ABSTRACT

A TRIASSIC SYNDEPOSITIONAL DETACHMENT SYSTEM, ISCHIGUALASTO PROVINCIAL PARK, NORTHWESTERN ARGENTINA

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The Ischigualasto basin of northwest Argentina contains ~4 km of non-marine strata. In the southeast part of the basin, the Middle Triassic Los Rastros Formation contains a ~1 km² area where rocks exhibit both extensional and contractional deformation features. To the east, both high angle and listric normal faults are the dominant structures. To the west, deformation consists of reverse and thrust faults, in addition to upright and overturned folds. Faults in both areas sole into a sub-horizontal detachment surface, below which rocks are undeformed. Deformed Los Rastros Formation strata are overlain by lightly-deformed/undeformed rocks of the Upper Triassic Ischigualasto Formation. The Agua de la Peña detachment system is interpreted to have formed as a result of gravity spreading/depositional loading of lacustrine delta platform and fluvial deposits above an overpressured shale décollement. Although 2-3 orders of magnitude smaller, the cross-sectional shape and interpreted driving mechanisms of the Agua de la Peña detachment are similar to paired extensional-contractional fault systems formed along continental margins. Based on reconstructed geometry and interpreted rheology, the contractional portion of the detachment can be modeled as a critical-tapered wedge, and provides a small-scale analogue for fold-thrust belts formed in passive-margin settings.
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1. PHOTO MOSAIC OF THE AGUA DE LA PEÑA CANYON EXPOSURE
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INTRODUCTION

The geological investigation presented below was conducted to determine the geometry, kinematics, and driving mechanisms of paired extensional-contractional deformation features observed in the Triassic rocks of the Ischigualasto basin, northwestern Argentina. The Ischigualasto basin is a Mesozoic continental back-arc rift basin that contains > 4 km of nonmarine strata. Near the Rio Agua de la Peña in the southeast part of the basin, the Middle Triassic Los Rastros Formation (~229-233 Ma) contains a small area (~1 km²) where rocks exhibit both extensional and contractional deformation features. To the east, both high angle and listric normal faults are the dominant structures. To the west, deformation consists of reverse and thrust faults, in addition to upright and overturned folds. Faults in both areas sole into a sub-horizontal detachment surface, below which rocks are undeformed. Deformed Los Rastros Formation strata are overlain by lightly-deformed/undeformed rocks of the Upper Triassic Ischigualasto Formation.

The detachment, roughly 10 km from the interpreted basin-bounding fault, formed at shallow depths (< 30 m from surface) in relatively shallow-water environments. Paired extensional-contractional detachment systems that have been described in the literature are most commonly associated with depositional loading and/or gravity gliding on low angle basin-ward dipping horizons in deltaic, continental shelf, and slope-rise strata along continental margins, and are 2-3 orders of magnitude larger than the detachment in the Los Rastros Formation. Although smaller, it can be assumed that the driving forces acting on this detachment were similar to those that act on larger detachment systems. The principal process involved in the development of these faults is considered to be depositional loading above rheologically weak strata at depth (usually evaporites or over-pressured shales). Given the absence of evaporites in the Los Rastros Formation, depositional loading and slip along an over-pressured shale horizon is the most likely cause of the detachment. The load that generated the gravitational potential to drive the detachment may have been created by Los Rastros Formation deltaic sedimentation and fluvial-channel deposition in the overlying Ischigualasto Formation. In this investigation, detachment-related deformation kinematics are reconstructed through detailed field mapping.

Comparisons with other gravity-driven systems allow the overall driving forces controlling deformation to be determined. Based on the geometry and rheological properties of the detachment system, the contractional portion of the Agua de la Peña detachment can be
modeled as a critical-tapered wedge, and has similarities to fold-thrust belts formed as a result of gravity spreading along modern-day passive continental margins.

GEOLOGICAL SETTING OF THE ISCHIGUALASTO BASIN

The Ischigualasto basin is situated in northwest Argentina, in the northeast part of the San Juan Province (Figure 1A, Figure 1B). During Mesozoic time, oceanic-continental plate interactions along the southwestern margin of Pangea produced a region of extensional deformation cratonward of the proto-Andean magmatic arc (Tabor, et al., 2004). Extension was focused along the northwest-trending boundary of Paleozoic accreted terranes and the Precambrian Gondwanan basement (Uliana et al., 1989). The Ischigualasto basin is one of a series of continental-rift basins that developed in the region as a result of this extension (Figure 1A) (Uliana and Biddle, 1988).

Rift-related deposition in the Ischigualasto basin began during the Early Triassic, as northeast-directed normal displacement on the paleo-Valle Fertil fault led to the development of a structural half-graben (Figure 1C) (Milana and Alcober, 1994). Deposition in the basin continued throughout the Triassic and resulted in the accumulation of > 3.5 km of nonmarine and volcanic strata (Alcober, 1996). The rocks of the Ischigualasto basin are exposed in the hanging wall of the Valle Fertil fault, which is interpreted as a northeast-dipping, reverse-reactivated, Mesozoic normal fault (Milana and Alcober, 1994). Reactivation of the Valle Fertil fault initiated at ~2 Ma during basement-involved shortening in the Andean foreland (Zapata and Allmendinger, 1996). Inversion of Ischigualasto basin strata has resulted in near-complete exposure of the Triassic stratigraphic interval in the vicinity of the Ischigualasto Provincial Park (Figure 1D).

The study area of this investigation is situated in the eastern part of the basin in the Rio Agua de la Peña drainage. Rocks in the study area have a regional dip of ~8° to the northeast, and are highly segmented by normal faults providing multi-level exposures of the Middle-Late Triassic-aged deformation in the Los Rastros and Ischigualasto formations. One exceptional exposure of the deformed Triassic interval is along the north wall of the Agua de la Peña Canyon.
Figure 1. Reference maps showing location of study area. A) Distribution of Triassic basins in southern South America. B) Map of Argentina with the Province of San Juan in blue. Inset C is represented by small box. C) Satellite photo of the southern part of the Ischigualasto Provincial Basin showing large-scale structures and location of inverted basin bounding faults. D) Air photo of southeastern part of the Ischigualasto Basin including study area showing contacts between the Los Rastros (LR), Ischigualasto (TR), and Los Colorados (TC) formations. Location of map in Figure 4 is outlined in black.
ISCHIGUALASTO BASIN STRATIGRAPHY

Triassic rocks of the Ischigualasto basin consist of the Lower Triassic Tarjados and Talampaya formations, the Middle Triassic (Ladinian) Chañares, Ischichuca, and Los Rastros formations, and the Upper Triassic (Carnian-Norian) Ischigualasto and Los Colorados formations (Figure 2) (Romer and Jensen, 1966; Alcober, 1996). All the stratigraphic units in the basin were deposited in terrestrial environments (Milana and Alcober, 1994).

