the Rio de Los Piojos, (2) projections to line of cross section from geologic map patterns on slopes above the river, and (3) projection of dip angles into subsurface. End points of cross section are shown in Fig. 3. Localities discussed in text are identified by number (numbers increase from east to west, not in order of discussion in the text).

Limestone (Fig. 4). The distance from the hanging-wall anticlinorium at Los Celestitos (locality 2, Figs. 3, 4) to the fault-tip fold west of Quebrada del Corral measures a probable detachment flat similar in magnitude to the exposed flat in the El Corral fault between the frontal ramp and the sub-Trapiche eroded leading edge (Fig. 4). The angular unconformity can be traced along strike at least 5 km south of the Rio de Los Piojos to the Quebrada Potrerillos (Fig. 3), where the angular discordance is ∼15° (Astini, 1991), suggesting that the truncated structure is elongate north–south, consistent with a

Fig. 5. Photograph of east-dipping footwall frontal ramp of El Corral fault and overturned syncline in Las Vacas Conglomerate in the El Corral footwall. View to south. Locality 1 in Figs. 3 and 4.

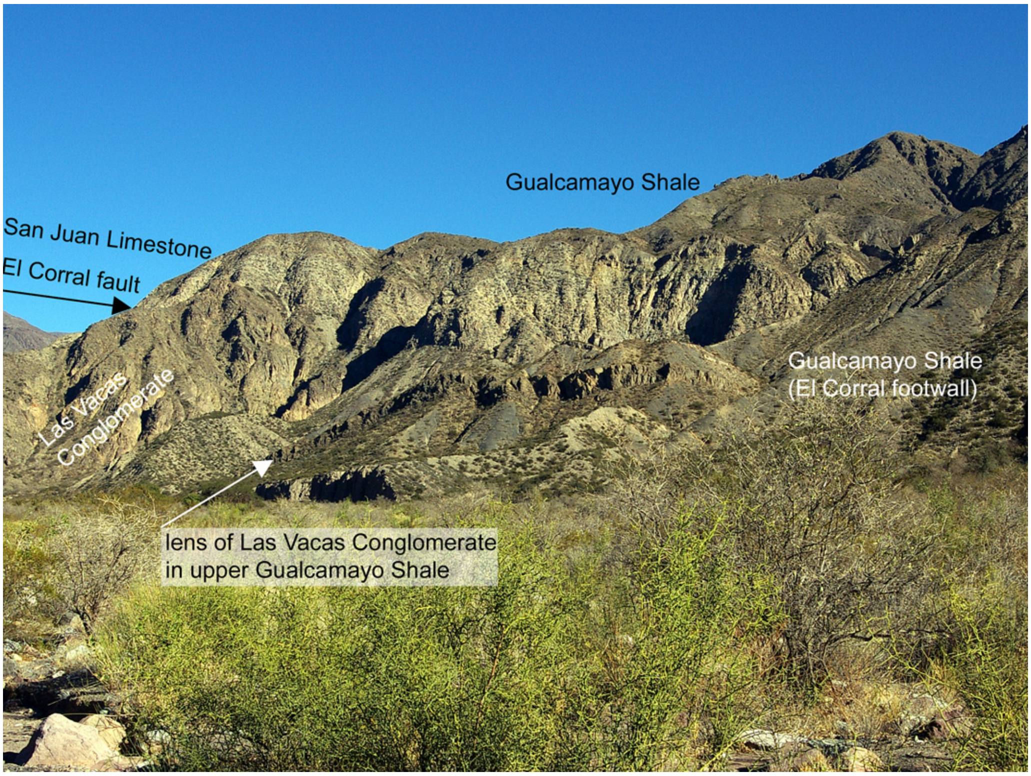

Fig. 6. Photograph of extensive hanging-wall flat of El Corral fault in San Juan Limestone with Gualcamayo Shale and Las Vacas Conglomerate in the footwall. View to north. Locality 3 in Figs. 3 and 4.

Fig. 7. Photograph of train of west-verging folds of San Juan Limestone in hanging wall of Los Celestitos fault. View to south. Locality 2 in Figs. 3 and 4.

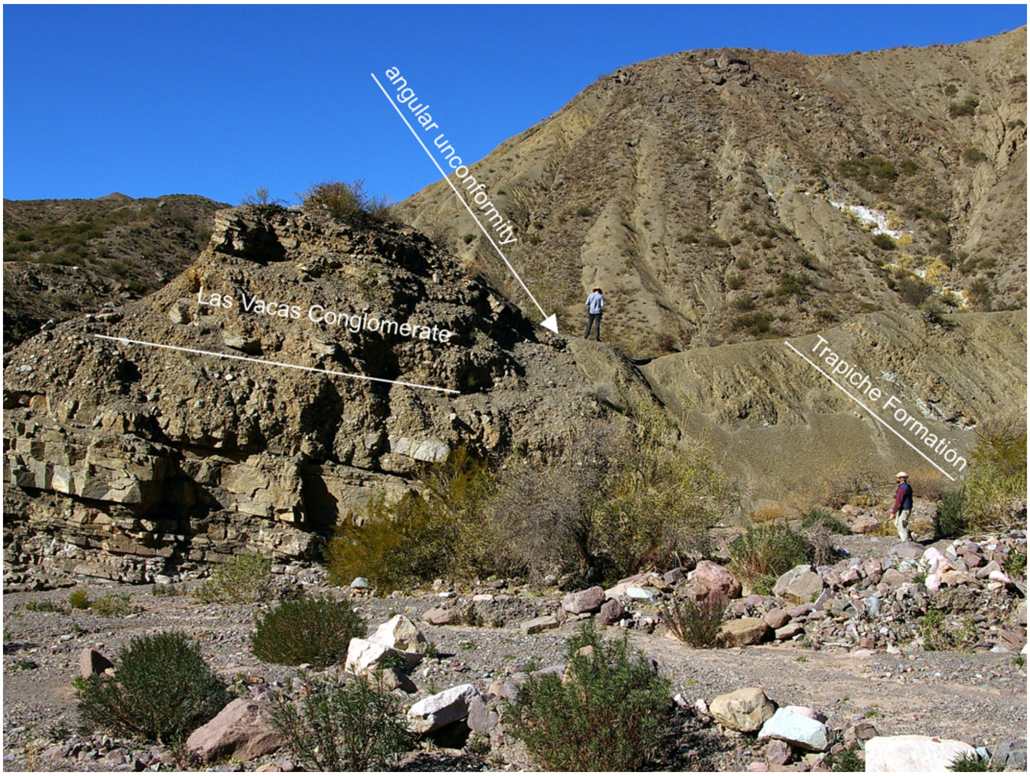

Fig. 8. Photograph of angular unconformity between Las Vacas Conglomerate (dipping ~13° west) and Trapiche Formation (dipping ~42° west). View to south. Locality 6 in Figs. 3 and 4.

west-vergent fault-tip fold. Northward from the Rio de Los Piojos, the angular unconformity cuts upward structurally, and the same unconformity truncates the leading edge of the El Corral thrust sheet (locality 9, Figs. 3, 4).

5. Limestone and shale olistoliths in the Las Vacas Conglomerate

In a coarsening upward succession above the Gualcamayo Shale, conglomerate beds in the Las Vacas Conglomerate contain rounded lithic clasts, <35 cm in diameter, including igneous rocks (mainly tonalites, diorites, gabbros, and andesites), quartzites, sedimentary rocks (mostly limestones, sandstones, and shales), and less common foliated metamorphic rocks and vein quartz. With the exception of the sedimentary rocks, the clasts represent extrabasinal sources, suggesting a supply of sediment from a rising orogenic belt east of the depositional basin (Astini, 1991).

In addition to the rounded clasts, the conglomerates contain 10-m-scale blocky olistoliths of limestone and black shale (locality 4, Figs. 3, 9). The olistoliths within the Las Vacas are within massive layers at several distinct levels, which are separated by intervals that lack olistoliths. The limestone olistoliths are exclusively from the San Juan Limestone, and the black shale is from the Gualcamayo Shale. The large size and angularity of the limestone blocks clearly indicate a proximal source, and the source was stratigraphically limited to a specific, relatively thin interval within the pre-Las Vacas stratigraphy of the Precordillera. Most of the olistoliths contain beds that appear planar and undeformed to very slightly bent; however, some olistoliths contain folded beds, ranging from open to tight. For example, one limestone olistolith contains a fold with an interlimb angle of <10° (locality 5, Figs. 3, 10), indicating contractional folding. The geometry of the fold in San Juan Limestone in the olistolith is similar to the geometry of the folds in San Jaun Limestone in the anticlinorium at Los Celestitos (compare Figs. 10 and 7). Beds in an olistolith of black shale are folded isoclinally (near locality 7, Figs. 3, 11). The olistoliths containing folded beds clearly document a source from beds that had already been deformed, thereby providing evidence of contractional deformation between the time of deposition of the lower part of the Gualcamayo Shale and that of the Las Vacas conglomerates (approximately from early Llanvirn to Caradoc). Many fold hinges in the San Juan Limestone are observed to be broken (e.g., Fig. 7), suggesting that blocks eroded from the limestone most likely are fragments of fold limbs and, thus, generally do not display fold geometry at the scale of the olistoliths. A modern analog can be observed at the present erosion surface in the Precordillera, where statistically <1% of blocks of limestone falling and sliding from frontal scarps contain distinctly folded beds. The few olistoliths that do contain folded beds, however, are unequivocal evidence that contractional folding occurred before the blocks were eroded. Lack of soft-sediment deformation of beds, distinct boundaries of olistoliths with no penetration by rounded clasts in the conglomerate, and a contrast of biostratigraphic ages of olistoliths (Arenig-Llanvirn) and conglomerate (Caradoc), all indicate post-lithification folding.

Fig. 9. Photograph of large limestone olistoliths from San Juan Limestone, in bouldery matrix in Las Vacas Conglomerate. View to south. Locality 4 in Fig. 3.