Structures studied as part of this investigation involve the Middle-Upper Triassic Los Rastros and Ischigualasto formations (Figure 3). In the basin, the Los Rastros Formation consists of ~300 m of fluvial/lacustrine sandstone and mudstone. Lacustrine strata contain upward-coarsening sequences of carbonaceous mudstone, siltstone, and sandstone that represent prodelta/delta slope deposits (Lopez, 1995). Individual upward-coarsening packages display clinoform geometries that indicate lake depths of < 15 m (Milana, 1998). Upward coarsening lacustrine rocks are commonly overlain by distributary- and fluvial-channel sandstone and associated delta platform/floodplain deposits (Lopez, 1995). Los Rastros channel deposits display scoured bases, consist of fining-upward beds of very coarse- to fine-grained sandstone, and are 20-500 m in width when measured perpendicular to paleoflow. Lacustrine delta platform and floodplain deposits consist primarily of tabular beds of mudstone, siltstone, and fine-grained sandstone that contain abundant carbonaceous material and plant fossils.

Radiometric dating of sanidine crystals from altered ash deposits and basalts from the base and top of the Los Rastros Formation, respectively, indicate deposition of the unit between 233-229 Ma (Valencio et al., 1975; Odin et al., 1982; Currie et al., in review). These ages, along with abundant plant fossils collected from the Los Rastros Formation (Alcober, 1996), indicate a Ladinian age of deposition according to the time scale of Gradstein et al. (1995).

The Los Rastros Formation is overlain by fluvial deposits of the La Peña Member of the Ischigualasto Formation (Currie et al., in review). Of particular interest to our study is the basal La Peña Member which consists of 10-15 m of vertically stacked, laterally coalesced, lenticular beds of pebble-cobble conglomerate and coarse-very coarse-grained sandstone. These beds are interpreted as braided fluvial channel deposits (Alcober, 1996) and contain sedimentary structures that include trough cross-stratification, ripple-cross lamination and plane-parallel beds.
Figure 2. Time-stratigraphic chart of Triassic rocks in the Ischigualasto Basin. The Los Rastros and Ischigualasto formations are the primary units of this research (Modified from Alcober, 1996). Radiometric ages for basin strata are from Rodgers et al. (1996), Shipman (2004) and Currie et al. (in review).
Figure 3. Log of stratigraphic section of the upper Los Rastros and lower Ischigualasto formations measured along the Agua de la Peña Canyon. Section displays lithologies, interpreted depositional environments, and position of detachment horizon.
containing primary-current lineations. Paleocurrent data from trough cross-strata in these bodies indicate north-northeast paleoflow directions (350°-030°). The basal La Peña sandstones also contain lenses of fine-grained sandstone and mudstone that are interpreted as abandoned channel deposits.

While the La Peña Member is undated, sanidine crystals from a bentonite sampled ~80m above the top of the member yielded an \(^{40}\text{Ar}/^{39}\text{Ar}\) age of 227.8 ± 0.3 Ma (Rogers et al., 1993). This age, along with abundant vertebrate fossils from the lower 2/3 of the Ischigualasto Formation, indicate a Carnian age of deposition according to the time scale of Gradstein et al. (1995).

**AGUA DE LA PEÑA DETACHMENT SYSTEM**

In the southeast part of the Ischigualasto basin a small area (~1 km\(^2\)) of Triassic extensional and compressional structures is exposed in and adjacent to the Agua de la Peña Canyon (Figure 4). The eastern part of the deformed area is dominated by both high-angle and listric normal faults, whereas the western part displays thrust and reverse faults, as well as upright and overturned folds. Faults in both areas sole into a bedding-parallel detachment horizon above which hanging wall rocks are slightly deformed. Below is a more detailed description of the deformation features observed in the study area as well as an interpretation of their origin.

**Extensional Structures**

Extensional structures in the study area consist primarily of north-striking normal faults that are concentrated in an ~100 meter-wide zone at the eastern edge of the deformed area (Figure 4, Plate 1). The dominant structures in this area are three north-striking listric normal faults that primarily deform Los Rastros Formation strata (Figure 5). These faults dip to both the west and east and have maximum-observed displacements of < 40 m, with collective displacements of ~80 m. The two primary west-dipping listric faults exposed in the Agua de la Peña Canyon merge into a single fault to the north (Figure 4). Rotation of Los Rastros Formation strata in the hanging wall of the listric faults produced a low-amplitude rollover anticline, the crest of which is centered and runs parallel to the area of extension (Figure 5). The rollover structure is dissected by numerous small-scale normal faults (displacements < 3 m),
Figure 4. Detailed geologic map of the study area. Faults related to Middle-Late Triassic deformation in red, younger faults in green. Location shown in Figure 1D.
Figure 5. Close-up view of the extensional area exposed in the Agua de la Peña Canyon. Interpreted faults are in red; colored lines represent interpreted stratal horizons. TRl: Los Rastros Formation; TRl: Ischigualasto Formation. Dashed line represents contact between undeformed/deformed strata in the La Peña Member.
many of which also display listric geometries (Figure 5, Figure 6). Sense-of-shear indicators along fault planes, in the form of normal-sense attenuation and drag folds, indicate primarily dip-slip along the fault surfaces. The association of these small-scale faults with the rollover anticline indicates these faults may be akin to keystone faults described by Rowan et al. (1999).

In the canyon exposure, the three primary listric faults sole into a bedding-parallel detachment in Los Rastros Formation ~30 below the contact with the La Peña Member (Figure 5). However, bedding relationships and observed faults in the hanging wall of the central listric fault indicate the existence of a shallow level detachment horizon which transitions into a thrust fault at the eastern edge of the extensional area (Figure 5). This shallow detachment and thrust are dissected by younger normal faults and folded by the rollover anticline.

Although there is some variability in the orientation of observed normal faults, average fault orientations define a conjugate-fault pair striking north-northeast (~005°-035°). The average orientation calculated for these faults is ~ 110° (Figure 7).