Fig. 10. Photograph of limestone olistolith with tightly folded beds from San Juan Limestone, in bouldery matrix in Las Vacas Conglomerate. View to south. Locality 5 in Fig. 3.

Fig. 11. Photograph of black shale olistolith with isoclinally folded beds from Gualcamayo Shale, in bouldery matrix in Las Vacas Conglomerate. View to south. Near (∼25 m southwest) locality 7 in Fig. 3.

The largest limestone olistolith observed in the Las Vacas Conglomerate is exposed along the Quebrada del Corral in the immediate footwall of the El Corral thrust fault directly below the San Juan Limestone exposed in the hanging wall (locality 8, Figs. 3, 12). The exceptionally large olistolith is >100 m long and contains a stratigraphic thickness of >20 m of San Juan Limestone. The large olistolith evidently was shed from the leading edge of the thrust sheet, which subsequently advanced over the proximal detritus.

One angular block of San Juan limestone, ∼1 m on a side, shows a clear impact relationship with the underlying beds of Las Vacas conglomerate (locality 7, Figs. 3, 13). The margins of the roughly cubic block, as well as bedding within the block, intersect bedding in the underlying conglomerate at an angle of ∼45°. Further, the conglomerate beds are depressed around the lower corner of the block, in geometry like that of a glacial dropstone, and higher conglomerate beds lap onto the block. Perhaps for these reasons, a glacial origin was suggested long ago (Rasmuss, 1917); however, the lack of any glacial features indicates that this rock fall was more likely from an eroded fault scarp (Astini, 1991, 1998a). The position of this cubic block and the relation of the block to the surrounding conglomerate beds indicate that the block must have fallen from some height on a steep scarp. The outcrop location of the fallen block is at the base of a steep slope directly below the exposed San Juan Limestone in the hanging wall of the El Corral thrust fault (locality 7, Fig. 3). Other olistoliths have less distinct relationships to bedding in the conglomerates, and some may have slid down slopes on the depositional surface rather than having fallen directly from a high scarp.

The stratigraphic restriction of the source of olistoliths, along with the documentation that the source beds had been folded already, limits the alternatives for the tectonic setting of the sediment source. The source evidently was detached in the San Juan Limestone and separated from the stratigraphically lower formations that are not represented in the olistoliths. A thin thrust sheet with a detachment flat in the lower part of the San Juan Limestone and with some internal contractional folds is the only tectonic setting that is fully consistent with the olistoliths. The conglomerate beds with olistoliths are in the footwall of the El Corral thrust sheet, and the thrust sheet is detached in the San Juan Limestone, consistent with shedding of broken blocks from the leading edge of the advancing thrust sheet onto the depositional surface of the Las Vacas conglomerate. This scenario requires that the El Corral thrust sheet advanced contemporaneously with deposition of the extrabasinal bouldery sediment of the Las Vacas. Blocks of second-cycle conglomerate within the Las Vacas (Fig. 14) further indicate synsedimentary deformation and recycling. Canyons eroded through the carbonate-dominated thrust sheet may have carried the coarse detritus from the orogenic hinterland on the east into the depositional basin on the west side of the advancing thrust sheet (Fig. 15). Evidence for erosion of canyons includes a local scour surface where Las Vacas conglomerate rests directly on San Juan Limestone (Figs. 3, 4), as well as rounded clasts of limestone and shale in the lithic

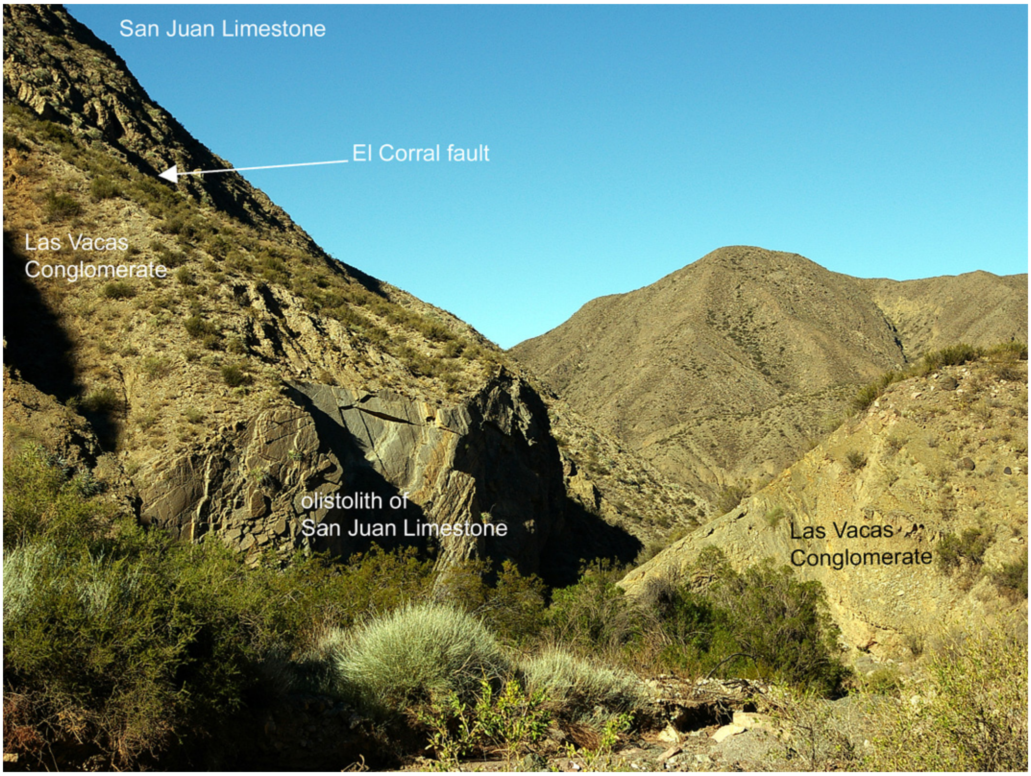

Fig. 12. Photograph of exceptionally large limestone olistolith from San Juan Limestone, in bouldery matrix in Las Vacas Conglomerate. The El Corral fault with San Juan Limestone in the hanging wall and Las Vacas Conglomerate in the footwall is visible in the upper part of the photograph. View to south along the Quebrada del Corral. Locality 8 in Fig. 3.

Fig. 13. Photograph of fallen block of limestone from San Juan Limestone, showing depression of beds below the block and onlap of beds onto the block within Las Vacas Conglomerate. The El Corral fault with San Juan Limestone in the hanging wall and Las Vacas Conglomerate in the footwall is out of the view to the top of the photograph. View to north. Locality 7 in Fig. 3.

Fig. 14. Photograph of recycled blocks of conglomerate in Las Vacas Conglomerate.

conglomerates. The large olistoliths of San Juan limestone and Gualcamayo shale, however, indicate block falls and slides from proximal sources at the leading edge of the thrust sheet.

A modern analog for this depositional setting can be observed in the present canyon of the Rio San Juan west of San Juan city (Fig. 1). The Rio San Juan, with headwaters in the high Andes to the west, flows eastward through canyons cut down into the frontal Andean thrust sheets that include the San Juan Limestone, as well as older carbonates of the Precordillera platform. Although the Andean thrust sheets include a much thicker stratigraphic succession than that of the El Corral thrust sheet, blocks broken from the carbonate strata are presently sliding down the slopes of alluvial fans of detritus from the Andean orogen to the west. A similar scenario for the El Corral thrust sheet includes drainage from the Ocloyic hinterland on the east, westward through canyons cut down into the thrust sheet of San Juan Limestone and Gualcamayo Shale, to supply the extrabasinal rounded boulders of the Las Vacas conglomerates, while blocks from the leading edge of the thrust sheet slid down the depositional slopes or fell onto the slope from steep scarps (Fig. 15).

6. Carbonate-boulder megabeds in Trapiche Formation

Lithofacies of the Trapiche Formation differ across large-scale Andean frontal thrust ramps along the Sierra de Trapiche and Cerro Negro west of the Rio de Los Piojos (Figs. 1, 2). On the east in the northeastern Precordillera, the Trapiche Formation above the angular unconformity (locality 6, Figs. 3, 4) that extends north–south across the Rio de Los Piojos (above the El Corral and Los Celestitos thrust faults) is a turbidite succession characterized by large-scale lenticular quartzose sandstone units within a mudstone succession (Astini, 1991). Distinctive

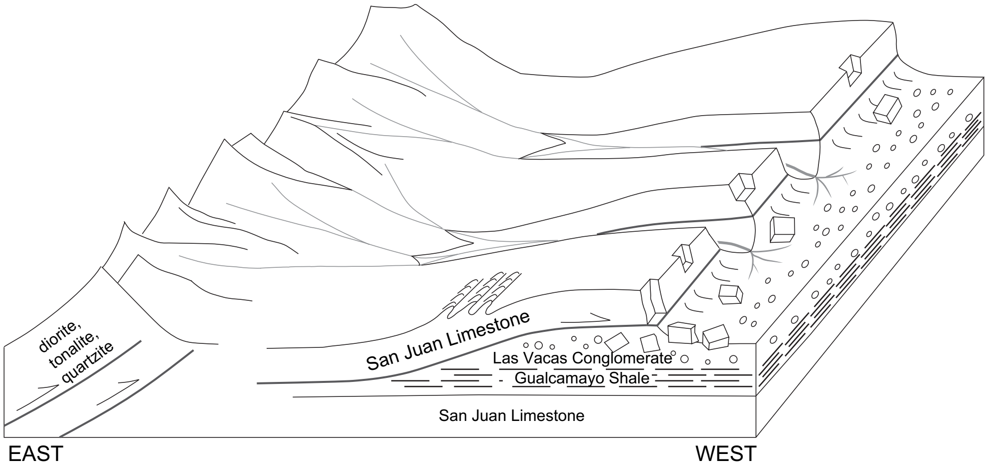

Fig. 15. Conceptual block diagram, illustrating proximal source of limestone olistoliths from San Juan Limestone in the advancing El Corral thrust sheet, dispersal of extrabasinal clasts from the Ocloyic internides through canyons cut into the carbonate thrust sheet, and supply of limestone olistoliths as block falls and slides from the leading edge of the thrust sheet.