The overall timing of extensional deformation can be discerned by evaluating the stratigraphy in both the hanging wall and the footwall of the primary listric normal faults. Approximately 10 m of Los Rastros Formation deposits in the hanging wall of the eastern-most listric fault are absent from the footwall (Figure 5). This 10 m-thick interval could be either hanging wall growth strata or deposits removed from the footwall by La Peña Member incision. The difference in hanging wall/footwall stratal thickness indicates that the majority of the extensional deformation in the area occurred prior to La Peña Member deposition. This interpretation is supported by the fact that most faults in the extensional zone are erosionally truncated by undeformed basal La Peña Member sandstones and conglomerates. However, in a few locations, small-scale normal faults (< 2 m) offset the base of the La Peña Member before being truncated by younger scour surfaces (Figure 8), indicating deformation was active during the initial stages of La Peña Member deposition.

Compressional Structures

Compressional structures are concentrated along an approximately 350 m wide zone at the western side of the deformed area (Figure 4, Plate 1). The primary structure in this area is an east-dipping thrust system in the Los Rastros Formation that soles into the master detachment fault (Figure 9). The thrust system is west-vergent, has a ramp-flat geometry, and contains two
Figure 6. Photographs of normal faults in the extensional area. A) Faults associated with primary listric normal fault in the eastern extensional area exhibiting normal drag. Hammer beneath carbonaceous bed in center of photo for scale. B) Small-scale “keystone” faults from central part of the extensional area. Faults in both photos are truncated by undeformed La Peña Member (Tr1) sandstones.
Figure 7. Stereonet showing contoured poles to the planes of normal faults in the study area. Two clusters are shown, which approximate conjugate fault pairs in the extensional area. The calculated maximum principle stress ($\sigma_1$) is nearly vertical with the minimum principle stress ($\sigma_3$) trending $\sim 110^\circ$. 
Figure 8. Field pictures of small-scale faults showing some displacement in both the Los Rastros Formation (TR1) and the lower part of the La Peña Member (TR1).
Figure 9. Photomosaic of structures in the contractional zone along the western wall of Agua de la Peña Canyon including a broad fault-bend anticline above thrust ramp, thrust duplex, and frontal imbricate of the system. Hanging wall floorwall cutoffs on the primary thrust indicate ~ 80 m of displacement.
primary imbricates. In addition, a small thrust duplex exists at the base of the primary thrust ramp (Figure 9). Hanging wall-footwall cutoffs in the canyon exposure indicate ~80 m of displacement on the observed thrusts. In the hanging wall of the thrusts, Los Rastros Formation strata exhibit north-trending, upright to overturned folds that display fault bend, fault propagation, and detachment geometries. Fault bend folds occur above ramps in the underlying thrusts, are symmetrical to asymmetrical, and have gentle to open inter-limb relationships (Figure 9). While these folds are generally upright, drag folding has overturned beds immediately adjacent to associated thrust surfaces.

Fault-propagation folds have been identified in fine-grained strata immediately adjacent to thrust faults in the structurally-highest thrust imbricate. These folds are asymmetric, upright to overturned, and display west-directed vergence (Figure 10). Detachment folds occur in Los Rastros strata in the hanging wall flat of the structurally-highest thrust imbricate. These folds are upright, symmetrical-asymmetrical, with open inter-limb relationships. In some cases fold limbs are truncated along the thrust décollement (Figure 10) suggesting distortional flow of hanging-wall lithologies into the cores of detachment anticlines (Wiltschko and Chappel, 1977; Mitra, 2003). Stereographic analysis of fold limb orientations indicates that average $\sigma_1$ orientation during deformation was $\sim$110° (Figure 11). This trend is nearly identical to the $\sigma_3$ orientation determined from the orientation of normal faults in the study area.

In addition to thrust faults and folds, several small displacement (< 4 m) reverse faults are also present in the western part of the study area (Figure 12). These structures are exclusively contained in the hanging wall of the upper-most thrust imbricate and are both west- and east-vergent. In the north part of the study area, reverse faults in Los Rastros Formation strata have been rotated by fault-bend folding (Figure 12), indicating they formed during the initial stages of compressional deformation.

The majority of compressional structures in the Los Rastros Formation are erosionally truncated by La Peña Member sandstones and conglomerates, which in places results in an angular unconformity between the two units (Figure 13). However, in the north part of the study area, the lower-most beds of the La Peña Member are folded into a syncline at the frontal part of the thrust system (Figure 14). At this location, deformed La Peña Member beds erosionally overlie deformed strata of Los Rastros Formation which are situated directly above the thrust
Figure 10. Folds in the contractional part of the Agua de la Peña detachment system. An overturned fault-propagation anticline (A) and syncline (B). (C) Truncated trailing limb of a detachment fold along thrust flat in the northern part of the study area.
Figure 11. Stereonet of orientations of fold limbs in study area. A) Orientation of bedding in fold limbs with corresponding poles to the planes. B) Pi diagram of fold limb poles to the planes showing best-fitting great circle, and calculated principle stresses.
Figure 12. Photo showing conjugate reverse faults rotated by folding. Fault was truncated by displacement by fault to the left and rotated by folding to produce normal-sense apparent offset of marker bed (green). Photo taken within eastern-most anticline in northern part of the study area.
Figure 13. Photograph of angular unconformity between the Los Rastros Formation and La Peña Member of the Ischigualasto Formation.
Figure 14. Field photo depicting observed folding in lower part of the La Peña Member of the Ischigualasto Formation (TRi). Yellow lines represent orientation of deformed Los Rastros strata in the hanging wall of the thrust. Green line marks the base of undeformed La Peña Member strata. Contact between the Los Rastros Formation (TRi) and La Peña Member in black. Frontal thrust of detachment system in red.
décollement. The folded conglomeratic sandstone is in turn truncated by undeformed beds of the upper La Peña Member. These relationships indicate that deformation occurred both prior to and following initial La Peña Member deposition. The final stages of deformation, however, preceded deposition of the youngest La Peña Member beds.

**Detachment Features**

An approximately 350 meter long, bedding-parallel detachment fault links the listric normal faults in the east part of the study area with the compressional thrust faults to the west. The rocks in the detachment zone consist primarily of ~1m of gray- to brown-colored mudstone that displays both color and compositional mottling (Figure 15). In addition, millimeter-scale, low-angle (<15°) fractures are present in the detachment zone. Other than the low-angle truncation of strata immediately above the detachment surface, rocks in both the hanging wall and footwall are little deformed.