Bouma sequences include some fine- to medium-sized gravels in the coarse basal lags; however, the succession includes no large limestone boulders or olistoliths. In contrast, to the west of the Andean frontal ramps in the Sierra de Trapiche and Cerro Negro, the Trapiche Formation turbidite succession includes megabeds of carbonate boulders and olistoliths (as large as 50 m thick and 100 m long). The large boulders and olistoliths include limestone and dolostone, the source of which included strata from the San Juan Limestone down through the Zonda (upper Los Hornos) Formation (dolostone) of the Precordillera carbonate-platform succession (Fig. 2). The carbonate megabeds and olistoliths in the Trapiche Formation to the west differ from the carbonate olistoliths in the Las Vacas Conglomerate to the east in several important ways: (1) the source of the clasts in the Trapiche megabeds has a greater stratigraphic range than that of the Las Vacas olistoliths; (2) the Trapiche boulders are somewhat rounded to subrounded, in contrast to the sharply angular Las Vacas olistoliths; (3) the boulders in the Trapiche Formation are commonly in clast-supported megabeds (Astini, 1994b), in contrast to the isolated, matrix-supported olistoliths in the Las Vacas conglomerates; and (4) the Trapiche megabeds are scattered at numerous levels through a thick (~1200 m) stratigraphic succession, in contrast to a thinner (330 m) stratigraphic succession of Las Vacas conglomerates that contain olistoliths. These differences demonstrate different tectonic settings of deposition for the Las Vacas olistolith-containing conglomerate and the Trapiche carbonate-boulder megabeds, and they also indicate differences in depositional settings between the Trapiche turbidites in Rio de Los Piojos and the Trapiche megabeds in Sierra de Trapiche.

The stratigraphic restriction of the source of carbonate boulders in the Trapiche megabeds indicates a source that was tectonically detached within the stratigraphic succession; however, the detachment was within the Zonda (upper Los Hornos) Formation, stratigraphically lower than the detachments of the El Corral and Los Celestitos thrust sheets in the San Juan Limestone (Fig. 2). The source of the megabeds must have been some distance west of the leading edges of the El Corral and Los Celestitos thrust sheets; however, the actual distance is not closely constrained because of uncertainties in restoring the shortening on the Andean thrust faults (Figs. 1, 16C). A possible source for the Trapiche megabeds is a break-forward thrust sequence, in which a lower-level detachment in the Zonda (upper Los Hornos) Formation broke forward westward into the Ocloyic foreland beneath the upper-level El Corral and Los Celestitos thrust sheets (detached in the San Juan Limestone). A frontal ramp and eroded fault tip provide the requisite geometry for the source of the Trapiche megabeds (Fig. 16C). The position of the megabeds in the Trapiche succession suggests analogy with progressive foredeep flexural waves in the Alpine and Apennine foredeeps, so that the megabeds in the Trapiche Formation represent deposition in a foredeep advancing westward together with the west-vergent Ocloyic thin-skinned thrust belt (Astini, 1994b).

The inferred Ocloyic frontal ramp, here called the Cerro Negro thrust fault, also provides a tectonic partition between the megabed succession in the western Trapiche Formation and the finer turbidites in the eastern Trapiche Formation above the El Corral and Los Celestitos thrust sheets. The eastern Trapiche Formation may represent deposition in a piggyback basin in a broad syncline in the hanging wall of the Cerro Negro thrust sheet (Fig. 16C), similar to examples in the Apennines (Ricci-Lucchi, 1987). The frontal ramp may have served as a submarine drainage divide, as well as a sediment source for the carbonate boulders within the western facies of the Trapiche Formation.

7. Ocloyic thin-skinned thrust belt

A frontal thin-skinned thrust belt propagating westward into the foreland basin from the internal structures of the Ocloyic orogen offers an explanation for (1) carbonate and shale olistoliths in the Las Vacas conglomerate, (2) a stratigraphically restricted source of the olistoliths, (3) contractionally deformed beds in some olistoliths, (4) west-vergent structures with styles different from Andean structures, (5) dip orientation of beds below Ordovician Trapiche beds at an angular unconformity, (6) truncation of a west-vergent thrust sheet beneath the same angular unconformity below Ordovician Trapiche beds, (7) carbonate boulders in megabeds in the Trapiche Formation, and (8) partitioning of depositional settings of the Trapiche Formation. Although none of the separate observations listed here offers exclusive proof of an Ocloyic thrust belt, taken together all of these observations are consistent with a thin-skinned thrust belt. Conversely, any other interpretations, some of which have been suggested in the past, seem to require a separate solution as a mechanism for each of the observations.