Although undramatic, the observed structures in the detachment zone are consistent with features associated with deformation within overpressured shale beds and horizontal fault planes. Non-pedogenic compositional and color mottling is associated with fluid expulsion through semi-lithified, overpressured-shale beds (Morley, 2003). The low-angle fractures may be R- or P-shears formed at low angles to the horizontal detachment (Wilcox et al., 1973), and indicate brittle deformation in at least some stages of detachment fault displacement.

**Soft-Sediment Deformation Features**

In the eastern part of the study area, Los Rastros Formation and La Peña Member strata display evidence for sediment mobilization during the time of deformation. In the eastern extensional area, directly overlying the eastern-most listric fault, Los Rastros Formation sandstone and mudstone were vertically and laterally injected into the basal La Peña Member prior to lithification (Location A Figure 4, Figure 16). This injection feature is associated with ~2 m of normal-sense displacement of the lower contact of the La Peña Member. Overlying and lateral to the injection features, beds and sedimentary structures in La Peña Member sandstones are extensively convoluted (Figure 17A). This soft-sediment deformation is overlain by undeformed La Peña Member sandstones.
Figure 15. Field photo showing deformation features in the basal detachment. Mudstone of the detachment exhibits both color and compositional mottling and contains abundant bedding-parallel fractures (red lines). In this photograph, overlying strata were translated from right to left.
Figure 16. Field photo showing Los Rastros Formation strata injected into the overlying Ischigualasto Formation along a west-dipping normal fault. Black line marks the contact between the two units.
Figure 17. Field photos showing convolute bedding in Los Rastros Formation and La Peña Member sandstones.  A) Photo of upwardly decreasing convolution in beds of basal La Peña Member sandstones in location immediately above eastern extensional area. B) Photo of highly convoluted beds along trailing limb of detachment fold in western contractional area.
These soft-sediment deformation features are interpreted as being formed by the entrainment and expulsion of Los Rastros lithologies by the upward-migration of fluids along normal faults during the late stages of extensional deformation. The liquefaction features in the adjacent basal La Peña Member sandstone are interpreted as being generated by pore fluids being expelled upward through unconsolidated sand due to seismicity associated with extension or fluids escaping from the underlying normal faults. In the western zone of compression, sandstones in the upper part of the Los Rastros Formation display liquefaction structures similar to those in the La Peña Member suggesting fluid migration along the frontal thrust system as well (Figure 17B).

**Structural Synthesis**

Observed extensional, compressional, and liquefaction structures in the deformed area are consistent with deformation associated with syndepositional, gravity-induced displacement above an overpressured detachment horizon (Maestro et al., 2002; Bilotti and Shaw, 2005). This interpretation is based on the observation that deformation is restricted to the upper 30 m of the Los Rastros Fm and the lower 5 m of La Peña Member, and that the primary normal and thrust faults have similar displacements and are linked by a bedding-parallel detachment fault. Evidence of elevated pressures within the detachment is displayed by compositional/color mottling in the detachment zone, as well as evidence for fluidization and liquefaction of Los Rastros and La Peña lithologies above faults in both the extensional and compressional areas. Potential growth strata in the hanging-wall of detachment normal faults suggests deformation was initiated during the final stages of Los Rastros Formation lacustrine delta deposition and that the majority of detachment-related deformation as occurring prior to La Peña Member deposition. However, the presence of fluid-injection features and folds in La Peña Member strata indicates that deformation continued during the initial stages of Ischigualasto Formation deposition (Figure 17).

Figure 18 shows a schematic sequential reconstruction of detachment-related deformation. In this scenario, deformation was driven by depositional loading on the platform of a delta that was prograding into a shallow Los Rastros lake from the east. Progressive deformation was driven by both aggradation and the filling of extensional accommodation on the platform. Deformation initiated with the development of a shallow compressional-extensional
Figure 18. Schematic cross sectional reconstruction of the Agua de la Peña structure (no vertical exaggeration). A) Small-scale detachment develops within lacustrine delta deposits. B) Larger listric normal faults form and sole into the main detachment, which is linked to the newly formed thrust in the contractional zone. C) Delta deposition continues and westward migration. D) After a drop in lake level and fluvial incision, initial La Peña Mbr. deposition triggers fault reactivation. E) Fluvial deposition continues with undeformed conglomerates and sandstones overlying deformed Los Rastos Fm. and lower La Peña Mbr. strata.
detachment system within the deposits of a lacustrine delta complex (Figure 18A). This was followed by the development of conjugate listric normal faults sloping into the primary detachment horizon (Figure 18B) and the development of a rollover anticline in the center part of the extensional area. Small-scale normal faulting during this stage of deformation dissected the older shallow detachment system. Normal-sense slip on faults in the eastern part of the deformed area was transferred along the detachment fault and into thrust faults to the west. From the level of the detachment, the thrust ramped through the upper part of the Los Rastros Formation before flattening in the shallow sub-surface and at the toe of the lacustrine delta. Displacement along the thrust resulted in the development of fault-propagation and drag folds adjacent to thrust surfaces and fault-bend and detachment folds in the hanging wall. Continued deltaic deposition resulted in the development of a second west-dipping normal fault in the extensional zone and a frontal thrust imbricate in the area of compression (Figure 18C). Following delta progradation, a drop in lake level led to fluvial incision and unconformity development. Subsequent fluvial deposition of the La Peña Member was accompanied by small-scale reactivation of both normal and thrust faults (Figure 18D). Continued fluvial-channel migration across the study area resulted in the deposition of La Peña Member conglomerates and sandstones above the entire area of detachment-related deformation (Figure 18E).

Driving Mechanisms

In the kinematic reconstruction presented above, the contractional frontal part of the detachment system is driven by extension produced by gravity spreading/depositional loading of lacustrine delta platform and fluvial deposits, with lateral translation occurring above an overpressured shale décollement. Below I present a more thorough discussion on the physical driving mechanisms of the Agua de al Peña detachment system.