8. Discussion of alternative interpretations

The olistoliths and conglomerates of the Las Vacas Conglomerate, as well as the angular unconformity between Las Vacas and Trapiche beds, have inspired alternative interpretations, commonly involving steep, basement-rooted faults. Suggested mechanisms include rift-related extension (e.g., Keller, 1999); extension during foreland flexural subsidence (Astini et al., 1995) and/or flexural reactivation of older rift-related faults (Thomas and Astini, 2003); post-orogenic collapse and extension (e.g., Astini, 1998a,b); and strike-slip faults in transtension (Baldis et al., 1989). In any of these mechanisms, a horst-and-graben geometry is predicted to produce uplifted sediment sources and adjacent depositional basins.

If the rounded clasts of igneous rocks and quartzites are inferred to be from the Precordillera basement (e.g., Keller, 1999), the minimum structural relief to supply sediment from fault blocks exceeds the total stratigraphic thickness of the Precordillera platform succession, which must have been eroded away to unroof the basement rocks in horst blocks. This interpretation implies erosional stripping of the cover, followed by erosion of basement rocks from horst blocks, and deposition of the bouldery detritus in adjacent graben blocks. The Las Vacas conglomerates, however, do not record progressive unroofing

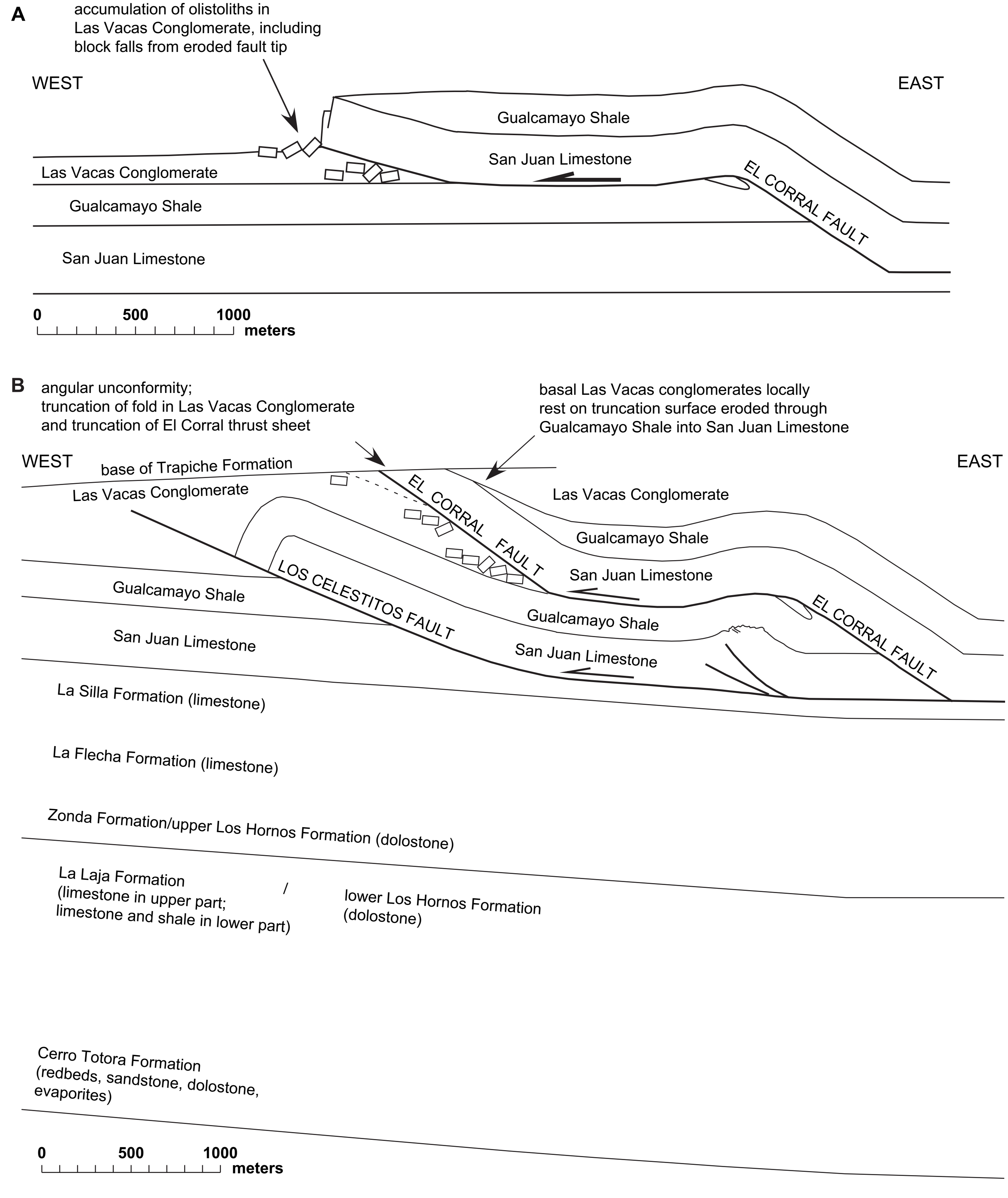