Gravitationally-driven, extensional-contractional fault systems, although unreported from fluvial-lacustrine depositional systems such as the Triassic-aged Ischigualasto basin, are common features in passive margin deltas (Rowan, et al., 2004, Peel, et al., 1995; Bilotti and Shaw, 2005). Continental-margin detachment systems have been previously described as a combination of large-scale gravity gliding and gravity spreading (Trudgill, et al., 1999; Rowan et al., 2004). These models, however, do not fully account for the geometry commonly associated with these systems. Specifically, many continental-margin detachment systems do not display
the basin-dipping or horizontal décollements associated with gravity gliding or gravity spreading, respectively (Schultz-Ela, 2001). Instead, many margin-detachment systems have décollements that dip landward and/or ramp up section in the direction of transport (Figure 19) (Rowan et al., 2004). This geometry, which is similar to the Agua de al Peña detachment system discussed above, is akin to the large-scale geometry of thrust belts and accretionary prisms (Rowan et al., 2004; Bilotti and Shaw, 2005). Because of this similarity, it has been proposed that the overall deformation mechanisms in some passive margin detachment systems are similar to critical-tapered wedges of collisional/accretionary fold-thrust belts (Rowan et al., 2004).

In a critical-taper wedge, the overall geometry of the wedge and the mechanics of deformation are governed by the internal strength of the wedge material, and the strength of the basal décollement above which the wedge moves (Figure 20) (Davis, et al., 1983; Dahlen et al., 1984). Wedge taper, which is defined by the angle of the surface slope and the angle of the basal detachment, is attained as a result of the addition of material to the wedge or by internal deformation. Once critical taper is achieved, the wedge will move forward as a coherent body along the basal detachment. Forward propagation results in the contractional deformation at the tip of the wedge as new material is incorporated into the wedge. Forward propagation, however, also has a tendency to lengthen the wedge, resulting in an overall reduction in taper. If taper is decreased below a critical angle, the wedge will cease its forward displacement. In the case of critical-taper wedges along continental margins, critical taper is attained primarily as a result of the addition of sediment at the rear of the wedge due to the progradation of delta/shelf depositional systems (Rowan et al., 2004). Sediment deposition increases the surface slope of the wedge, which in turn may result in the wedge achieving a critical angle (Bilotti and Shaw, 2005). Shelf/delta sedimentation also provides the gravitational potential to drive the proximal extension observed in passive margin detachment systems (Peel et al., 1995; Rowan et al., 2004).

The overall geometry of the Agua de la Peña detachment system is similar to the linked extensional-contractional fault systems of passive continental margins. As these fault systems have been described as critical-taper wedges (Rowan et al., 2004; Bilotti and Shaw, 2005), below I evaluate whether the deformation associated with the Agua de la Peña detachment system can be explained within the context of critical-taper-wedge theory.
Figure 19. Cross section from the central Gulf of Mexico displaying the wedge-shaped fold-thrust belts that can develop on passive margins. Displacement on this system was facilitated by salt withdrawal (remaining salt in black), but overall deformation style is similar to overpressured-shale detachments. Vertical exaggeration ~10 x. Modified from Peel et al. (1995).
Figure 20. Schematic diagram showing nature of a critically-tapered wedge. Equation relates taper (\(a\) + \(b\)) to the basal and internal strength of a wedge. Modified from Dahlen et al. (1984).

\[
\frac{[Hd^d/C + ((\phi)\sin(-1))/(\phi)\sin(\gamma-1) + (d/m - 1)]}{[Hd^d/C - (\gamma-1)\eta + g(d/m - 1)]} \approx g + a
\]
**Agua de la Peña Wedge Geometry**

In order to determine the applicability of critical-wedge theory to the Agua de la Peña detachment system, the geometry of the wedge must be quantified. This is not straightforward because the original surface slope of the wedge (e.g. the topographic-bathymetric transition across the platform and slope of the upper Los Rastros Formation lacustrine delta) was eroded by subsequent La Peña Member fluvial incision. However, in stratigraphically lower parts of the Los Rastros Formation adjacent to the study area, the maximum thickness of lacustrine-delta clinoforms are $\sim 15$ m (Lopez, 1995). As this thickness represents the vertical component of the topographic-bathymetric transition, a change of $15$ m averaged across the width of the compressional area ($\sim 450$ m), results in a reconstructed surface-slope angle ($\alpha$) of $\approx 1.9^\circ$ (Figure 21). The angle of the basal detachment ($\beta$) can be estimated based on the observed cross-sectional geometry in the canyon exposure (Figure 21), where $\beta \approx 3.8^\circ$. Combining these two angles results in a reconstructed wedge taper ($\alpha + \beta$) for the Agua de la Peña system of $\approx 5.7^\circ$. It should be noted, however, that this is most likely a maximum value. The surface slope of the Los Rastros lacustrine delta front/platform may have been lower, as most clinoforms in the measured section are $< 15$ thick (Milana, 1998). In fact, the measured thickness of progradational lacustrine delta deposits in the Agua de la Peña Canyon measured (Figure 3) are 5-8 m thick. As such, the overall surface slope of the depositional system in the deformed could have been $< 1.9^\circ$. However, given that the thinnest observed progradational sequences are $\sim 5$ m, depositional slopes over the deformed area were most likely $> 0.5^\circ$. When combined with the observed $\beta$ value of $\approx 3.8^\circ$, this results in a minimum wedge taper of $4.3^\circ$. The implications of a reduced wedge taper are discussed in more detail below.

The taper of a critical wedge is a function of the relationship between the internal strength of the wedge and the strength of the basal detachment (Chapple, 1978; Davis et al., 1983). Critical taper with respect to wedge/detachment strength can be evaluated using the force-balance equation of Davis et al. (1983) as modified by Dahlen (1990):

$$\alpha + \beta \approx \left[ \frac{(1-\rho_w/\rho)\beta + \mu_b(1-\lambda_b)-S_b/\rho g H}{(1-\rho_w/\rho)+2(1-\lambda)(\sin(\phi)/(1-\sin(\phi)))+C/\rho g H} \right]$$  

**Equation 1**
Figure 21. Schematic representation of how $a$ and $b$ were determined for the Aguas de la Peña structure. The red lines in the center represent the observed area of contractional deformation. Dotted line is the generalized wedge shape with $a$ and $b$ angles shown in the bottom wedge.
where: \( \alpha \) is the surface angle of the wedge and \( \beta \) is the average angle of the basal detachment; \( \rho_w \) and \( \rho \) are the densities of water and siliciclastic sediment, respectively; \( \mu_b \) is the basal coefficient of friction; \( \lambda_n \) are the basal and wedge pore-fluid-pressure ratios, respectively; \( S_b \) and \( C \) are the detachment and wedge cohesion, respectively; \( g \) is the gravitational constant, \( H \) is the average thickness of the wedge; and \( \phi \) is the angle of internal friction. These variables, which are standard components in critical taper wedge theory, are described in more detail below and presented in Table 1.

In my calculations, I assumed water and sediment densities of 1000 kg/m\(^3\) and 2200 kg/m\(^3\) respectively. Basal cohesion \( (S_b) \) is assumed to be near zero since the detachment horizon behaved as a frictional fault during deformation (Bilotti and Shaw, 2005). Wedge cohesion \( (C) \) is assumed to be in the range of 5-15 MPa as determined from rock-mechanics experiments (Hoshino et al., 1972; Bilotti and Shaw, 2005).

The angle of internal friction \( (\phi) \) for the wedge can be calculated using the equation:

\[
\phi = \pi/2 - 2\delta_b - 2\psi_b
\]

Equation 2

where \( \delta_b \) is the basal detachment step-up angle that is equal to the observed angle of the frontal-thrust ramp of the detachment (22°, Figure 9), and \( \psi_b \) is the estimated angle between the maximum principle stress \( (\sigma_1) \) and basal detachment during deformation (Dahlen et al., 1984).

Given the relatively low angle of the detachment and a near horizontal \( \sigma_1 \), I assume \( \psi_b \approx 1° \), resulting in a calculated \( \phi = 44° \). The tangent of \( \phi \) gives the wedge coefficient of internal friction \( (\mu) \) (Davis et al., 1983). In this case \( \mu = 0.97 \), which falls within the range of empirically-derived rock-strength values (Byerlee, 1978). Given that the rheological properties of the wedge are most likely similar to the basal detachment, it is assumed that \( \mu \) is equal to the basal coefficient of internal friction \( (\mu_b) \) (Davis et al., 1983).

The wedge fluid pressure ratio \( (\lambda) \) is estimated to \( \approx 0.6 \) based on observed shallow (<100 m) pore-fluid pressures in both normal and overpressured sections (Moore and Tobin, 1997; Taylor and Leonard, 1990). In order to determine a possible range of basal pore-fluid pressure ratios \( (\lambda_b) \) for a critical wedge, Equation 1 can be simplified to:
Table 1. Variables used in basal pore fluid pressure model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Slope - $\alpha$ (degrees)</td>
<td>&lt; 1.9°</td>
<td>Measured from outcrop and cross-section reconstructions</td>
</tr>
<tr>
<td>Detachment dip - $\beta$ (degrees)</td>
<td>&lt; 3.8°</td>
<td></td>
</tr>
<tr>
<td>Sediment Density - $\rho$ (kg/m$^3$)</td>
<td>2200</td>
<td>Average density of mud-rich siliciclastic sediment (Bilotti and Shaw, 2005)</td>
</tr>
<tr>
<td>Water Density - $\rho_w$ (kg/m$^3$)</td>
<td>1000</td>
<td>Fresh water density</td>
</tr>
<tr>
<td>Gravitational Constant - $g$ (m/s$^2$)</td>
<td>9.8</td>
<td>Known</td>
</tr>
<tr>
<td>Average Wedge Thickness - $H$ (m)</td>
<td>45 m</td>
<td>Calculated from restored cross sections</td>
</tr>
<tr>
<td>Angle of Internal Friction - $\phi$ (degrees)</td>
<td>44°</td>
<td>Calculated from frontal thrust step-up angle</td>
</tr>
<tr>
<td>Wedge Fluid Pressure Ratio - $\lambda$</td>
<td>0.3-0.9</td>
<td>Potential range in normal-overpressured wedges (Moore and Tobin, 1997; Taylor and Leonard, 1990)</td>
</tr>
<tr>
<td>Basal Fluid Pressure Ratio - $\lambda_b$</td>
<td>0.7-0.94</td>
<td>Modeled results using formula of Davis et al. (1983)</td>
</tr>
<tr>
<td>Basal Step Up Angle - $\delta_b$ (degrees)</td>
<td>22°</td>
<td>Measured from outcrop photographs</td>
</tr>
<tr>
<td>Angle between max stress ($\sigma_1$) and detachment - $\psi_b$</td>
<td>1°</td>
<td>Assumed near horizontal $\sigma_1$ and observed detachment angle</td>
</tr>
<tr>
<td>Internal Coefficient of Friction - $\mu$</td>
<td>0.97</td>
<td>Calculated from $\delta_b$ and $\psi_b$ (Dahlen et al., 1984)</td>
</tr>
<tr>
<td>Basal Coefficient of Friction - $\mu_b$</td>
<td>0.97</td>
<td>Assumed to be similar to wedge coefficient of friction (Davis et al., 1983)</td>
</tr>
<tr>
<td>Wedge Cohesion - $C$ (MPa)</td>
<td>5-15 MPa</td>
<td>Determined by rock mechanics studies (Hoshino et al., 1972)</td>
</tr>
<tr>
<td>Basal Cohesion - $S_b$ (MPa)</td>
<td>0</td>
<td>Negligible cohesion in a frictional fault (Davis et al., 1983)</td>
</tr>
</tbody>
</table>
\[ \alpha + R\beta = F \]  
Equation 3

where

\[ R = \frac{(1 - \lambda)K}{(1 - \rho_u/\rho) + (1 - \lambda)K} \]  
Equation 4

\[ F = \frac{(1 - \lambda_b)\mu_b}{(1 - \rho_u/\rho) + (1 - \lambda)K} \]  
Equation 5

and

\[ K = \frac{2(\sin(\phi))/(1-\sin(\phi))}{1} \]  
Equation 6

Using these equations, observed values of \( \alpha \) vs. \( \beta \) can be plotted against a range of \( \lambda_b \) ratios to evaluate the criticality of the wedge given its geometry (Figure 22A) (cf. Davis et al., 1983). Given the parameter values listed above, and the reconstructed geometry of the Agua de la Peña detachment, the wedge would have reached a critical state at \( \lambda_b \geq 0.78 \) (Figure 22A). This, however, is a minimum value given that the \( \alpha \) and \( \beta \) used in the calculations are maximum estimates of wedge taper. Any decrease in taper would require an increase in \( \lambda_b \) for the wedge to reach criticality. For example, if \( \alpha + \beta \approx 1 \), \( \lambda_b \) would have to be \( \sim 0.96 \) for the wedge to exist in a critical state.