Fig. 16. Sequential cross sections to illustrate Ocloyic thin-skinned thrusting (rectangles schematically showing olistoliths are not to scale). (A) El Corral thrusting and supply of olistoliths into Las Vacas Conglomerate, erosional truncation of Gualcamayo Shale and San Juan Limestone in El Corral hanging wall. (B) Los Celestitos thrusting, folding of San Juan Limestone and Gualcamayo Shale at Los Celestitos, back folding of El Corral fault in hanging wall of Los Celestitos fault, fault-tip folding of Las Vacas Conglomerate, erosional truncation of Las Vacas Conglomerate in fault-tip fold and of leading edge of El Corral thrust sheet before deposition of Trapiche Formation. (C) Cerro Negro thrusting, transporting El Corral and Los Celestitos thrust sheets in Cerro Negro hanging wall, deposition of Trapiche Formation in piggy-back basin east of Cerro Negro frontal ramp, supply of carbonate boulders from the succession of carbonates in Zonda (upper Los Hornos) through San Juan into boulder beds and olistoliths into western facies of Trapiche Formation.

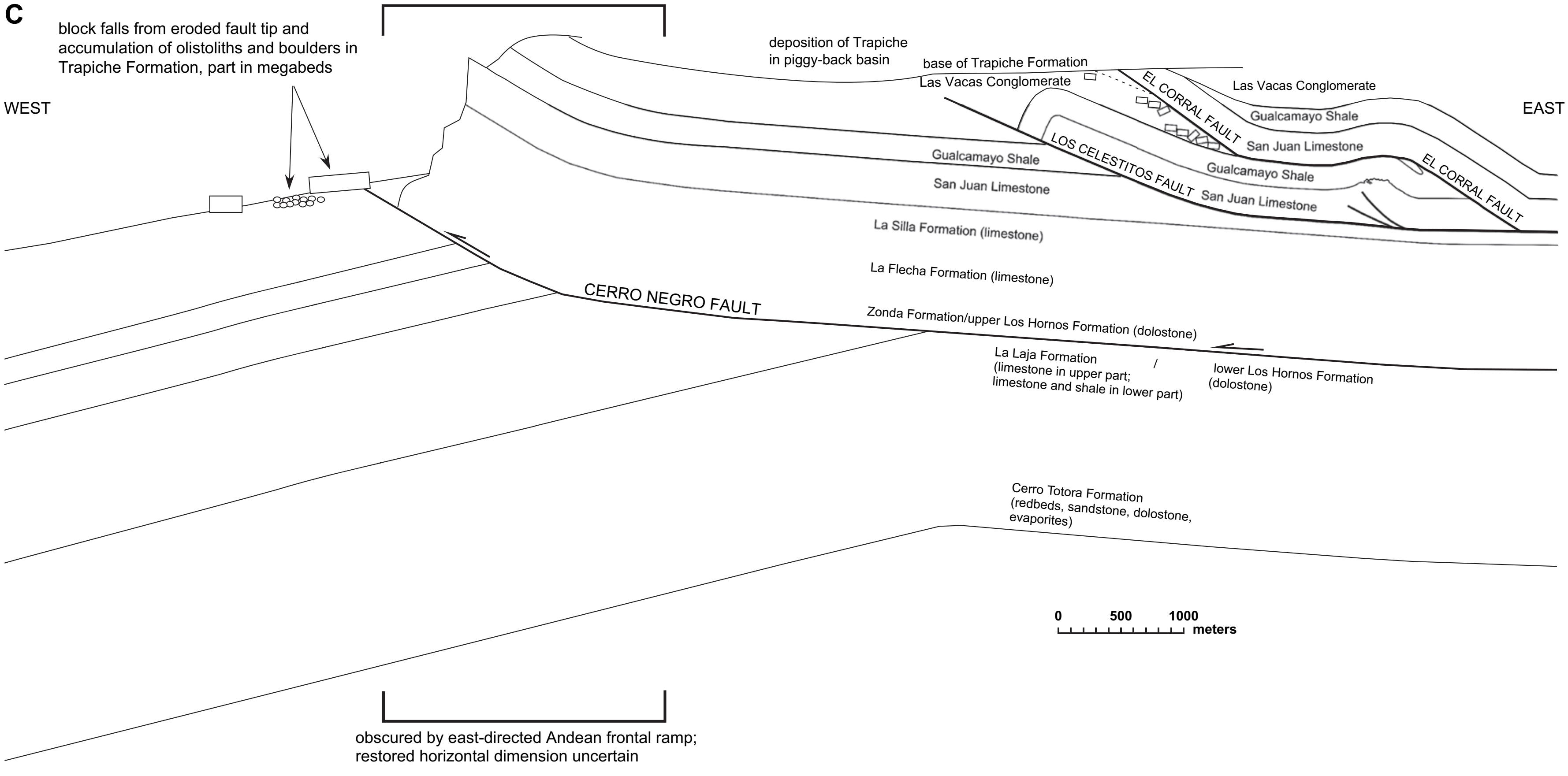

Fig. 16 (*continued*).

of horst blocks. Instead large, angular olistoliths of the youngest stratigraphic units on the inferred horst blocks are mixed with rounded boulders of the presumed basement rocks, but stratigraphic units between the San Juan Limestone and basement are not represented in the detritus. This mechanism does not account for the preservation of a proximal source for the large, angular olistoliths simultaneously with exposure of an appropriate source for the rounded clasts of igneous rocks and quartzites.