High pore-fluid pressure in shale detachments is required because displacement will not occur until the frictional yield-strength of the décollement lithology is surpassed. It is commonly thought that a thick overburden section is required to elevate fluid-pressure in the décollement sufficiently to overcome the yield strength of the detachment lithology (Rowan et al., 2004). However, in the study area the interpreted depth to detachment was a maximum of \( \sim 45 \) m. At this shallow depth, it is unlikely that overburden alone would have been sufficient to generate enough fluid pressure so as to permit slip on the detachment. However, elevated pore-fluid pressures along the detachment could have been enhanced due to the presence of methane produced by the decomposition of organic material in carbonaceous beds both above and below the detachment (Figure 3). High pore-fluid pressures along the detachment horizon at the time of deformation is supported by field observations in the study area including liquefaction features in sandstones along the frontal thrust ramp, injection of underlying Los Rastros rocks into the La Peña Member, and compositional mottling along the detachment horizon. In addition, it has been shown that shale décollements can be impregnated with and confine gas at relatively shallow depths. Extensional deformation along shallow (\( \sim 25-150 \) m) shale décollements in the
Figure 22. A) Graph defining critical-subcritical stability field for Agua de la Peña contractional wedge for a range of basal pore-fluid ratios. Graph shows that for the estimated \( \alpha \) and \( \beta \) angles of the wedge, the system would have been at a critical state at \( \lambda_b > 0.79 \). B) Graph showing comparison of the Agua de la Peña wedge with other critically-tapered wedges. Shaded blocks represent observed or interpreted ranges of \( \alpha \) and \( \beta \) given possible variations in \( \lambda_b \). Modified from Bilotti and Shaw (2005).
Quaternary strata of Ebro delta of Spain has been attributed to gas-related overpressuring (Maestro et al., 2002), indicating that the above scenario is plausible.

The Agua de la Peña system, although much smaller in width and depth to detachment, has a consistent geometry with much larger detachment-related and convergent-related critically tapered wedges. Not only does the geometry closely resemble detachments like the Gulf of Mexico and the Niger Delta, but is also similar in shape to compressional wedges like the Appalachian, Canadian Rockies, and Western Taiwan fold and thrust belts (Davis et al., 1983; Peel et al., 1995; Bilotti and Shaw, 2005). These examples are much larger, but in general display the same basinward-dipping surface slope and hinterland dipping décollement, which converge to a point at the toe of the wedge. The Agua de la Peña system compares well with convergent and passive-margin wedges with low tapers such as the Makran accretionary wedge, the toe of the Barbados accretionary wedge, and the contractional wedge at the toe of the Niger Delta (Figure 22B), all of which have been interpreted to have relatively high basal pore fluid pressures (Bilotti and Shaw, 2005).

COMPARISONS WITH PASSIVE-MARGIN DETACHMENT SYSTEMS

While the Agua de la Peña detachment is the first syndepositional, extensional-contractional fault system to be described from lacustrine rocks, its first-order geometry is comparable to passive margin detachment systems including those in the Gulf of Mexico and near the Niger Delta in the eastern Atlantic (Bilotti and Shaw, 2005; Peel et al., 1995; Rowan et al., 2004; Trudgill et al., 1999). Both the Gulf of Mexico and Niger Delta detachment systems have been fed by large fluvial systems since the Mesozoic and Tertiary, respectively (Bilotti and Shaw, 2005; Cohen and McClay, 1996; Damuth, 1994; Feng, 1994; Feng et al., 1994; Salvador, 1991; Winker and Buffler, 1988). Consequently, much of the Gulf coast of North America and the coasts of Nigeria and Cameroon have developed large prograding wedges of sediment. In terms of depositional processes and overall geometry, these continental-margin detachment systems are similar to the Agua de la Peña system discussed above, although they are 2-3 orders of magnitude larger. The mechanisms driving deformation in all of these systems, however are interpreted to be similar (Bilotti and Shaw, 2005; Peel et al., 1995; Rowan et al., 2004). Given that the geometry of a critical wedge with a given taper should be scale independent, normalized wedge dimensions in large-scale, paired extensional-contractional systems should be similar to
those of smaller systems. A comparison of the overall geometry of paired extensional-contractional systems of the Niger Delta, Gulf of Mexico, and Ischigualasto basin is presented below to illustrate both the similarities and differences between the systems.

The wedge created by the Niger Delta system is over 200 km wide with a maximum thickness of ~7.5 km (Table 2; Figure 23). The slope of the bathymetric surface dips seaward at ~1° (Damuth, 1994). The deformation system is arcuate in map view, with displacement on both extensional and contractional faults decreasing towards the margins (Morley, 2003). Structurally, the Niger Delta is segmented into three zones with an extensional zone near the coast, a transitional area above a low angle detachment, and a frontal fold-thrust belt (Damuth, 1994; Morley, 2003; Bilotti and Shaw, 2005). The maximum width of the contractional part of the deformation system is ~125 km. In most of the system, the basal décollement has a dip of ~1.7° (Bilotti and Shaw, 2005), although the frontal thrust ramps up section an angle of ~ 22° (Bilotti and Shaw, 2005). Seismic and well-bore data show the hanging wall of the detachment system sits on top of two overpressured shale horizons, with $\lambda_\phi$ estimated at ~98% (Rowan, et al., 2004; Bilotti and Shaw, 2005).