Recognizing that the rounded boulders are from extrabasinal sources and not from the underlying basement allows that horst blocks of smaller structural relief might have exposed only the upper beds of the Precordillera platform carbonate succession. In this interpretation, rounded boulders from extrabasinal sources were transported into the graben blocks either longitudinally or transversally through canyons or transfer fault zones (Astini, 1998a; Astini and Thomas, 1999). Olistoliths from the San Juan Limestone and Gualcamayo Shale were supplied from proximal sources, perhaps fault scarps, along the margins of horst blocks. Although this interpretation accounts for the mixture of rounded extrabasinal clasts with much larger olistoliths from a restricted stratigraphic interval, it offers no explanation for the olistoliths that consist of contractionally folded beds, and the stratigraphic restriction of the source of olistoliths requires a persistent fortuitous exposure of a limited part of the stratigraphic cover.

The angular unconformity in the Rio de Los Piojos between Trapiche beds and the palinspastically restored east-dipping Las Vacas beds can be explained in the context of a rotated half-graben block in the hanging wall of a listric normal fault (Astini and Thomas, 1999). An east-dipping rotated block is consistent with a down-to-west, west-dipping listric extensional fault. The possible mechanisms for east–west extension in the Precordillera include (1) reactivation of rift-related basement faults, (2) flexural extension during down-to-east foreland subsidence (in the mechanism described by Bradley and Kidd, 1991), or (3) extension during post-orogenic relaxation. In each of the alternatives, the eastern Precordillera has an eastern rift margin, and subsidence of the platform was down to east. In those settings, the most likely sense of extensional listric faults is down to east, requiring that rotated hanging-wall blocks dip to the west. The east-dipping eroded Las Vacas beds, therefore, must be placed as an exceptional counter-regional rotation within a dominantly down-to-east system. The lack of recognition in the field of any example of an extensional normal fault, or any exposed eroded horst block, leaves all of these alternatives as hypotheses, depending on reconstructions for separate observations.

9. Conclusions

None of several isolated, seemingly unrelated observations uniquely defines an Ocloyic thrust belt, which has been fragmented and obscured by east-vergent Andean thrusting; however, taken together, the vestiges of thrust-belt style suggest consistent geometry of a west-vergent, thin-skinned thrust belt. The structurally higher El Corral and Los Celestitos thrust faults have detachments near the base of the San Juan Limestone. The exposed west-vergent footwall frontal ramp of the El Corral fault has the geometry of a fault-bend fold, and an inferred subsurface frontal splay in the Los Celestitos thrust sheet accounts for an exposed west-vergent fold train. An angular unconformity beneath the Trapiche Formation truncates the east-dipping backlimb of a fold associated with the fault tip of the subsurface Los Celestitos fault, and the same unconformity truncates the leading edge of the El Corral thrust sheet, indicating that thrusting was coeval with deposition of the Las Vacas Conglomerate. Stratigraphic restriction of the source of the olistoliths in the Las Vacas Conglomerate confirms detachment within the San Juan Limestone, and folded beds in olistoliths indicate contractional deformation of the olistolith source. Carbonate-boulder megabeds in the western facies of the Trapiche Formation indicate a local, stratigraphically less restricted source, suggesting break-forward propagation of a lower-level thrust fault into the Ocloyic foreland, where a leading fault-tip fold provided a mechanism for exposure of the carbonate strata in the thrust sheet. Stratigraphic distinctions in the Trapiche Formation suggest that the fault-tip fold also separated a piggy-back basin on the east from the open foreland to the west.

Shortening indicated by top-to-west ductile shear zones within the exposed basement east of the Precordillera has the same sense of contraction as the west-vergent thin-skinned thrust faults of the Ocloyic foreland. Unroofing indicated by rock types of clasts in the clastic-wedge conglomerates documents structural separation between the metamorphic and igneous rocks on the east and the sedimentary cover on the west, suggesting a westward rise in the level of the décollement and a break-forward sequence of thrusting over the Ocloyic foreland.

Geometry of the interpreted Ocloyic thrust faults indicates break-forward thrust propagation into the proximal fill of the foreland basin. Depositional settings of the synorogenic turbidites indicate that the thrusts propagated into subaqueous sediment, giving rise to downslope movement of the large intrabasinal olistoliths. Coeval with thrusting, sediment dispersal from the orogenic hinterland on the east supplied coarse extrabasinal detritus to the foreland basin.

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