**Table 2.** Contractional-wedge dimensions for passive margin-Ischigualasto basin detachment systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Thickness Km</th>
<th>(H)Contractional Width (L_c) Km</th>
<th>H/L_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Isabel</td>
<td>7.5</td>
<td>34</td>
<td>0.22</td>
</tr>
<tr>
<td>Niger Delta</td>
<td>6.0</td>
<td>50</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Agua de la Peña</strong></td>
<td><strong>0.045</strong></td>
<td><strong>0.455</strong></td>
<td><strong>0.10</strong></td>
</tr>
<tr>
<td>Perdido</td>
<td>20.0</td>
<td>250</td>
<td>0.08</td>
</tr>
<tr>
<td>Central Gulf</td>
<td>20.0</td>
<td>375</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Deformation systems in the Gulf of Mexico are varied. Much of the Gulf of Mexico is underlain by the Jurassic-aged Louann Salt, which serves as the basal detachment for the majority of the paired systems. In the Gulf of Mexico, as the wedge of shelf sediment slowly migrated basinward, the underlying salt was gradually expelled. Subsequently, where shelf strata were translated basinward, large, salt-soled extensional systems developed. In some locations, extensional slip was translated along a horizontal/landward dipping detachment to
Figure 23. Diagram comparing relative geometries of a number of contractional wedges from paired detachment systems. Port Isabel, Perdido, and Central Gulf profiles modified from cross sections of Peel et al. (1995); Niger Delta profile modified from cross section in Bilotti and Shaw (2005). See Table 2 for actual wedge dimensions.
form a wedge-shaped, fold-thrust belt near the continental shelf-slope break (Figure 19). Other similar linked extensional-contractional deformation systems with shale décollements formed at shallower levels. Most of the larger extensional-contractional systems in the Gulf of Mexico, including the Central and Perdido Fold belts are related to displacement above mobile salt. The Port Isabel system, however, is primarily associated with shale detachments (Rowan et al., 2004). The dimensions for the deformation systems described below are derived from regional/reconstructed cross sections for the Gulf of Mexico presented in Peel et al. (1995), Trudgill et al. (1998), and Rowan et al. (2004).

The Central Gulf deformation system is ~650 km wide, with a contractional zone ~375 km in width (Table 2; Figure 23). The maximum thickness of the contractional wedge is ~20 km thick, with an average surface slope (α) and a detachment angle (β) of ~0.5°, ~2.4°, respectively. Based on growth strata in both the extensional and contractual zones, deformation began during the Cretaceous and has continued into the Holocene (Peel et al., 1995).

The Perdido deformation system in the western Gulf of Mexico is ~270 km wide, with a contractional length of ~180 km, and a maximum thickness of ~20 km (Table 2; Figure 23). The contractional portion of the Perdido system has an average α of ~0.8°, and a β of ~2.4°. Growth strata in both the extensional and contractual zones indicate the majority of deformation occurred during the Oligocene (Trudgill et al. 1998).

The Port Isabel fold belt is situated the hanging wall of the Perdido system. The Port Isabel system contains multiple detachments, including a deep detachment horizon that soles into the Louann Salt, and shallower detachments in Cenozoic shales. Because the deeper salt-related detachment is associated with Perdido belt deformation (Peel et al., 1995), below I focus on the shallower shale-detachment systems. The Port Isabel shale detachment system is ~50 km wide, and has a maximum contractual width of ~37 km. The contractional portion of the Port Isabel system has a relatively low angle (< 2°) that increases to > 50° at its tip (Figure 23). The average basal detachment angle is ~10°. Structural reconstructions indicate a surface slope of ~ 0.5° during deformation (Peel et al., 1995). The maximum thickness of the wedge is ~7.5 km. Growth strata in both the extensional and contractual zones indicate deformation occurred during Oligocene-Miocene time (Peel, et al., 1995).

Collectively, for each of the passive margin detachment systems described above, there is a correlation between wedge thickness and width. For example, narrow wedges tend to be thin.
while wider wedges are thicker. This is expected if the overall wedge taper drives deformation (Davis et al., 1983). Plotting thickness vs. width ($H/L_c$) in these systems yields a linear relationship with an $R^2$ value of 0.88 (Figure 24A). Likewise, plotting $H/L_c$ vs. average taper angle in these systems produces a relationship with an $R^2$ value of 0.78 (Figure 24B). Although the sample size may greatly influence the statistical relationships, the lack of a 1:1 ratio in these systems, either between $H/L_c$ or $H/L_c$ vs. taper angle, is most likely related to the rheological properties of the basal detachment. Thicker and wider wedges (Central Gulf and Perdido) have salt detachments while the narrower/thinner wedges (Port Isabel, Niger Delta), however, have shale detachments. This may be due to the fact that salt, unlike shale, has little to no shear strength, which allows it to move as a viscous fluid in response to relatively small shear stresses.

The geometry of the Agua de la Peña detachment system matches closely with the four passive margin detachment systems described above. The Agua de la Peña contractional wedge, with a reconstructed thickness of ~45 m, and a width of ~450 m has a $H/L_c$ ratio of 0.1, which is very similar to the Niger Delta and Perdido contractional wedges (Table 2). In addition, the overall cross sectional geometry is also similar to the Niger Delta and Perdido contractional wedges (Figure 23). Given these similarities, the Agua de la Peña system, and associated deformation features, may provide an excellent scale analogue for passive margin extensional-contractional detachment systems associated with both shale and salt décollements. (Rowan, et al., 2004). As a result, larger volumes of sediment can be mobilized to generate a wedge with relatively low $H/L_c$ ratios and average taper (Dahlen, 1990).

**CONCLUSIONS**

The deformation exposed in the Agua de la Peña Canyon formed as a result of lacustrine/fluviial depositional loading in the Middle-Late Triassic Ischigualasto basin. On the eastern side of the ~ 1 km$^2$ study area, structures are dominated by north-striking normal faults. To the west, thrust faults and north-trending folds are the foremost structures. The eastern extensional area and the western contractional zones are linked by a bedding-parallel detachment fault, above which strata were translated to the west. Soft-sediment deformation and fluid-injection features along both thrust and normal faults indicate the presence of high pore-fluid pressures during deformation. Kinematic restoration of the paired extensional/contractional
Figure 24. A) Graph showing the relationship between maximum thickness and contractional width of the four passive-margin contractional wedges and the Agua de la Peña system. B) Graph showing the relationship between wedge thickness/length ratio and wedge taper.
system indicates that ~80 m of horizontal extension in the east is balanced by an equal amount shortening in the west.

The Agua de la Peña detachment system is interpreted to have formed as a result of gravity spreading/depositional loading of lacustrine delta platform and fluvial deposits above an overpressured shale décollement. Although 2-3 orders of magnitude smaller, the overall cross-sectional shape and interpreted driving mechanisms of the Agua de la Peña detachment are similar to gravitationally-driven, paired extensional-contractional fault systems formed along passive-continental margins. Given the geometry and interpreted rheological properties of the Agua de la Peña system, the contractional portion of the detachment can be modeled as a critical-tapered wedge and provides a small-scale analogue to fold-thrust belts formed in passive-margin settings.
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PLATE 1: Photo mosaic of the Agua de la Peta Canyon exposure. The mosaic shows the entire structure in cross sectional view. The contact between the Los Rastros and Ichigualasto formations depicted in black, interpreted faults are in red.